MODERNIZING LIFE CYCLE ASSESSMENT VIA INFORMATIC TECHNIQUES

by

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To Xing for her unwavering support and encouragement over the years.

To Mia for her angelic smile over the months.

Love you always and forever.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Life Cycle Assessment (LCA) is a widely recognized tool used to evaluate environmental impacts of a product or process, based on environmental inventory database, and supply chain information. Although significant progress has been made on the development of LCA methodology and growth of LCA applications, there are issues to be addressed. As the number of LCA related publication increases rapidly it becomes challenging to gain a comprehensive understanding on the state-of-the-art: only a small number of review papers have been published and they tend to narrowly focus on a particular field or application while literature search is largely done manually. In addition, almost all LCA software tools are still using the legacy desktop application which have steep learning curve, unfriendly user interface, and complicated installation and maintenance requirements. Moreover, life cycle inventory databases, which serve as the data foundation of LCA, are designed and managed as a centralized structure with slow updates and low spatial and temporal resolution i.e., not supply chain specific. The development of informatics techniques opens up numerous opportunities to address these issues. This dissertation reports one of the first effort on applying informatics techniques i.e., automatic content analysis (ACA), web-based application, and blockchain to modernize LCA.

For the first time, ACA is applied on LCA related research to comprehend the big picture and get a better overview regarding the focus and evolution of LCA related research. The results show that while the field changed overtime, the most interested environmental category remained to be carbon emissions. However, the result also shows that while computer science has evolved considerably, modern informatic techniques have only had a scattered impact on LCA. To overcome the limitation of current LCA software, an idea of developing a web-based application to benefit LCA implementation is proposed, especially for a certain type of industry with complex and hierarchical bills of materials. In cooperation with International Electronics Manufacturing Initiative (iNEMI), a web-based application is developed named Eco-impact Estimator (EiE). EiE is capable of performing quick and straightforward eco-impact estimation, especially for information and communication technology (ICT) products, with more than 50 users currently. To further optimize LCA, decentralized structure might be necessary. A new method is needed that can automatically back track supply chain along with material flow, with robust data availability and privacy. A blockchain-based LCA (BC-LCA) is proposed to solve this problem, with a

framework built up, a detailed mechanism discussed, and a case study provided based on a practical industrial supply chain. Result shows that BC-LCA could improve data availability by providing increased data privacy and timeliness with the application of blockchain. Furthermore, the more nodes from a supply chain that join in BC-LCA, the better it could get.

With the help of informatic techniques, LCA can be improved significantly, including generating a more quantitative research overview, developing a more user-friendly LCA web-based application for ICT product manufacturing, and providing a LCA framework with more data availability, data privacy and data timeliness. Though it is still necessary to estimate the budget for such implication, which e is left as future work, trialing on interdisciplinary solutions may bring a new possibility to classic LCA.

1. INTRODUCTION

1.1 Rising Attention to Environmental Problems

As society and scientific technology has progressed, environmental problems have garnered more and more attention. The public has started questioning whether their shopping bags are reusable or recyclable, whether the straw from fast food store is environmentally friendly, whether their vehicles could be more energy efficient with less carbon emission. All these questions are meaningful for our planet, but they are too simplistic and do not consider other problems. For example, whether paper bags are better than plastic bags, whether paper straws are more environmentally friendly than plastic straws, and whether electric vehicle could emit less carbon than gas vehicle. To answer these questions, a tool is needed to quantitatively evaluate the environmental performance.

1.2 Introduction to Life cycle assessment

Originally started in 1990s, life cycle assessment (LCA) is first developed to evaluate the environmental impact during manufacturing phase or to compare the environmental performance of two products, by gathering bills of material in every manufacturing step (Klöpffer, 2005). Overtime, this tool is enhanced to not only manufacturing, but also transportation, use and end-of-life phase. In this way, LCA become a standard tool to accurately and quantitatively calculate environmental performance, considering various pertinent environmental impact categories such as global warming or eutrophication. Afterwards the goal of LCA would expand from products to processes, which may have one or multiple outputs. Under this phase of LCA development, many organizations started to collect environmental impact data of various unit process, which is called environmental inventory. Simultaneously, LCA software (OpenLCA, SimaPro, etc.) is being developed, trying to provide a generic platform for researchers and industry (Herrmann & Moltesen, 2015). After several year of growing and preparing, these organizations become commercial companies, specifically developing LCA software and maintain environmental inventory database. Years after, these LCA tools and database are widely used in academic and industrial field.

1.3 Development of informatic technology

LCA is not the only field that has made progress. In recent decades, computer science and informatic technology have experienced dramatic growth, including hardware development and algorithm innovation. Hardware development guarantees more calculation power, and algorithm innovation has led to many fancy functions become reality, such as facial recognition, artificial intelligence, internet of things and so on. With the help of these technologies, our daily life has become more convenient. However, this makes us wonder - is it possible to apply these informatics technologies to improve LCA?

This is the premise of this thesis. When enjoying the benefit from technology development, it is worthwhile to think about how to bring this benefit to other fields. Detailed examples of how we bring this interdisciplinary approach to LCA are presented.

2. AUTOMATED CONTENT ANALYSIS (ACA) IMPLICATION ON LIFE CYCLE ASSESSMENT (LCA) RELATED RESEARCH

2.1 Introduction

The exponential growth of scientific literature, called 'big literature' phenomenon, has created great challenges in literature comprehension and synthesis. The traditional manual literature synthesis processes are often unable to take advantage of big literature due to human limitations in time and cognition, creating the need for new literature synthesis methods to address this challenge.

Automated Content Analysis (ACA) is a specific algorithm that is designed to treat large texture information and provide a visual output (Smith & Humphreys, 2006). It has been developed since 1990s (Papadimitriou et al., 2000), and the original process includes sifting, classifying and simplification of published research. In this project, we are looking into how the research topic – namely, LCA research -- changes in the last 18 years and make some expectations in the developing trend for the future.

2.2 Automated Content Analysis

Previously, literature review process is done manually, where typically researchers read all the papers, posters and book chapters from all the sources. This process has lots of limitations, including biased estimation and uncovered topics (Nunez-Mir et al., 2016). Meanwhile, due to the time limitation and the efficiency of manual reading, sample size could be another problem affecting the estimation. For example, many LCA review papers only consider the result from top 5 journals, stating this limitation of time and efficiency. However, that may lose some important information from other journals, and result in some biased conclusion. Thus, we may need a new method to overcome these disadvantages and use a more efficient and reliable procedure. There is some research that considers using computer-assisted method to analysis published papers.

ACA is one such computer-assisted method which could make up the cons and is widely accepted or introduced by many scholars, in many fields. Besides, there are some research about the confirmation of the ACA method result, which shows the accuracy and liable of such kind of methodology (Cheng, 2016; Cheng & Edwards, 2015; Jin & Wang, 2016). Leximancer is such a software based on ACA method, consisting of two stages: semantic and relational. Each stage uses different algorithm, which includes statistical analysis with non-linear dynamic and machine learning (Smith & Humphreys, 2006). It is the first time to introduce Leximancer into the field of LCA study, as this field is traditionally more about physical science or engineering, rather than social science or business management. Details about the algorithms, development background and output validation of Leximancer software could be found from the company's website and inventor Smith, A. E. Here we briefly introduce the ACA procedure (Smith & Humphreys, 2006).

The whole ACA procedure is divided into 3 steps, shown in Figure 2.1, including concept definition, concept identification and text classification.

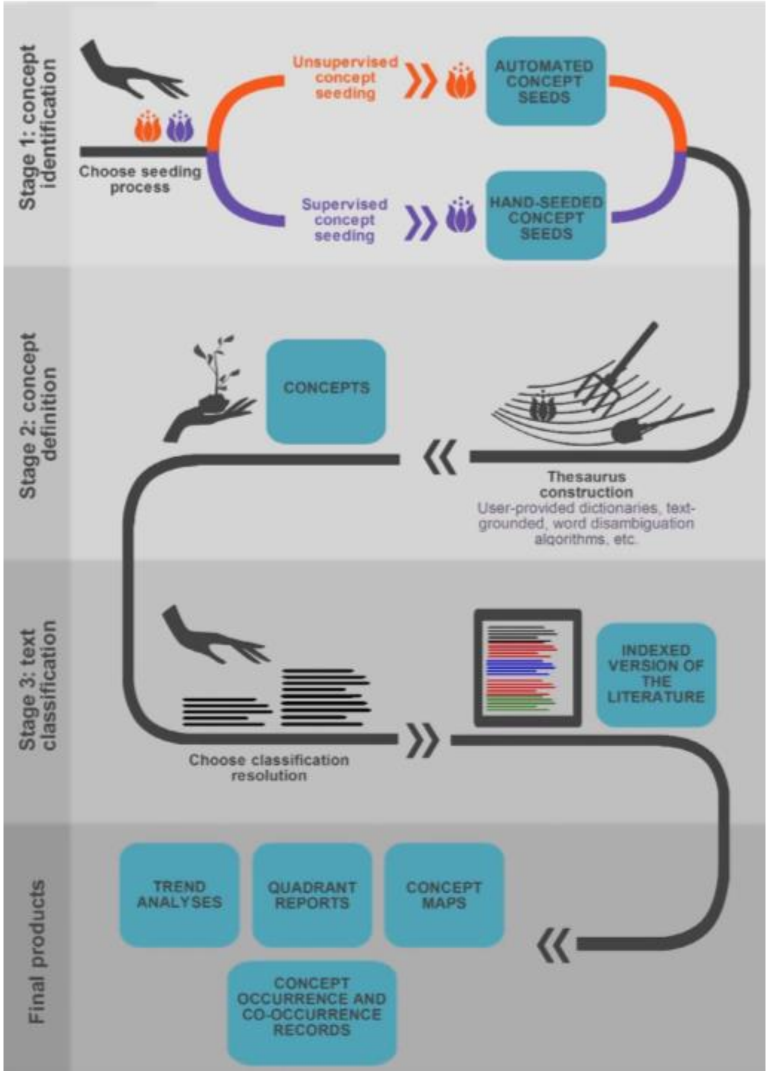


Figure 2.1 ACA Procedure Flow Chart (Nunez-Mir et al., 2016)

1. Concept Identification
   a. Aim: to determine the concept.
   b. Process: A concept seed should be chosen automatically or manually, so that these concept seeds can lead to the concept identification. Afterwards, users need to modify the expected concepts and their identification.
2. Concept Definition
   a. Aim: Building thesaurus, which is another group of words that can describe the specific concept.
   b. Process: Using topic model or concept mapping algorithm

    c. Some algorithms may give every word in the thesaurus a weight, depends on their correlation to the concept.
    d. A specific concept can be defined by a series of words, with their accumulative correlative weight reach a threshold.
3. Text Classification
    a. Aim: Classify the literature by the identified and defined concept.
    b. Process: High resolution is preferred, which means the text segment is comparatively very small.
    c. If a text segment matches the definition of a specific concept, hit occurred.
4. Afterwards
    a. Visualization
    b. Statistical output (hit count, correlation between different concepts, etc.)

2.3 Methodology

In this study, 19,354 abstracts about LCA research are obtained from Scopus. All these researches contain keywords "life cycle assessment" or "LCA" either in titles, abstracts or index keywords, with impact factors greater than or equal to 1.0. The time interval of these researches is from 2001 to 2017, as the concept of LCA was established in 1990s, and this study was done in early 2018.

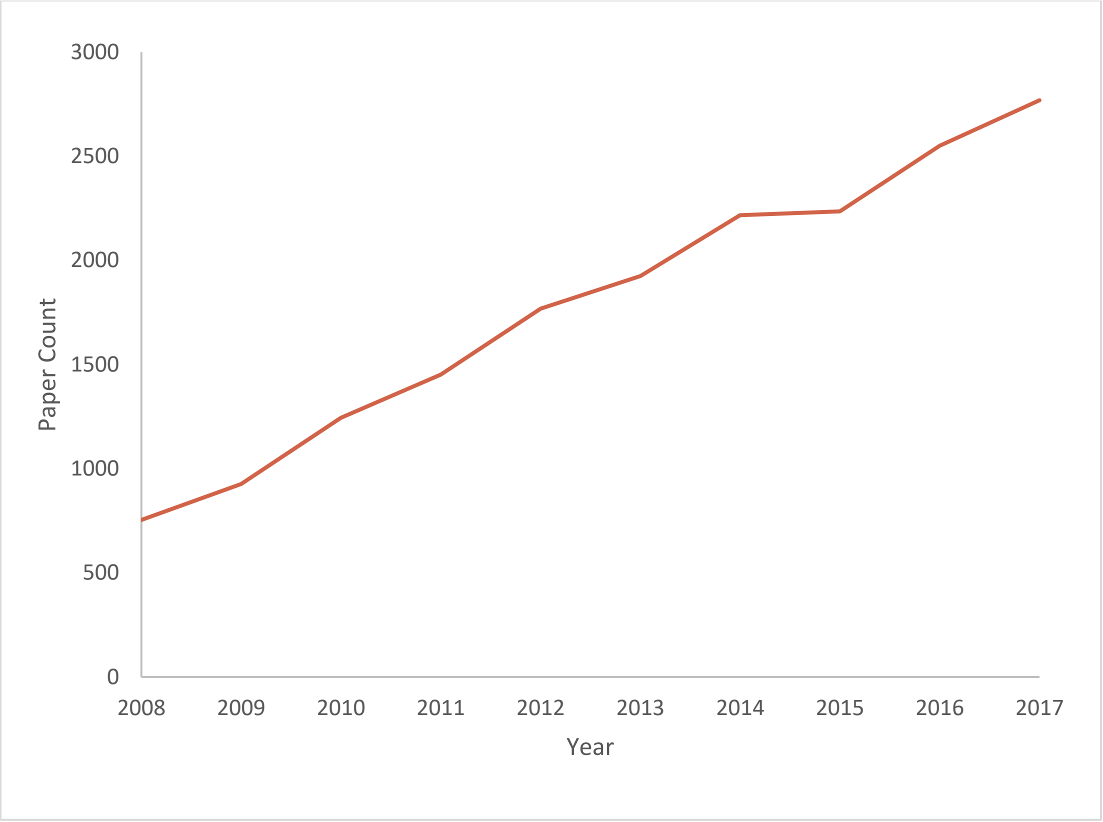


Figure 2.2 Total Paper Count on LCA related research

Figure 2.2 shows the total paper count on LCA related research. It is obvious that the total number of papers have consistently increased, which also means the impact of LCA is increasing.

After all abstract datasets are ready, it is necessary to perform a manual reading, to get a comprehensive understanding about different topics in LCA, including application and methodology. Here, 50 review papers related to LCA are selected, according to their impact factors and publication year: the papers that are more recently published in journals with higher impact factor would be first selected. This reading provides an approximation on LCA research trend and different view of researchers on how a study field is developed. Furthermore, several concepts could be selected as hot topic, according to words frequency and importance, to generate concepts dictionary.

Here's the selected concepts, which are grouped into 3 sections: LCA application, LCA methodology and environmental impacts. In LCA application, all topic related to the implication of LCA are included. In LCA methodology, all research that focus on LCA itself, from conceptualization to algorithm. And in environmental impacts, it counts the number of papers interested in different environmental impacts.

1. LCA application:

   Clean energy, Fossil energy, Recycling, Human health, Agriculture, Waste, Manufacturing, Building construction, Material, Packaging, Waste treatment, Economic sustainability

2. LCA methodology:

   Consequential, Dynamic LCA, Social LCA, Method, Data analysis, Information, Case study

3. Environmental Impacts:

   Ozone depletion (kg CFC-11 eq), Global warming (kg CO2 eq), Smog formation (kg NOx eq), Acidification (H+ moles eq) , Eutrophication (kg N eq), Human health cancer (kg benzene eq), Human health noncancer (kg toluene eq), Human health criteria pollutants (kg PM2.5 eq), Eco-toxicity (kg 2,4-D eq), Fossil fuel depletion (Surplus MJ/yr), Land use (density of threatened and endangered species), Water use

Afterwards, these key concepts would be input into ACA, and the output includes hit ratio data grouped by sections, and a cloud map to describe the relationship in between concepts. Hit radio is defined as: when a concept is detected present in an abstract once, then it would count as one hit. The ratio between hit count and paper count, is hit ratio. Thus, hit ratio could be larger than 100%, if a concept is so popular that on average, every abstract would mention that concept more than once.

2.4 Results

All statistical results from ACA are posted here separated into five sections: LCA application, LCA methodology, environmental impacts, overview, and cloud map. More results are shown in Appendix A.

2.4.1 LCA application related topics

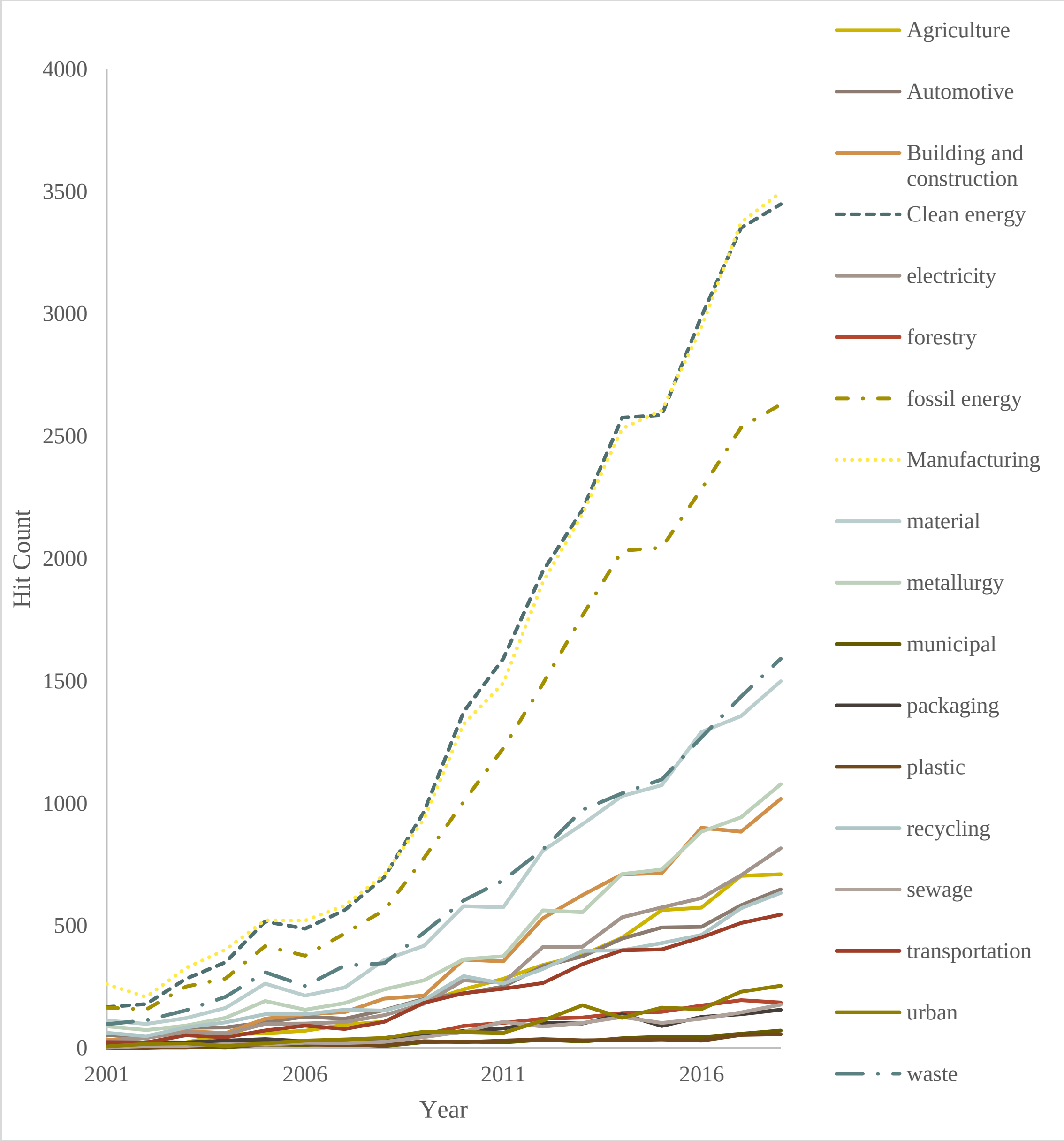


Figure 2.3 LCA application related paper count

Figure 2.3 shows the hit count of different LCA implication from 2001 to early 2018. The hottest topic is clean energy related and manufacture related LCA. Due to the development of clean energy, increasingly research focuses on the comparison of clean energy and traditional fossil energy(Deng & Kendall, 2019; Ling-Chin et al., 2016; National Renewable Energy Laboratory (US) et al., 2013), offering a reason why fossil energy could be the third hottest topic.

Manufacturing is one of the classic application of LCA, based on which the original framework is designed(Guinée, 2002). In early 2001, the hit count for manufacture is the most significant among all topics, which proof that at the very beginning, LCA is mainly used to estimate the environmental impact in manufacturing.

As the number of published papers has increased, the difference between the hit count of clean energy and fossil energy is growing, which means more papers prefer to mention clean energy than fossil energy. However, the hit count of manufacturing and clean energy stays on a similar trend. From the manual reading, it is observed that more and more papers focusing on clean energy manufacturing, because the popularity of clean energy facilities (Mälkki & Alanne, 2017). Material science is also a very hot topic in LCA application, as shown in Figure 2.3, because almost all manufacturing related research has some connection with material development, and the environmental impact of material cannot be ignored.

One more interesting topic is waste, as waste management, or end-of-life stage, is the end of the whole life cycle, and plays a significant role. From Figure 2.3, waste is one of the most significant topics in 2001, which means there are a certain number of papers focusing on waste management, even in the early stage of LCA development. Along with the development of LCA and optimization of the whole industrial ecological environment, the popularity of waste management is decreasing (Laurent et al., 2014). The reason behind might be the improvement of end-of-life technology, so that waste management is not as pressing as a problem. Or researchers realize that such topic might not be only an academic problem, but also a political problem, as the improvement of policy could largely optimize this problem.

2.4.2 LCA methodology related topics

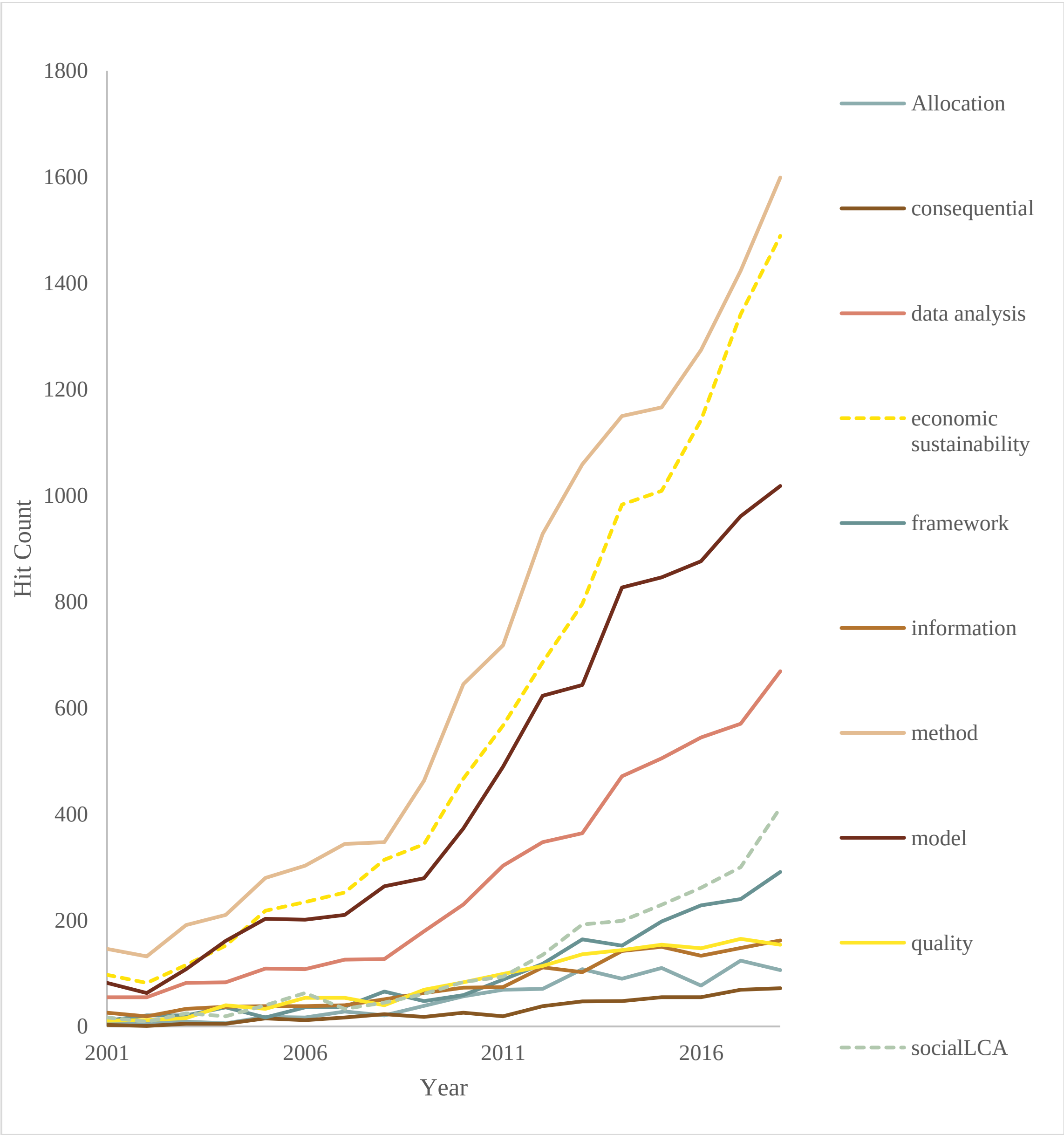


Figure 2.4 LCA Methodology Related Paper Count

Figure 2.4 is the hit count of LCA methodology related research. One interesting thing is, the hottest topic, beside “method” itself, is economic sustainability. It seems academia cares about economic concerns, while analyzing environmental impact(Bałys et al., 2021; Kaushik & Muthukumar, 2018; Lawrence Berkeley National Laboratory et al., 2020; Wu et al., 2018).

Next hot topic is “model”, which relates to the mathematic model behind LCA. This topic shows there is some research related to model modification or improvement. Another interesting observation was that social LCA is not a significant topic among all the methodology related papers. Framework is another key topic in LCA methodology, which means a significant number of papers are trying to do some research around LCA framework(Gracey & Verones, 2016; Kalberlah et al., 2018; United States Dept of Energy Office of Scientific and Technical Information, 2019). Though LCA framework is one of the classic theories compared to other LCA methodology topics, there is still some possibility to make some improve. However, the difference between the hit count of LCA framework and economic sustainability shows that the improvement potential of LCA framework is not that much.

2.4.3 Environmental impacts related topics

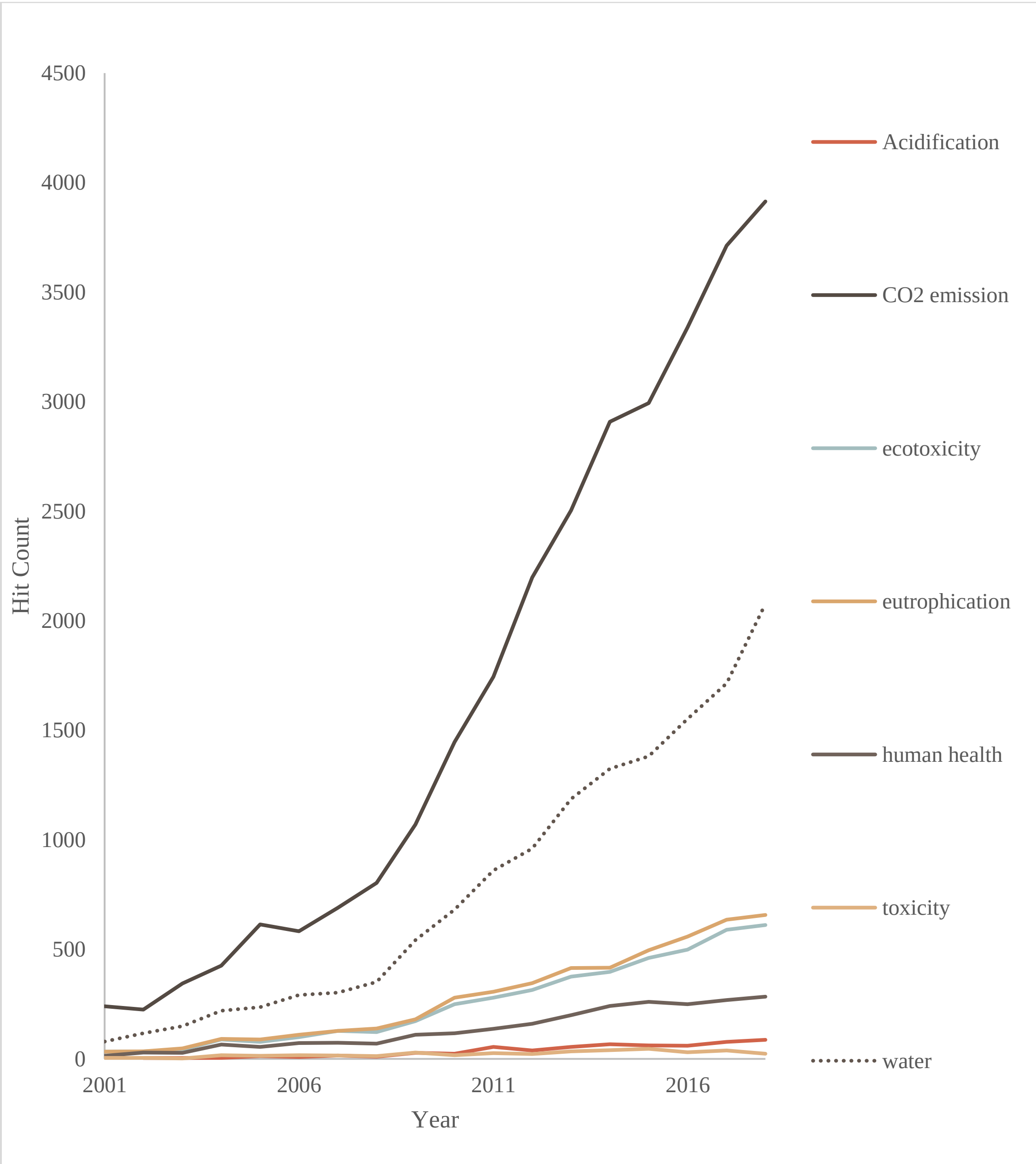


Figure 2.5 Most Discussed Environmental Impacts

Figure 2.5 shows the environmental impact that were mentioned the most among all papers. There's no surprise that carbon emission takes the most significant place, and water takes the second. Global warming is a very thorny problem, which affects everyone, and gets the most attraction(Miller, 2013). Especially after Paris Agreement under the United Nations Framework Convention on Climate Change, there is a high amount of attention given to research related to carbon emission(National Research Council (US) Committee on Methods for Estimating Greenhouse Gas Emissions, 2010; United States Congress House Committee on Science and Technology Subcommittee on Energy and Environment, 2009; World Meteorological Organization Commission for Agricultural Meteorology et al., 2004).

Another interesting point is water consumption. Water consumption itself does not belong to environmental impact, because no matter how much water consumed, it will always return back to mother nature. However, what industrial and academic really care about water is the emission that goes into water body, which may result in some environmental problem or even health issue to humanity. The increasing attention for water consumption as one kind of environmental impacts, shows that scholars are trying very hard to limit the environmental impact, by evaluating the water consumption during a process.

The third and fourth most popular topics are toxicity and ecotoxicity. These two topics have some correlation, but pointing at different target. The correlation between them lead to a very similar trend in Figure 2.5.

2.4.4 Overall view of different topics

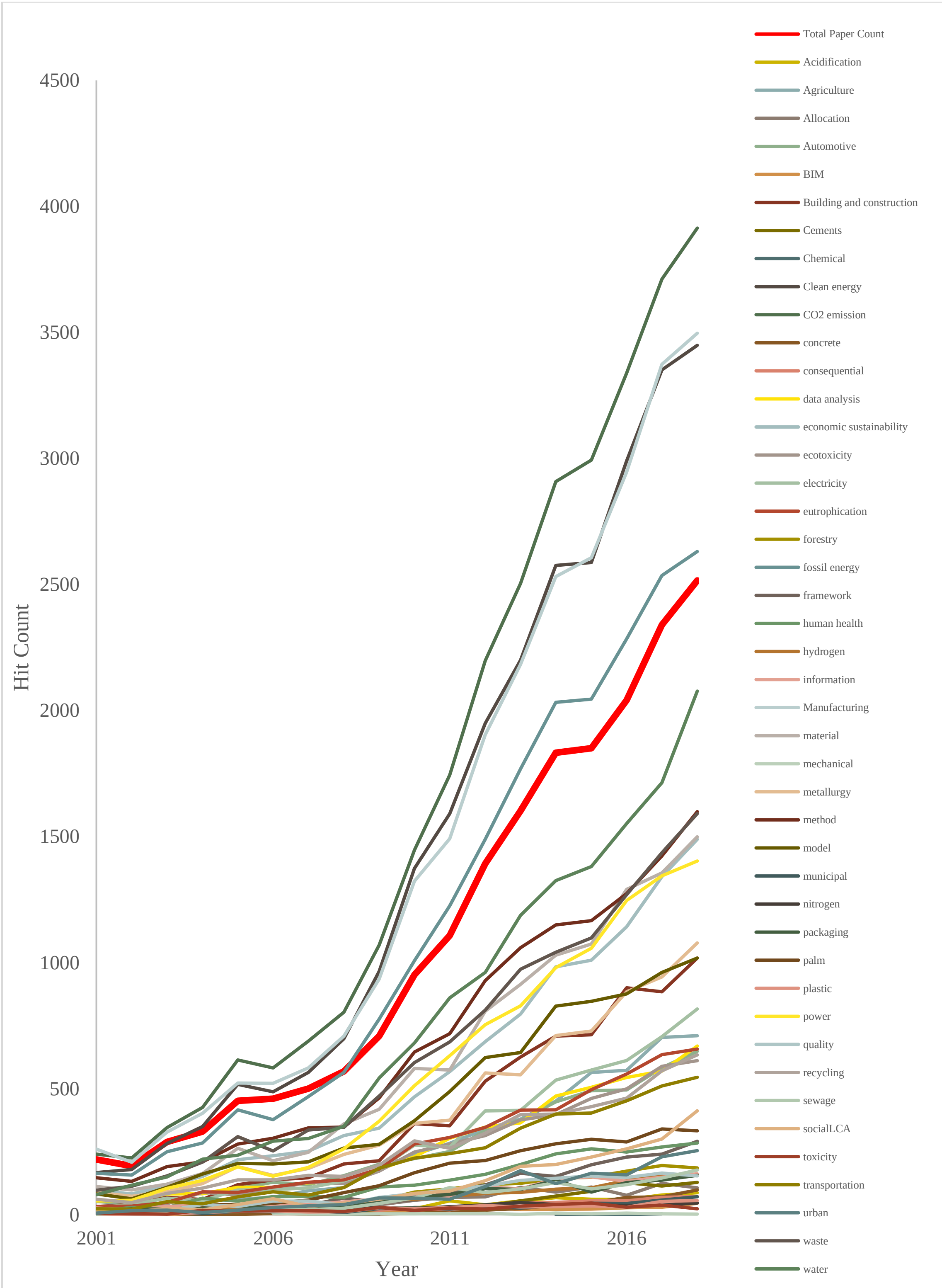


Figure 2.6 Overall Most Mentioned Concepts

Figure 2.6 is the overall count on different topics mentioned in all of the papers. The most obvious red line is the total paper count. And some concepts have even higher hit count than total paper count, which means on average, in every abstract, this concept would be mentioned more than once. There are four concepts having hit count higher than paper count: carbon emission, manufacture, clean energy, and fossil energy. As discussed before, these are the hottest topic in LCA related fields.

Overall, carbon emission is the most popular topic among all other topics(Morris, 2017). On average, every abstract would mention carbon emission 1.5 times. Carbon emission is also the indicator of the one of the most important environmental impact, global warming potential(Klöpffer, 2005).

Manufacturing takes the second place among all LCA related topics. Manufacturing is originally the most significant application of LCA, and LCA framework is somehow designed based on the analysis of manufacture process(Milà et al., 1998; Muthu, 2015). The popularity of manufacturing is keep growing until today, shows a very good development on LCA, as the original target is never lost.

Clean energy and fossil energy are two correlative topics, both of which are always forming a comparison, to evaluate if a clean energy related technology can really decrease environmental impact(Cherubini et al., 2009). However, the hit count of clean energy is higher than fossil energy, since 2001. The reason behind is, some papers are more focusing on cleaning energy technique, and there is no such fossil energy technique that can compared with.

2.4.5 Cloud map of LCA topics

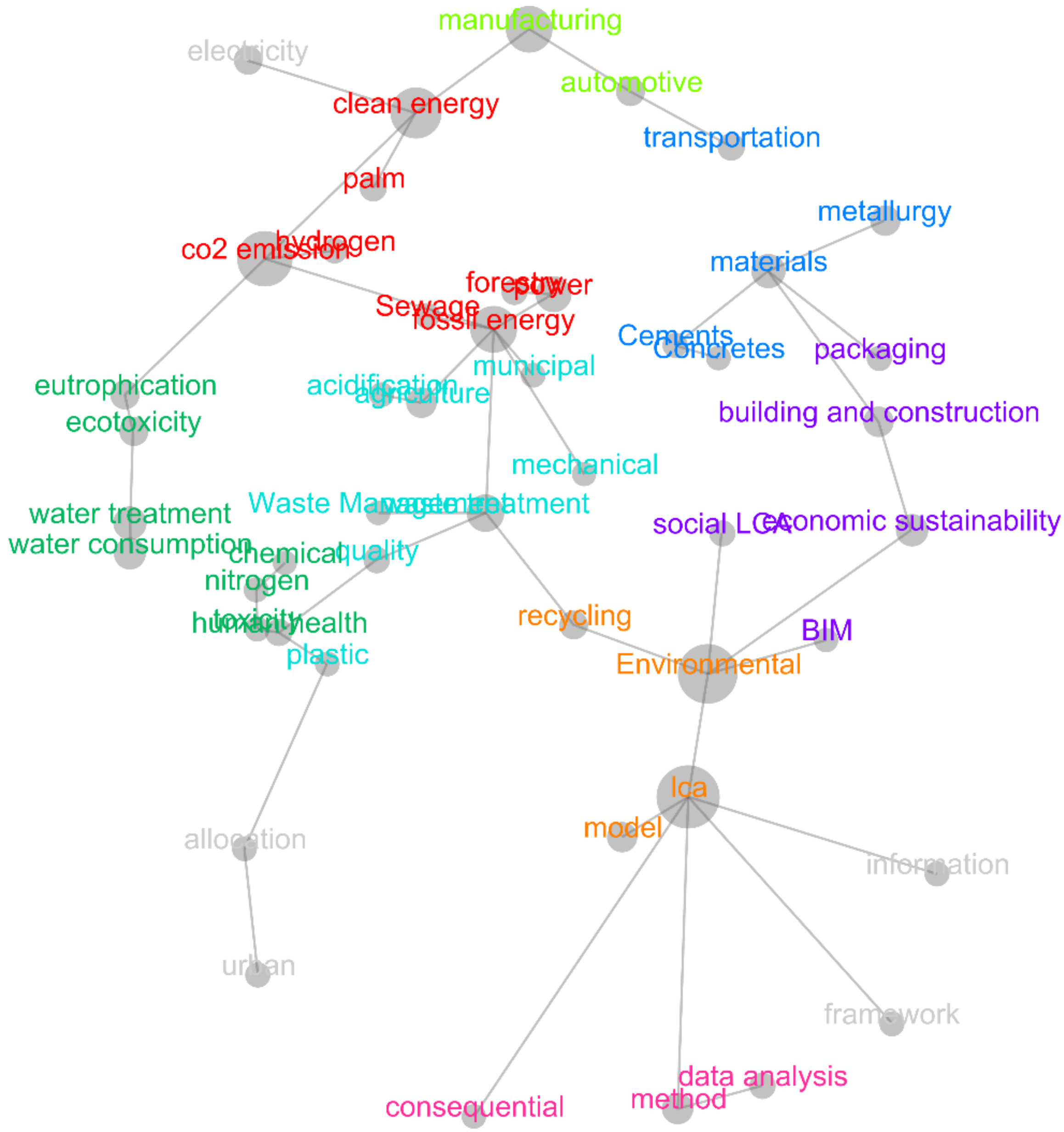


Figure 2.7 ACA Cloud Map showing the Relationship between Topics

Figure 2.7 is the cloud map from ACA, which shows the relationship between each topic. The distance between two nodes shows the likelihood, which means, if one concept is mentioned, what is the chance that the other topic is also mentioned. The area of the circle behind one topic, shows the significance of this topic. Color of one topic shows the cluster, which means, all topics are classified, and these topic under the same class would be marked the same color(Wilk et al., 2021). There are many observations to read from this figure. One such observation is that every topic in LCA, either directly connected or indirectly connected, is related to every other topic in LCA. Or in short, there is no isolated topic in LCA.

Another insight from Figure 2.7 is, by focusing on the distance between two concepts, the topics that could be take into consideration when doing related research. For example, if a researcher wants to do some research on LCA “data analysis”, then he/she can consider looking into “method” and “framework”, both of which have very high likelihood with “data analysis”.

2.5 Discussion and Next Step

After showing the result from ACA, it would be clear to see the research trend of LCA research. However, as mentioned before, there is a blank field. No result shows that the implication of informatic technology in LCA is a topic, not even stand out in the pre-reading process.

Thus, next step would be, select one informatic technology to improve LCA. Since this interdisplinary field is not popular before, there is chance to do some work and find out some interesting results.

3. INEMI EIE – A WEB-BASED APPLICATION

3.1 Introduction

Information and Communications Technology (ICT) is very important in the current informatic era, playing a significant role in the economy, and consuming a large number of resources and energy, which results in tremendous environmental impact during manufacturing, transportation, use and end-of-life. ICT products have comparatively short lifetime, and large demand, both of which magnify their negative impacts. Currently, climate change is a tough challenge that would affect everyone. Therefore, for ICT manufacturing, environmental impact reduction becomes a priority task to help combat climate change.

To successfully reduce environmental impacts, it is necessary to use a tool to measure the environmental impacts. Life cycle assessment (LCA) is a widely used methodology to evaluate environmental performance along with the life cycle of one product, from raw material extraction to disposal. It is common to use LCA software and correlated environmental inventory database to apply LCA in ICT products, but the whole process is time consuming and pricy. In industrial implications of LCA, the learning curve of LCA software is very high, which is not good to popularize LCA. The interface and operation of LCA software is also not user-friendly.

Here comes the idea to simplify the process for evaluating environmental performance of ICT products. A web-based application is developed, and demonstrated to a group of ICT company representatives, together with the help of the International Electronics Manufacturing Initiative (iNEMI) to demonstrate this simplification. This application provides a more efficient and easy way to calculate environmental impact of an ICT product and can also optimize the design. For now, this application only focusses on carbon emission.

3.2 Objective

The major objective in this section is to develop a practical user-friendly web-based application to perform LCA specifically on ICT product. With the help of iNEMI, the maintenance of data and back tracking supply chain could be accomplished (Okrasinski et al., n.d.). The linear regression model and parameters are all provided by iNEMI, and all .NET development was done by this study with the help of web-form technique. This sections below provide a summary of the work related to this eco-impact estimator (EiE), including framework innovation and database maintenance.

3.3 Functions

To evaluate the carbon emission along with the whole life cycle of an ICT product, EiE is designed to function as different modules. In this section, some screen shots are presented to demonstrate the working procedure of EiE. The link for EiE is: https://purduelca.ecn.purdue.edu/

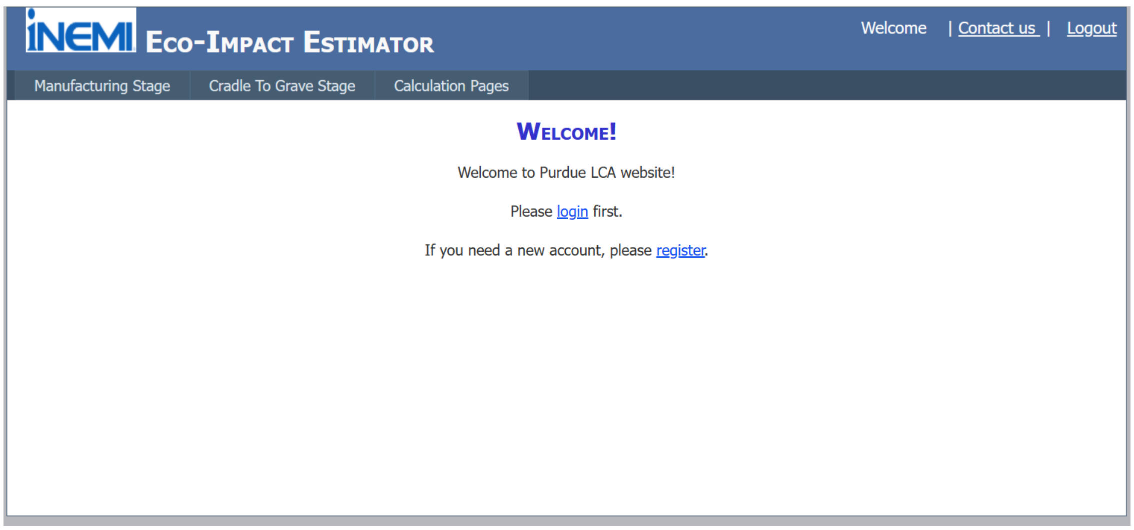


Figure 3.1 EiE index page

Figure 3.1 shows the index page of EiE, where there is a navigation bar, a welcome message, and a log-in system with contact information on right upper corner. Navigation bar allows users to switch page and function whenever. But please note that "Admin Search" is only open to administrator users. Welcome message would lead users to log-in first or register for a new account. And log-in system with contact information allows users to contact maintenance team when necessary. Generally, the very first step when using EiE is log-in. All functions are only open to legally registered users.

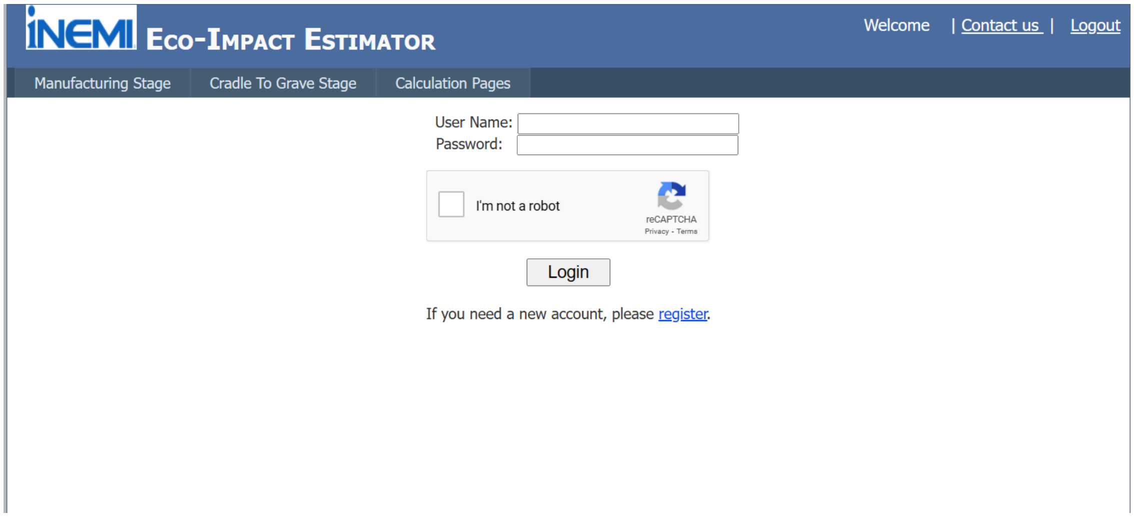


Figure 3.2 EiE Log-in Page

The log-in page is presented in Figure 3.2, where there are two textbox for username and password, along with a reCAPTCHA, which is a seamless fraud detection tool ("Teaching Computers to Read," n.d.), to prevent a distributed denial-of-service (DDoS) attack (Zargar et al., 2013).

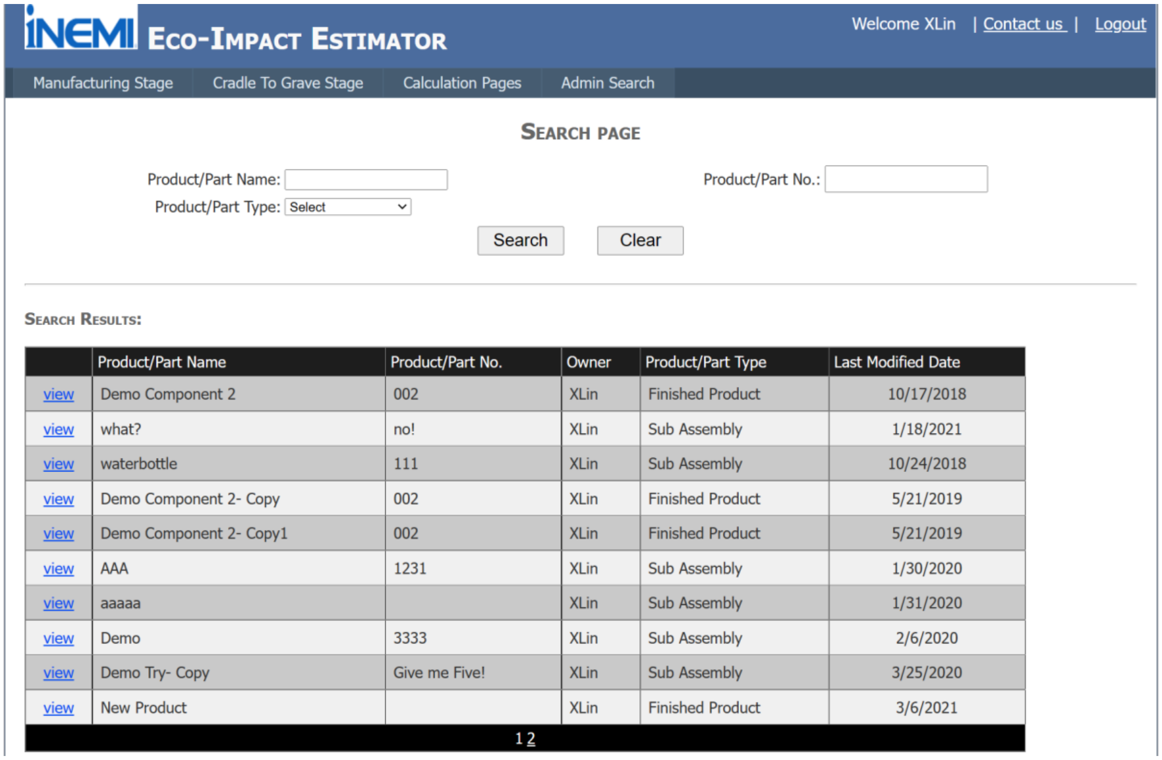


Figure 3.3 Personal Database page sample

After logging in, a user can see personal database page, shown in Figure 3.3. This page contains an inventory of all the components/products/pieces that the user created. There are also some search bar and categories drop down list for user to quick search. Note that a regular user can only view the items (components/products/pieces) that created by this user.

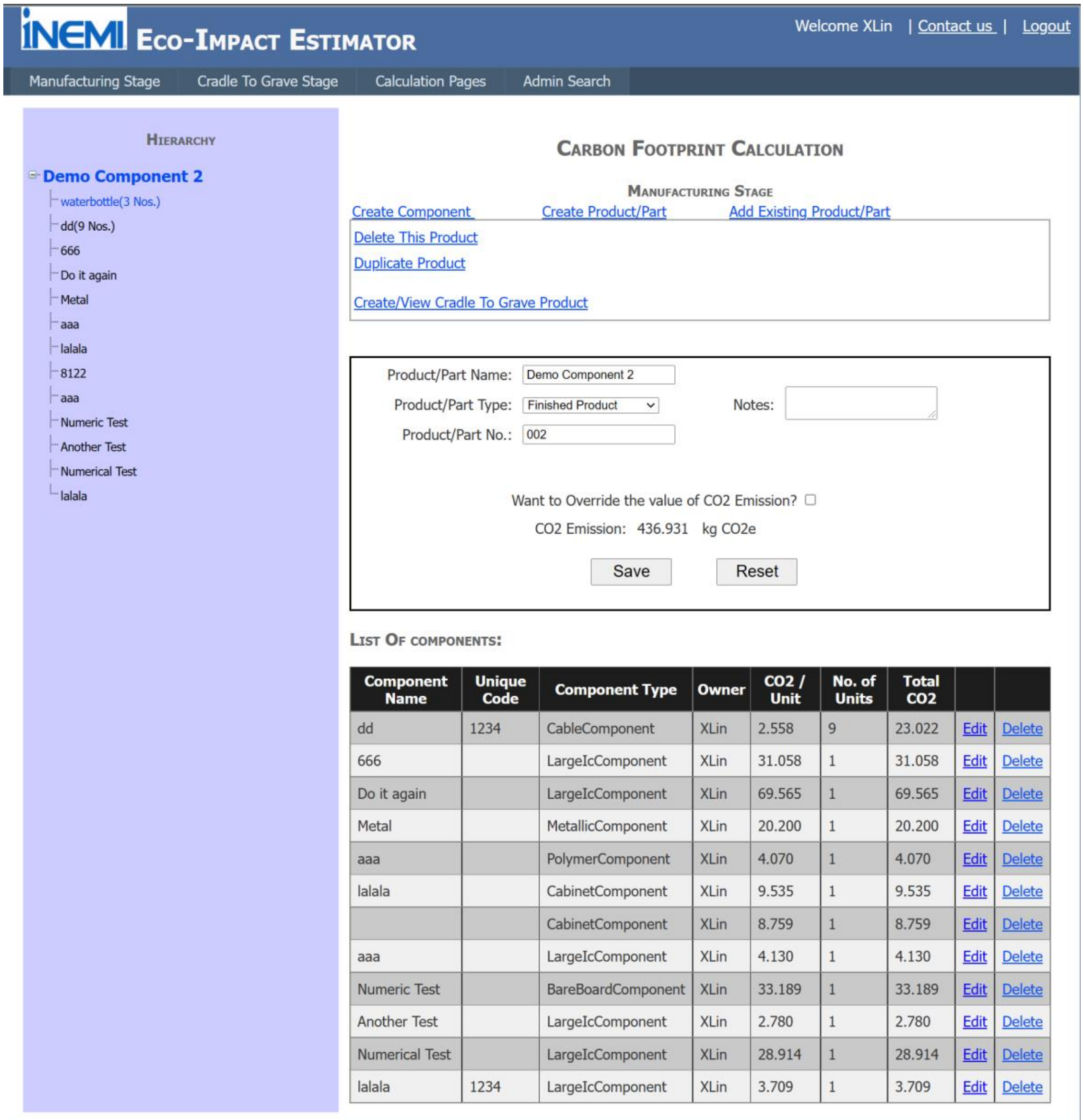


Figure 3.4 Item detail information page

When any item in personal database page selected, EiE would show the detailed information of this item, like Figure 3.4. In this item detail information page, all sub-components would be shown as “List Of Components”, together with a hierarchy graph, some basic operations to this item (duplicate, delete, add, etc.), and some basic information about this item (name, type, number, etc.). The user has the functionality to edit/create/delete one sub-component.

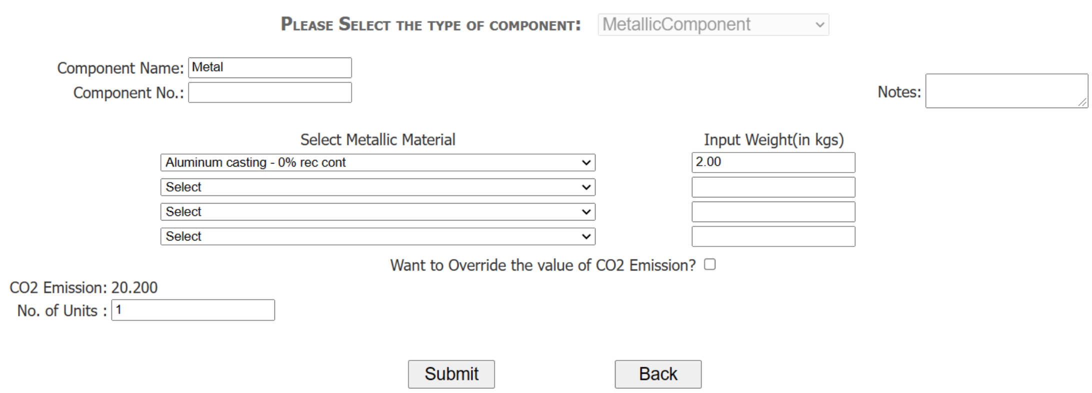


Figure 3.5 Create and edit component page sample

After clicking "Edit", the web tool turns to create and edit component page, shown in Figure 3.5. Here, Metallic Component is taken as an example. Users would need to select metallic materials and their weight, based on which carbon emission are calculated.

Above are all about manufacturing phase, but EiE can do much more than that. Usage, transportation, and end-of-life phase are also considered.

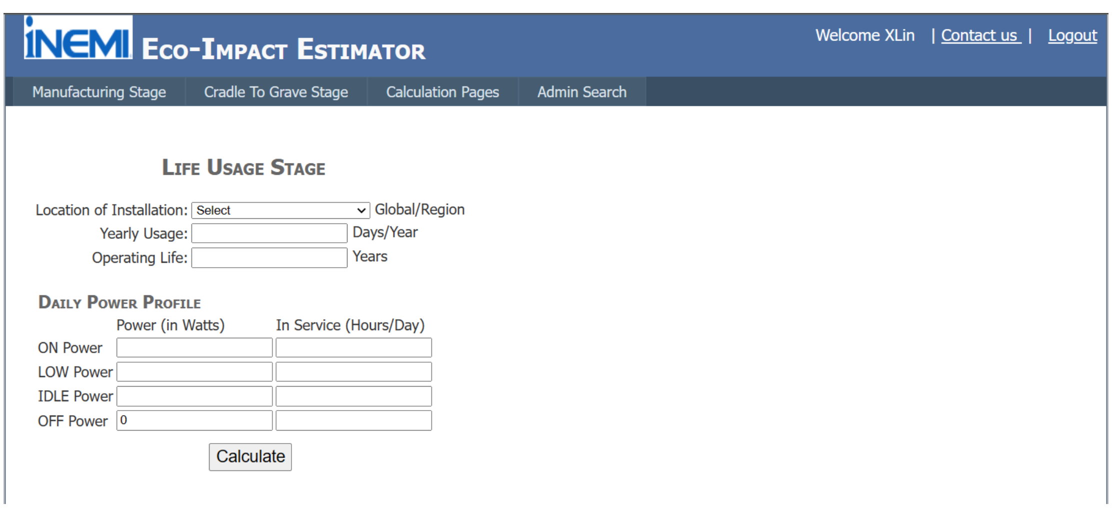
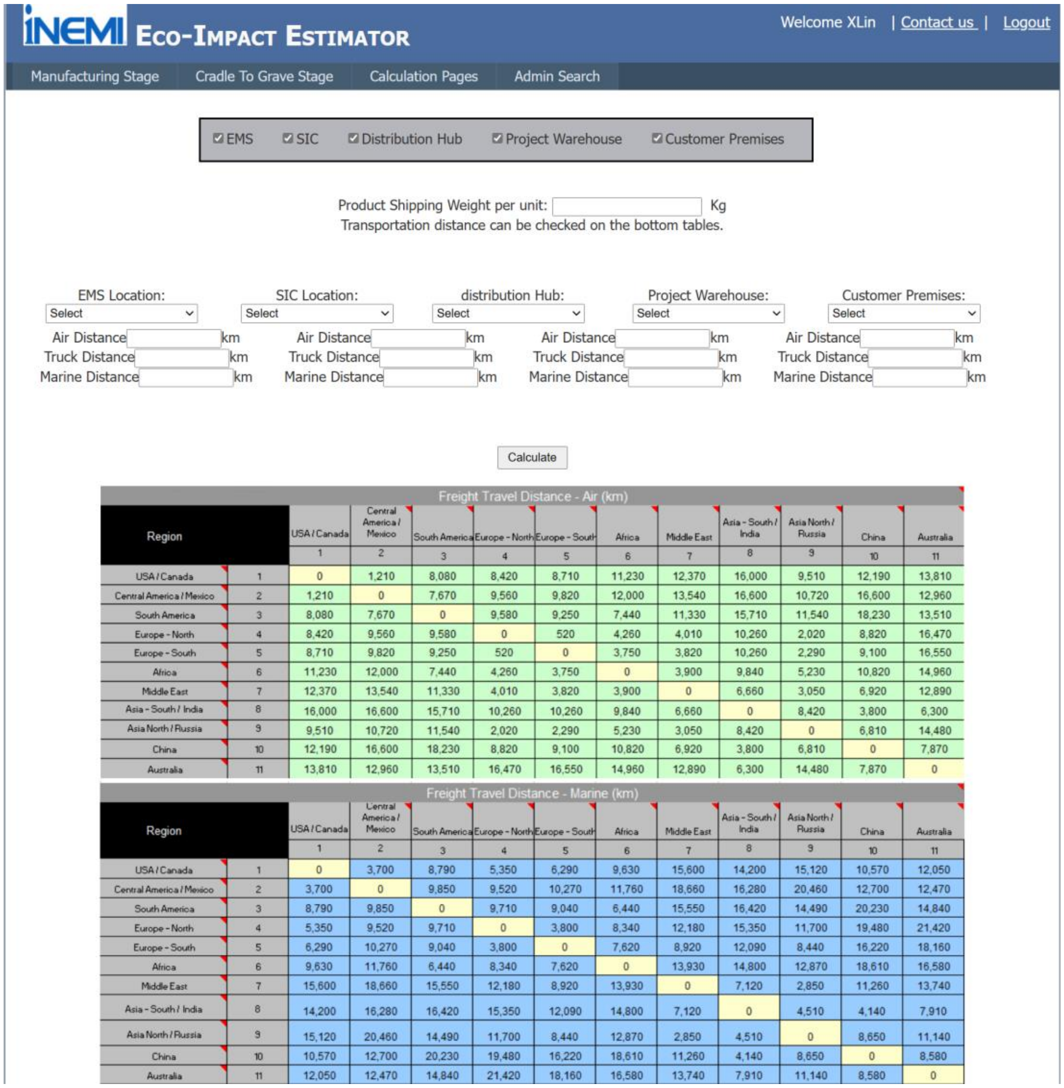


Figure 3.6 Use Phase page

Figure 3.6 shows the use phase page, where use phase carbon emission is calculated based on energy consumption. Parameters are comparatively simple, but useful.



Freight Travel Distance - Air (km)

Region		USA / Canada	Central America / Mexico	South America	Europe - North	Europe - South	Africa	Middle East	Asia - South / India	Asia North / Russia	China	Australia
		1	2	3	4	5	6	7	8	9	10	11
USA / Canada	1	0	1,210	8,080	8,420	8,710	11,230	12,370	16,000	9,510	12,190	13,810
Central America / Mexico	2	1,210	0	7,670	9,560	9,820	12,000	13,540	16,600	10,720	16,600	12,960
South America	3	8,080	7,670	0	9,580	9,250	7,440	11,330	15,710	11,540	18,230	13,510
Europe - North	4	8,420	9,560	9,580	0	520	4,260	4,010	10,260	2,020	8,820	16,470
Europe - South	5	8,710	9,820	9,250	520	0	3,750	3,820	10,260	2,290	9,100	16,550
Africa	6	11,230	12,000	7,440	4,260	3,750	0	3,900	9,840	5,230	10,820	14,960
Middle East	7	12,370	13,540	11,330	4,010	3,820	3,900	0	6,660	3,050	6,920	12,890
Asia - South / India	8	16,000	16,600	15,710	10,260	10,260	9,840	6,660	0	8,420	3,800	6,300
Asia North / Russia	9	9,510	10,720	11,540	2,020	2,290	5,230	3,050	8,420	0	6,810	14,480
China	10	12,190	16,600	18,230	8,820	9,100	10,820	6,920	3,800	6,810	0	7,870
Australia	11	13,810	12,960	13,510	16,470	16,550	14,960	12,890	6,300	14,480	7,870	0

Freight Travel Distance - Marine (km)

Region		USA / Canada	Central America / Mexico	South America	Europe - North	Europe - South	Africa	Middle East	Asia - South / India	Asia North / Russia	China	Australia
		1	2	3	4	5	6	7	8	9	10	11
USA / Canada	1	0	3,700	8,790	5,350	6,290	9,630	15,600	14,200	15,120	10,570	12,050
Central America / Mexico	2	3,700	0	9,850	9,520	10,270	11,760	18,660	16,280	20,460	12,700	12,470
South America	3	8,790	9,850	0	9,710	9,040	6,440	15,550	16,420	14,490	20,230	14,840
Europe - North	4	5,350	9,520	9,710	0	3,800	8,340	12,180	15,350	11,700	19,480	21,420
Europe - South	5	6,290	10,270	9,040	3,800	0	7,620	8,920	12,090	8,440	16,220	18,160
Africa	6	9,630	11,760	6,440	8,340	7,620	0	13,930	14,800	12,870	18,610	16,580
Middle East	7	15,600	18,660	15,550	12,180	8,920	13,930	0	7,120	2,850	11,260	13,740
Asia - South / India	8	14,200	16,280	16,420	15,350	12,090	14,800	7,120	0	4,510	4,140	7,910
Asia North / Russia	9	15,120	20,460	14,490	11,700	8,440	12,870	2,850	4,510	0	8,650	11,140
China	10	10,570	12,700	20,230	19,480	16,220	18,610	11,260	4,140	8,650	0	8,580
Australia	11	12,050	12,470	14,840	21,420	18,160	16,580	13,740	7,910	11,140	8,580	0

Figure 3.7 Transportation calculation page

Figure 3.7 is a sample transportation calculation page. In transportation phase, carbon emission depends on transportation distance and shipping weight. On the bottom of this page, there are three reference table, showing the distance between different area.

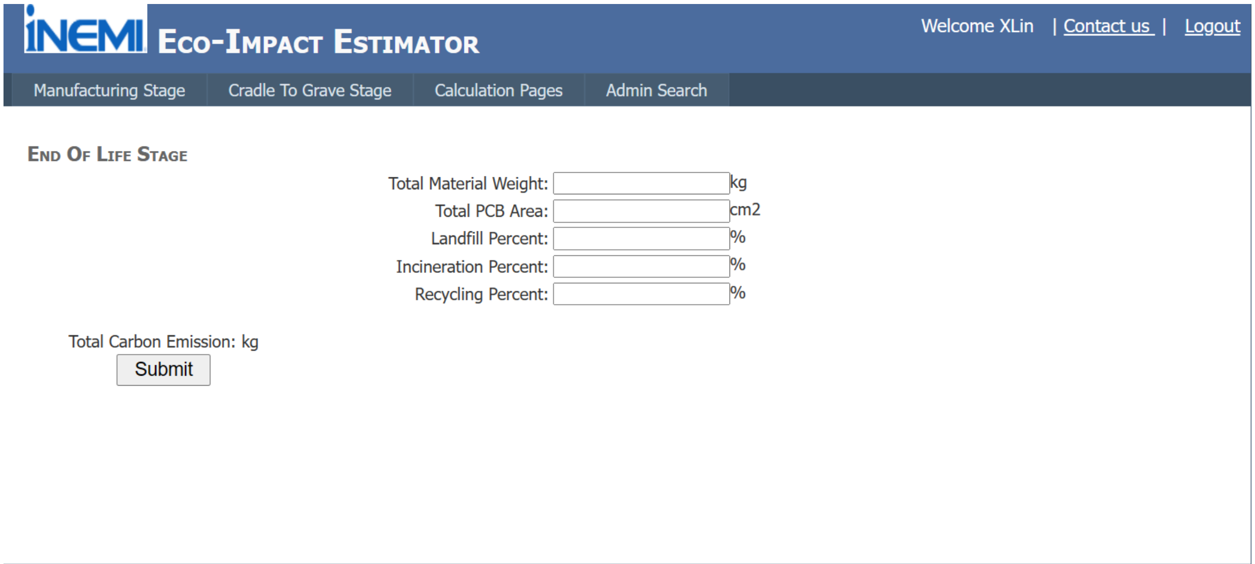


Figure 3.8 End-of-life calculation page

The last phase in the life cycle of one product is end-of-life, and Figure 3.8 shows end-of-life calculation page, where users need to input material weight and PCB area, together with the percentage of different ways of disposal. Total carbon emission would be calculated out when “submit” is clicked.

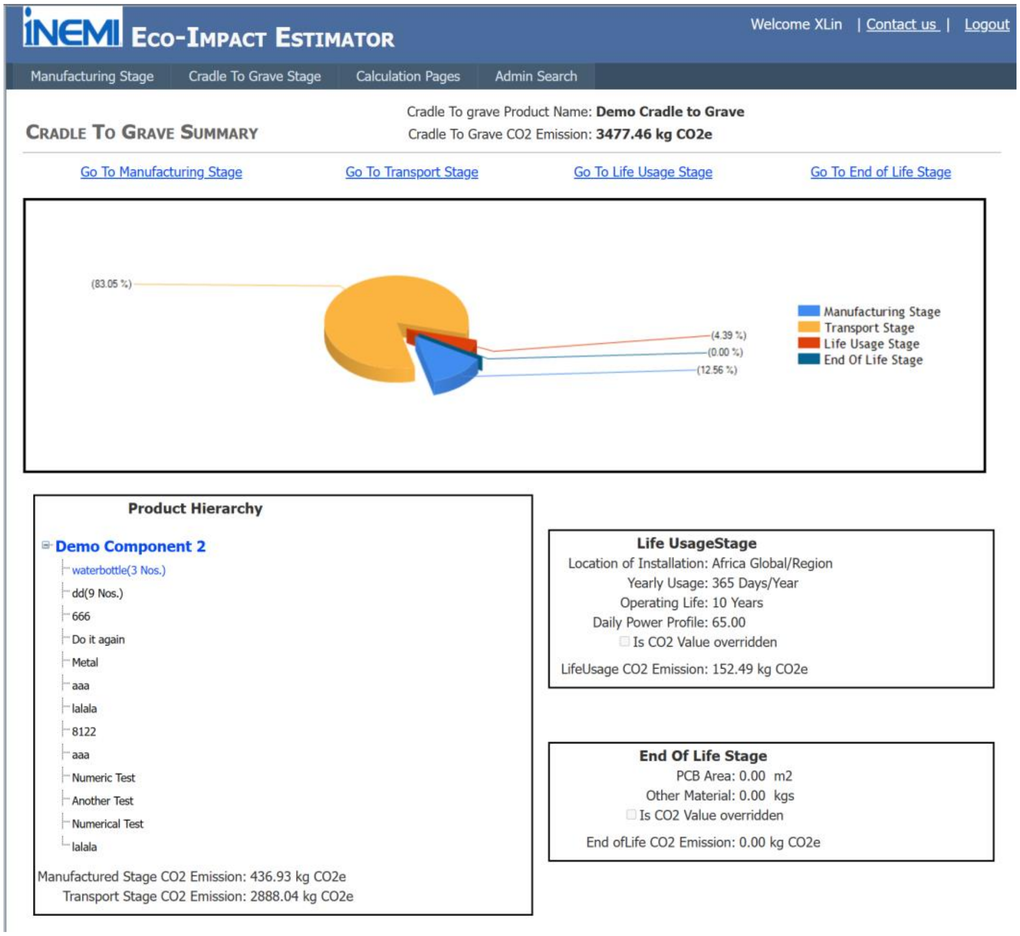


Figure 3.9 Cradle To Grave page sample

EiE also provide an overview of carbon emission throughout whole life cycle process: cradle-to-grave. As Figure 3.9 shows, users can store all the data of one product, from manufacturing to end-of-life, and EiE would automatically calculate the carbon emission and the contribution from each phase. The hierarchy graph would also be shown on the bottom left corner, so that it would be clear what this product consists of.

EiE provide variety of functions for ICT product specifically. Users are able to evaluate global warming potential (carbon emission) via EiE.

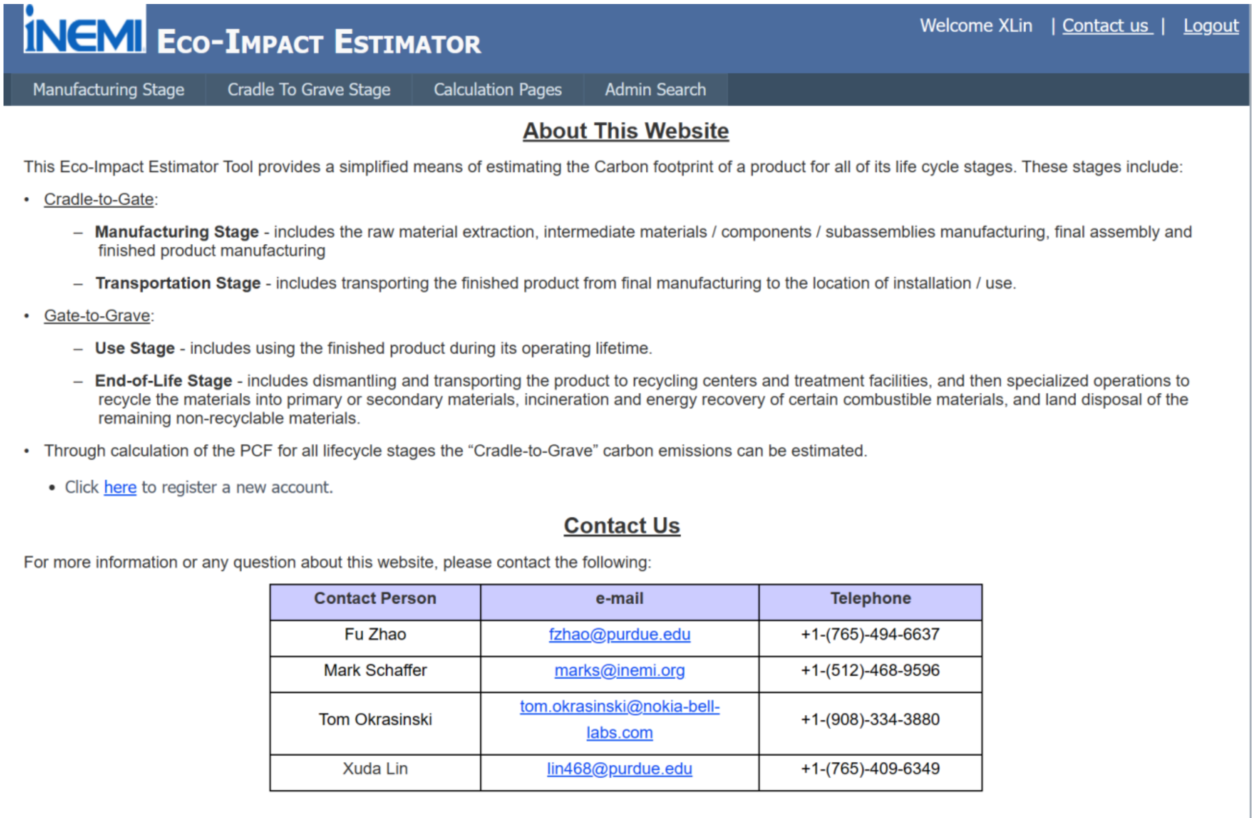


Figure 3.10 Contact page

Contact page includes a brief introduction to EiE, and information regarding contact person if there are any questions, shown in Figure 3.10.

3.4 Framework

EiE is designed to evaluate ICT product, which consists of hierarchical component and pieces, and can be classified into specific categories, such as printed circuit board (PCB) or integrated circuit (IC) component. These categories have their own common attributes and parameters, describing the size of this component, the number of pins of this PCB board or the weight of metal of this cabinet, etc., based on which the environmental impact could be calculated.

The primary component categories include printed circuit board (PCB), integrated circuits (IC), cooling fans, metallic components, polymeric components, cables, cabinet, special cable, packaging and specialized components that need manually input carbon emission. In this application, global warming potential (GWP) over 100-year time interval is selected as the only environmental impact in EiE, as this is one of the most widely used environmental impact indicators.

Primary parameters are defined to assess the environmental impacts of components and pieces categories. These parameters can represent the most significant environmental impact contribution that depends on a dataset, which is gathered from ICT manufacturers. There is also a correlated algorithm to calculate environmental impact depending on the given category and primary parameter selection.

The whole web-based application is running on two servers: Internet Information Service (IIS) server (a.k.a. front-end) and Microsoft Structured Query Language (MS-SQL) server (a.k.a. rear-end). IIS server is to host front end, where all webpages are running. MS-SQL server is to manage dataset, including environmental inventory data, parameter related factors, username and password hash, component hierarchy, and so on. Okrasinski discussed the data source and regression model in detail. The framework behind EiE could be descripted as: all input, including component category, correlated parameters and operation type, would be fetched by IIS server, and environmental impact would be calculated here. Then, this information would be transmitted to MS-SQL server via pipeline, together with the requested operation to database (search for exist data, add new data, edit exist data, etc.). Afterwards, MS-SQL would treat this request, and return feedback to IIS server, which could be a Boolean value (True or False), an integer, a float, or a data table. IIS would present this feedback to user, showing that this operation is finished.

3.5 Database

Database is another key point in EiE, due to the complexity of database design. In total there are 10 different component categories in manufacturing phase, and transportation, usage and end-of-life need their own dataset. For each component category, an independent table is built, to record the parameters and carbon emission result, because every component category has its unique parameters. Every time after a component is created or edited, the carbon emission result would be automatically calculated by front-end (IIS server) and updated to rear-end (MS-SQL server). The mechanism is the same on transportation, usage and end-of-life phase, that they all own one independent table, including parameters and carbon emission result.

The linkage between different component categories is shown in the hierarchical information table. In EiE, there is a key problem, which is the treatment of hierarchical component. In ICT manufacturing, one parent-component may consist of hundreds of other sub-components. To efficiently manage this 1-to-N relationship, a specific table is built, with only two columns: parent-component number and sub-component number. This table is s quite long, as N rows is needed to describe one 1-to-N relationship. Every time when front-end wants to show a whole hierarchy graph, this hierarchical information table need to be traversed.

Other than the tables related to environmental impact calculation, there are also some datasets for privacy and security, such as user information and operation log.

3.6 Summary and future work

Eco-impact estimator provides a more convenient and straightforward method for product designers and environmental engineers to evaluate the GWP of ICT product, considering the whole life cycle. The learning curve of EiE is comparatively much lower than traditional LCA software, and user interface is much more user-friendly. It is clear to see the hierarchy graph, and the parameters under each stage. With the help of iNEMI, more practical data and accurate regression model can be integrated into EiE.

Until now, there are approximately 50 registered users on EiE. With further advertisement and functionality expansion, it is hoped that EiE could have more impact on both industrial and academic field. Other than carbon emission, more environmental impact might be taken into consideration in the future, such as water usage.

4. BLOCKCHAIN-BASED LCA FRAMEWORK AND CASE STUDY

This article has been submitted to Sustainability for publication.

4.1 Introduction

In recent decades, environmental problems have been an increasingly global issue, affecting everyone. Typical environmental problems include global warming, chemical pollution, depletion of nature resources and the loss of biodiversity(Luthra & Mangla, 2018). The blooming of new technologies and demand of products brings growth of industry, but also leads to more serious environmental problems. Thus, to produce a more accurate and fast quantification of the environmental impacts caused by a certain process, a reliable tool is required, which could measure and calculate the environmental impacts in different aspects(Balaguera et al., 2018).

Life Cycle Assessment (LCA) is a widely used tool to analyze environmental im-pacts. The users of LCA include governments, non-governmental organizations, industrial sectors, and academic and education institutes. The results of LCA could pro-vide customers a reference, so that they can make comparisons. LCA can also benefit decision making, by providing information on several alternative products or processes, so that there could be some space for trading off(Levasseur et al., 2016).

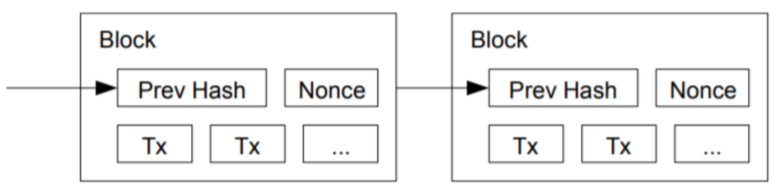


Figure 4.1 Classic blockchain framework in Bitcoin(Nakamoto, n.d.)

Blockchain, prominently implemented in cryptocurrency Bitcoin(Nakamoto, n.d.), could be a promising and complementary addition to LCA. Besides cryptocurrency, blockchain is widely used in financial service, health and medical service, energy rebalancing, agricultural service and so on. Previous research shows that blockchain can also be ap-plied to improve the sustainable performance as well as the resilience of supply chain(Min, 2019; Saberi et al., 2019). LCA has a very close relationship with the bill of material for products, which are derived from the supply chain. Thus, the integration of blockchain and LCA theoretically and practically would lead to a more convenient and reliable database.

Blockchain is a data structure, composed as a chain of blocks interconnected in a unidirectional order via an encrypted Hash function. The classic blockchain framework is shown in Figure 4.1. Each block contains three parts: a previous hash, a nonce and transaction data. The previous hash contains information acting as a pointer to the previous block, allowing us to back trace the information along the blockchain. The second part is a nonce, which formats the hash of the whole block into a string with a certain number of zeros in the very first several digits. The third part is transaction data, which would be stored in a tree(Lee, 2015).

In classic blockchain, mining is a process performed to find a nonce such that it can make the hash of the whole block into a string with a certain number of zeros in the very first several digits. Each node must generate a nonce, then do the SHA-256 (an encipher algorithm), and repeat, until such a nonce is found. This circular process is defined as proof -of-work, as each processor (CPU) can only finish a limited number of SHA calculations. After the nonce is found, the node can pack up the transaction data into a block, using this nonce, and broadcast this block to the whole network, allowing all the nodes in the network to verify if this block is a legal (which means this block follows all the rules and restrictions on blockchain) one. After the verification, all other nodes would copy the information on that block, so that all the transaction data on that block could be applied. The node who finds out that nonce and pack up the transaction data would be rewarded several cryptocurrencies (e.g., Bitcoin or Ethereum).

The research about using blockchain on life cycle assessment is in its early stages. Smetana mentions the impact of artificial neural network (ANN) and blockchain on revolutionizing Material Flow Analysis (MFAs) and LCAs(Smetana et al., 2018), which is more like a conceptual reference, saying that some new technology, especially ANN and block-chain, could provide positive improvement on MFAs and LCAs. In 2020, more re-search about blockchain-related life cycle assessment was published. A framework about implementation of blockchain-based LCAs was developed(Zhang et al., 2020), with a budget estimation. This study combined blockchain-based LCA with Internet of Things (IoT), trying automatically fetch data from sensors, but with very limit discussion about mechanism. A fuzzy DEMATEL analysis on blockchain-based LCA in China was provided(Farooque et al., 2020), which gives a result that blockchain-based LCA could improve manufacture data accuracy. A strategy related research on blockchain-enabled LCA was published(Teh et al., 2020), discussing the concern that BC-LCA might get support from strategy. In 2021, a conference paper of blockchain-based LCA and aircraft related application was published in CIRP (The international academy of production engineering)(Rolinck et al., 2021), which provides a good example on BC-LCA application.

This paper provides a much more detailed description on BC-LCA framework and mechanism, comparing with previous research, together with a case study based on a practical industrial supply chain about chemical manufacturing, to quantitively proof the improvement on data availability, data accuracy and data privacy. So that BC-LCA can better support environmental related strategy and interact with other modern technologies.

This paper is organized as follows. In Section 4.2, the disadvantages of current LCA framework that can be fixed by a blockchain enabled LCA (BC-LCA) would be dis-cussed. Section 4.3 presents the key assumptions that this study based on. Section 4.4 pro-vides the framework and mechanism about BC-LCA, and its benefits would be dis-cussed in Section 4.5. A case study discussing the potential implementation of BC-LCA for a chemical generation process is also provided in Section 4.6.

4.2 Disadvantages on Current LCA

In any product's supply chain, there are many enterprises (suppliers, shipping, manufacturing, raw material acquisition, etc..), which considered as "nodes". The partnership in-between two nodes, is an "edge"(Fang et al., 2018). LCA often faces challenges in collecting reliable data from supply chain, especially from a supply chain with multiple nodes and complex edges. Theoretically, the results of LCA only depend on two critical parts: the bills of material and environmental inventory data. Obtaining reliable data is a very challenging problem(Hospido et al., 2009). In classic LCA, each node should obtain the environmental inventory data by its own. Currently, most facilities would use published environmental inventory databases such as ecoinvent. All the data provided by researchers are under some assumptions (e.g., the scope definition), but when these data are implied, these assumptions might be ignored by the user. In fact, not all the LCA research can find appropriate data. The practical LCA application needs the database that has higher accuracy, higher availability and is more specific to the product or process being studied.

4.2.1 Inefficiency of Data Transmission

The most popular environmental inventory databases are always from centralized companies and organizations (e.g., Sphera, ecoinvent). These databases are collected and compiled by a specific organization first, and then published to users all over the world. Theoretically, all the data transmission in centralized structure should go through a center. This center could be a facility (e.g., a bank in wired transfer process) or a network (e.g., cellular network in the process of a phone call) and should process all the restrictions and the verifications. It might be too abstract to directly talk about the data transmission efficiency without any example. Banking system is one of the most typical centralized structures, and it is close to daily life, easy to explain. If customer A wants to transfer 3 dollars to customer B, the bank needs to check if there's enough money on A's account, and whether the account information about B is correct. All the restrictions and verifications happen in the bank, which is easy to update the rule. However, wired money transfer may take up to days, and international money transfer may take up to weeks. This is a tradeoff for the efficiency in using centralized structures. On the one hand, considering restriction and verification processes, centralized structure is efficient enough and powerful, because all the restrictions and verifications are easy to imply(McElheran, 2012); on the other hand, there is a significant disadvantage commonly shared by centralized structures: data transmission inefficiency(Minas et al., 2012).

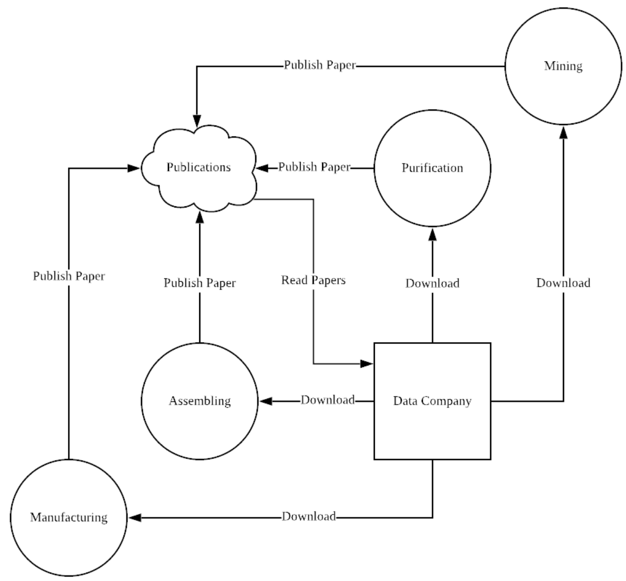


Figure 4.2 Centralized LCA Structure

The inefficiency of centralized structure in data transmission is worse in LCA data exchange, as there is no such a shared centralized platform to do the data collection. The procedure of data updating in LCA is much more inefficient: If researcher A have done some LCA research and updated some data, researcher A must publish a paper to describe this update. Then, the environmental inventory data companies and organizations (e.g., PRé, ecoinvent, Sphera) must keep reading papers to catch up with this kind of updates, so that the database companies and organizations can then record these updates into a new version of environmental inventory database. Eventually, all the users could see this update after the new version is released by the database companies and organizations. Figure 4.2 shows the whole process based on the previous example: if any node in a supply chain wants to do LCA, it is necessary to download the environmental inventory data from a centralized data company. Meanwhile, the LCA results would be published via papers or other publications, which could be used as data source for these companies or organizations who publish environmental inventory database.

4.2.2 Lack of Data Availability

Current environmental inventory database contains a lot of information about different kinds of manufacturing processes. The recent ecoinvent database contains more than 16,000 datasets(Wernet et al., 2016). For researchers, if generic environmental inventory information is needed about one generic type of process, then the aggregated (average) environmental inventory dataset might be enough. For example, if researchers are interested in the comparison between two different types of products, such as a paper cup and a polymer cup, then the generic data might work. However, if a user wants to know the environmental impact of one specific process, then generic information is not enough. For example, if a user wants to know the environmental performance about a laptop with specific model, such as HP Envy X360 with 8GB RAM from Kingston, 1T HDD from Western Digital and Core i5-8500 processor from Intel, then generic data can only provide the user the environmental impact about a generic laptop, instead of this specific model. With current database, a user will never know the accurate environmental impact of one specific product or process.

4.2.3 Concerns on Data Privacy

According to ISO 14044, the results of LCA depend on two critical parts: environmental inventory database and bills of material. In most cases, environmental inventory data are provided by public organizations or companies, which is a typical centralized structure. The reason behind is, manufacturers are hesitant to share their data, no matter if it is their inventory data or environmental inventory data of their final products. Even within one company, the data privacy problem also can exist be-tween different departments. The priority of protecting their own data is much higher than sharing these data to benefit the whole supply chain. Thus, probably the only way to solve this problem is finding a trustworthy third party (e.g., a data company) to manage these data, and make the data anonymous to all database users. However, there is still possibility that this third party would leak out the name or bills of material to public. Therefore, few manufacturers are willing to share their data.

4.3 Key Assumptions

Current circumstances do not only depend on platform or engineering, but also on the natural unwillingness on data sharing. Companies or organizations are more concerned with personal gains or losses during data sharing, instead of how data sharing can benefit them and the whole industry. It is understandable that companies or organizations are responsible of keeping their own data confidential. However, this is one of the most important factors that impedes a good data sharing atmosphere. To solve this problem, an engineering solution is not sufficient. A more powerful and effective administrative solution should come out, to help guide companies to a beneficial solution.

There are three major assumptions that this study is based on:

1. Companies or organizations are willing to share their data and improve the environmental performance;
2. Economic consideration is not the only threshold to consider during the selection on alternatives. Environmental impact also plays a significant role, and the product with better environmental performance could be more attractive;
3. Stakeholders are willing to pay more for environmentally friendly products.

Under these assumptions, this study provides a solution to do automatic LCI data transmission and LCA calculation.

4.4 Framework and Mechanism

In this study, by applying blockchain technology, BC-LCA can replace the traditional centralized structure and improve the efficiency in data transmission. In BC-LCA, all the data verifications and restrictions can be done by an arbitrary node, instead of a fixed "center" (Figure 4.3), thereby drastically improving the efficiency of data transmission. However, there's one thing that needs to be considered: every node should contain the rule to do restrictions and verifications. In other words, if a manufacturer decides to join in the BC-LCA, this manufacturer should act as a node with the full function to do the verifications and imply all the restrictions. Thus, BC-LCA re-quires a more meticulous design than traditional LCA framework. BC-LCA can over-come the limitation of centralized structure and improve the performance of classic LCA.

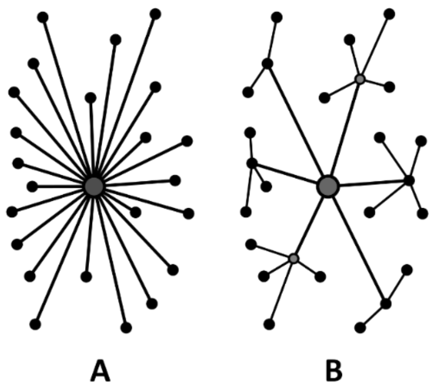


Figure 4.3 Graphical comparison of a centralized (A) and a decentralized (B) system.

Based on the classic LCA framework and classic blockchain framework (Figure 4.1), the new blockchain based LCA network could have the full function in both LCA and blockchain. It could analysis the environmental impact of a product or process, and all the data transmission would go through the blockchain. The new blockchain-based LCA framework would also be more automatic and accurate.

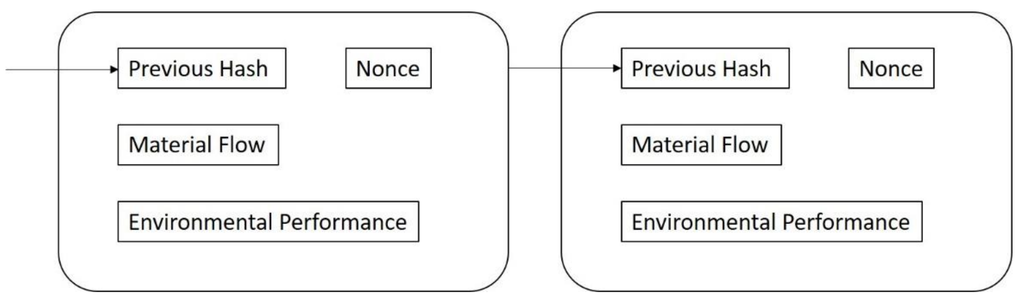


Figure 4.4 Framework of BC-LCA.

Figure 4.4 shows the framework of BC-LCA. In every block, “Previous Hash” and “Nonce” acts as linkage between blocks. “Material Flow” and “Environmental Performance” data would be stored in each block. In this case, during every time that a material flow occurs, this data would be broadcast into the BC-LCA network, and environmental performance of this material flow would be sent directly to the down-stream node (which is the receiver). Each block has its capacity limitation, which means one block can store limited number of material flow data and environmental performance data. Thus, after one block is filled up, an arbitrary node would come up and “seal” the whole block and broadcast the block to the whole network.

The mechanism of BC-LCA is simple, but powerful. All information would be transferred via broadcast to the whole BC-LCA network. There are three types of nodes that participate in this information transfer: sending node, receiving node and transfer nodes. Sending node is the one who broadcast information into BC-LCA network, as well as the node who send out material flow. Receiving node is the node that receives the material flow. Transfer nodes are these nodes that only participate in information transfer but are not the sender nor receiver nodes.

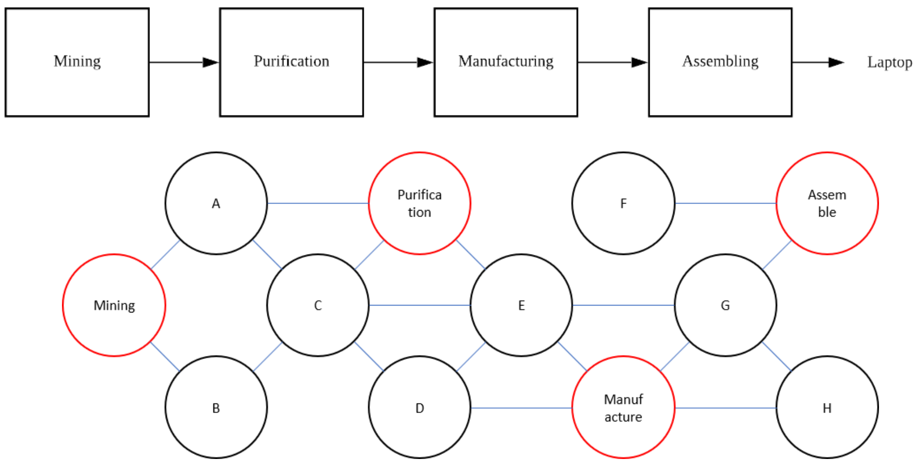


Figure 4.5 Decentralized LCA Network Sample.

Figure 4.5 shows an example of information transfer. Node Mining want to transfer 1 tons of Product A to Node Purification, which is defined as “material flow”. Simultaneously, Node Mining would broadcast this information to the whole network with the following procedure:

1. Getting information ready: Node Mining will need to prepare the list of products (1 tons of Product A), and environmental impacts related to these products (environmental impacts of Product A);
2. Notify Node A and Node B: The closest nodes of Node Mining are Node A and Node B, which would be the aim of broadcasting. Here, Node Mining would send out the prepared information to Node A and Node B directly;
3. Node A would notify Node Purification and Node B would notify Node C: However, the closest nodes for Node A are Purification and C and the closest node of Node B is C. Therefore, Node A will send information to Node Purification and Node C, and Node B will also send information to Node C. It does not matter who will send Node C the

information first, as finally both Node C and Node Purification gets the necessary prepared information;

4. Node Purification receive environmental impacts, all other nodes keep the record: After the prepared information received by Node Purification, Node A, Node B and Node C would always keep the prepared information. Furthermore, the prepared information would keep spreading, until it is received in all the nodes in the BC-LCA network. Here, beside Node Mining and Node Purification, all other nodes would keep the prepared information for record and prevent cheating.

There would be bunch of information spreading in BC-LCA network at the same time. However, it is not necessary to worry if one information would be transferred duplicated between one node pair. Every time when a node receives an info, the node would check if this info already existed. Any node would only accept the information which is not received. When the last node in BC-LCA receive the information, the node would find no other node to send, then the whole broadcasting is over.

In BC-LCA, any node can perform the LCA calculation. At the time a node receives a material flow information, it would automatically calculate the environmental impact. Here, the update of products' environmental performance occurs every time this node receives material flow information. The calculation would be consisted of two parts: bills of material and LCI data. Both parts come from BC-LCA network and could be auto updated if the upstream nodes provide update information. This calculation could directly provide the results of product final environmental inventory table, and broadcast to the whole BC-LCA network.

Addition to the external-node data transition, there are three pre-processes that should be considered in the internal-node calculation:

1. Bills of material confirmation: The very first step before calculation, is to make sure the input data is valid. Here, a node needs to check whether the input bills of material table is legal, and whether each element of this table has appropriate format;
2. LCI dataset confirmation: The second step is to confirm the LCI dataset is up-to-date and contain all the information to calculate. Each node should have multiple versions of LCI dataset, including the dataset directly from upstream nodes, and the dataset for recording only. Before any calculation, a node should search for and sort out appropriate LCI dataset;

3. Unit consistent inspection: After confirming bills of material and LCI dataset, the next step should be checking the unit consistence. Different unit could lead significant impact to environmental performance factors. The unit in bills of material should match with the unit in the LCI dataset.

After these pre-processes, a node could perform a matrix multiplication(Heijungs & Sun, 2002), to figure out environmental impact results of one product. Multiple products need multiple calculations, with all 3 pre-process steps for each calculation. When a node finishes an environmental impact analysis for one product, this node can then broadcast the results to the whole BC-LCA network. Then, all downstream nodes, which may be impacted by this analysis, could update their related products. The whole process, starting with the first node who change its product environmental impact data, until the last node finishes updating, is called cascading.

4.5 Benefits of BC-LCA

4.5.1 Data Availability

To make the accurate environmental inventory data available for a specific product, the first step is to acquire the accurate data on every item in this product's bills of material, which means the upstream nodes (i.e., suppliers) should provide accurate information for their products. The easiest way to let the supplier provide the environmental inventory data for their products, is bringing the supplier into the same blockchain network. In this case, while material goes from upstream to downstream, the environmental inventory data should follow the same direction. This is the meaning of blockchain based LCA network: digitization all the material flow and providing accurate data to all the nodes.

4.5.2 Data Privacy

Benefited by the cryptocurrency, blockchain technology has already has a practical enciphering algorithm: Security Hash Algorithm (SHA), published by National Institute of Standards and Technology (NIST) as a U.S. Federal Information Processing Standard (FIPS)(Stevens et al., 2017). This method can promise that enciphered private information can only be read or edited by the user who has the key, with no exception. Key is a string with the information to decipher user's private data. Even the enciphered data owner cannot read the enciphered data without the key. By doing this, user's privacy could be protected, and they could be more willing to share their environmental inventory data of their products to the downstream users.

Here recall Figure 10 as example. When Node Mining sends 1 ton of Product A to Node Purification, a Key, which contain the information to decipher, would be sent from Node Mining to Node Purification. Then the transition of material happens, and transition information (1 ton of Product A and the environmental impact of 1 ton of Product A) would be broadcasted to the whole network. However, during this step, the product list (1 ton of Product A) is enciphered, but the environmental inventory in-formation (the environmental impact of 1 ton of Product A) is open to public. The sender and receiver are also anonymous, which means all other nodes (except Node Mining and Node Purification) can only see that Node X send Node Y some unknown product, together with a certain known amount of environmental impact. And Node Purification, who has the Key from Node Mining, can decipher the broadcasting in-formation, and know that this transmission includes 1 ton of Product A, and calculate out the environmental impact of 1 unit of Product A.

4.5.3 Cheating Prevention

In the long term, all nodes should have a balanced input and output environmental impact, even consider the inventory of storage. With BC-LCA, preventing cheating becomes easy: any node can calculate the input and the output environmental impact and therefore can tell whether there any cheating has occurred. Just like Bitcoin network, a user can know the budget in his/her account, any BC-LCA user is able to know what’s the accumulative environmental impact in its node. Because every transaction in BC-LCA has a timestamp, it would be easy to track the growth/decay rate of accumulative environmental impact and use an algorithm to judge if that node is cheating or not.

4.6 Case Study based on an Industrial Supply Chain

Willems provides some simplified supply chain data(Willems, 2008), which could be used to demonstrate the application of BC-LCA. Here, an industrial organic chemical supply chain is selected, whose picture is shows as Figure 4.6.

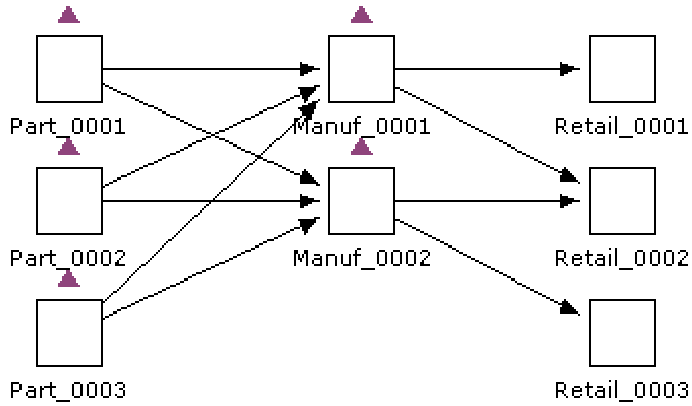


Figure 4.6 Sample supply chain picture(Willems, 2008)

This supply chain includes 3 procure stages, 2 manufacture stages, no transportation stage and 3 retail stages. In total, there are 8 nodes with 10 edges. This supply chain is comparatively simple, but it could show the difference with and without BC-LCA application. Here, a Python based BC-LCA is developed for simulation.

Due to the lack of material flow information in the supply chain sample, six assumptions are made:

1. Manuf_0001 and Manuf_0002 share the same manufacturing recipe;
2. Carbon footprint is calculated using US-EEIO based on cost data provided;
3. All nodes locate in California;
4. Only carbon emission is considered;
5. Transactions (material flow) between any two connected nodes happens once a month;
6. The whole model runs from Jan-2018 until July-2020;

In this case study, five scenarios are considered:

0. No node joins BC-LCA
1. Only Manuf_0002 joins BC-LCA
   a. The percentage of clean energy using in manufacturing is increasing(U.S. EIA, n.d.)

b. Due to the procedure upgrade, material waste is decreasing

c. The energy consumption for supplement (light, A/C, etc.) varies seasonally

2. Part_0001, Part_0002, Part_0003 and Manuf_0002 join BC-LCA

a. The energy consumption to fetching raw material is decreasing

b. The percentage of clean energy used in manufacturing is increasing due to assumption 3

c. Due to the procedure upgrade, material waste is decreasing

d. The energy consumption for supplement (light, A/C, etc.) varies seasonally

3. Only Manuf_0002 joins BC-LCA

a. The energy consumption is increasing due to the aging of equipment

b. The energy consumption for supplement (light, A/C, etc.) varies seasonally

4. Part_0001, Part_0002, Part_0003 and Manuf_0002 join BC-LCA

a. The energy consumption to fetching raw material is decreasing

b. The energy consumption is increasing due to the aging of equipment

c. The energy consumption for supplement (light, A/C, etc.) varies seasonally

Because Manuf_0001 never joined BC-LCA, instead, Manuf_0001 always use classic LCA, and the results stay constant over years. The result of Manuf_0001 could be used as a baseline to compare with Manuf_0002, which contains more conditions, and updated monthly. Based on these scenarios, results are shown as below:

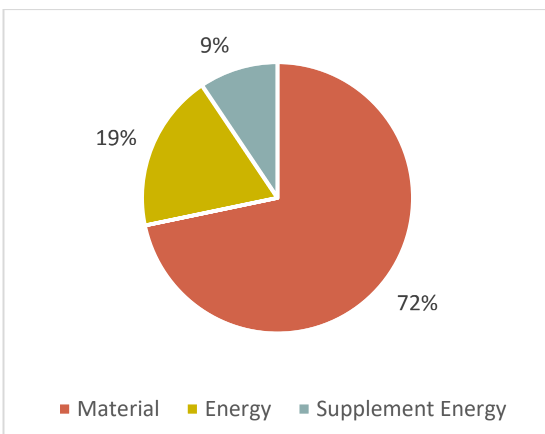


Figure 4.7 Carbon Emission of Final Product under Scenario 0.

Figure 4.7 shows the carbon emission of final product under Scenario 0, which considered no node joining the BC-LCA. All carbon emission data are calculated from US-EEIO v2.0(Yang et al., 2017), where a factor is provided, so that the stage cost of a node can be directly convert to carbon footprint. Scenario 0 is a baseline, where carbon emission would not change, and all results depend on the manufacturing recipe.

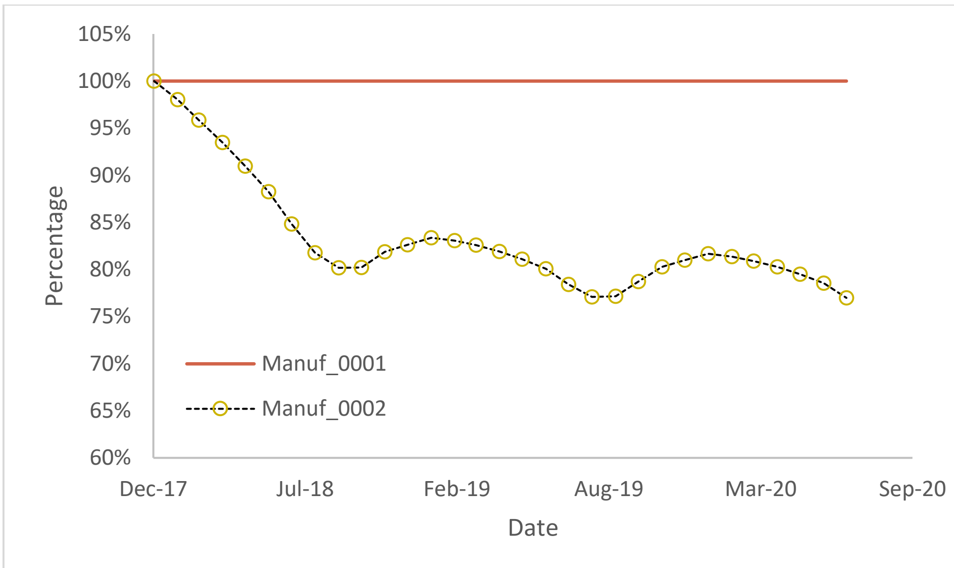


Figure 4.8 Carbon Emission Compare Percentage of Final Product under Scenario 1.

Figure 4.8 shows the carbon emission under Scenario 1. It is obvious that due to condition 1a and condition 1b, the overall trend of carbon emission is decreasing. Some variance in this curve is due to condition 1c, which means in every winter, Man-uf_0002 would need more energy to keep room temperature. Compared with Man-uf_0001, Manuf_0002 shows accurate seasonal variance.

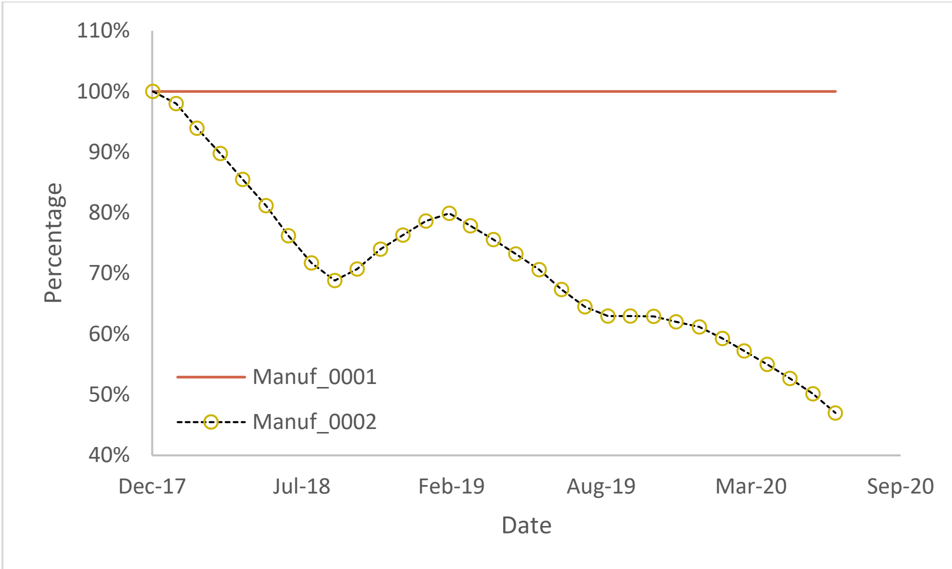


Figure 4.9 Carbon Emission Compare Percentage of Final Product under Scenario 2.

For Scenario 2, BC-LCA performs more accurate and variable results. In Figure 4.9, when more nodes join in BC-LCA, the overall trend of decarbonization is more obvious, which depends on condition 2.a.

With the comparison of Figure 4.8 and Figure 4.9, which represent the carbon emission variance when only 1 node joins BC-LCA and when 4 nodes join BC-LCA, it would be safe to say that with more node in one supply chain join BC-LCA, the results of environmental impact would be more and more accurate. The reaction to periodical waving and long-term trend is both shown in Scenario 1 and Scenario 2.

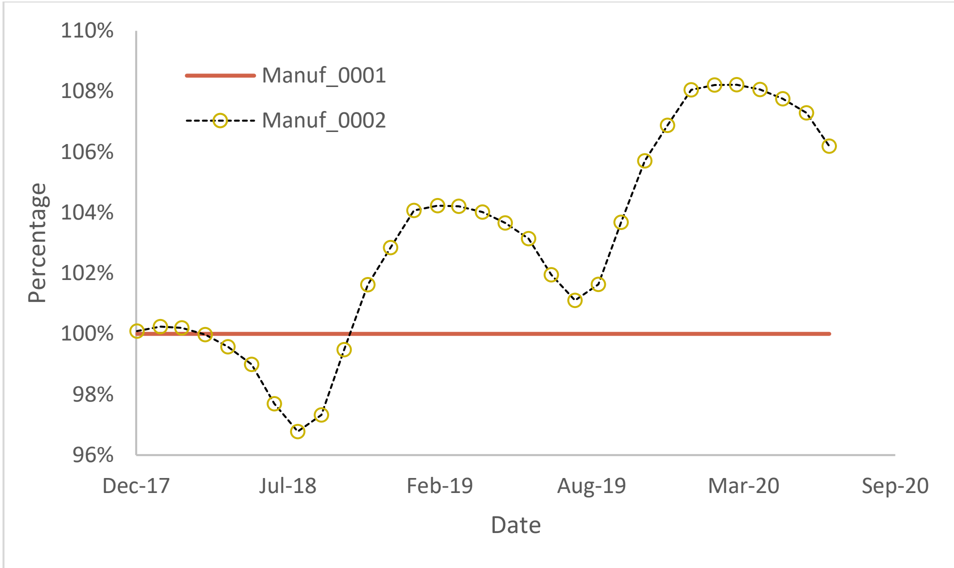


Figure 4.10 Carbon Emission Compare Percentage of Final Product under Scenario 3.

However, the decreasing of overall carbon emission is due to the scenario assumptions. The results from BC-LCA could only be more accurate, but not necessarily more environmentally friendly, than traditional LCA. Figure 4.10 shows the carbon emission results under Scenario 3, where the overall trend of increasing carbon emissions is mostly due to condition 3a.

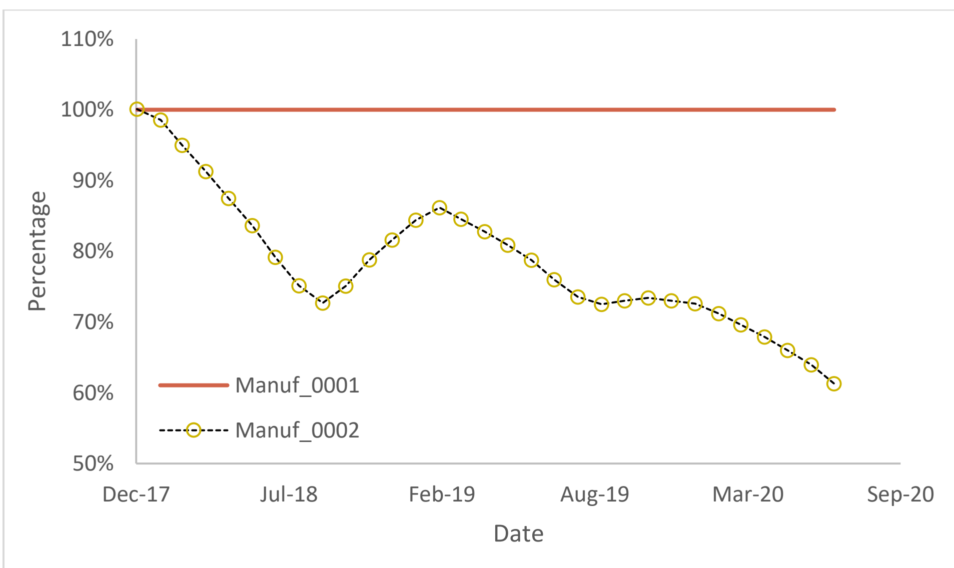


Figure 4.11 Carbon Emission Compare Percentage of Final Product under Scenario 4.

Figure 4.11 shows that, under Scenario 4, even though the energy consumption in Manuf_0002 is increasing due to the aging of equipment, the overall carbon emission is still decreasing.

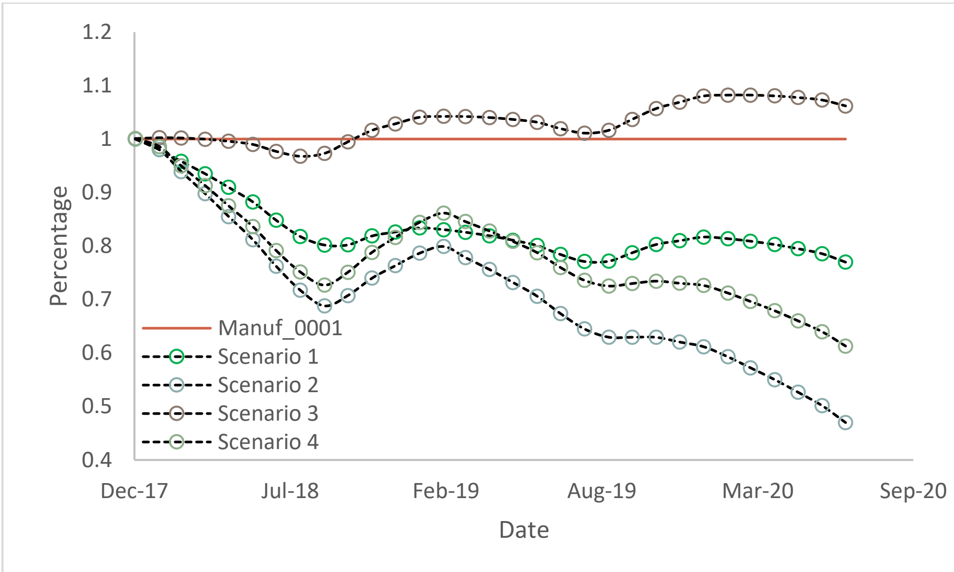


Figure 4.12 Carbon Emission Comparison of All Scenarios.

Based on these scenarios, some comparisons are made (Figure 4.12). The analysis results show that even this case study implies a simple supply chain, the difference between BC-LCA and classic LCA is significant. Carbon emission results are more ac-curate and specific. Manuf_0001 carbon emission could be seen as an average, which is good for general analysis. When Manuf_0002 join the BC-LCA (Scenario 1 and 3), it is obvious to see how energy consumption, material waste and supplement energy consumption affect carbon emission. When Part_0001, Part_0002 and Part_0003 also joined in BC-LCA (Scenario 2 and 4), which means the whole supply chain join BC-LCA, more factors are considered, so more variances could be observed.

During the whole case study, all data transmissions are under blockchain rule. As mentioned before, bills of materials would be enciphered, but total environmental im-pact of one material flow would be open to public. The strength of SHA-256 is much higher than classic security method like username and password(Velmurugadass et al., 2021).

Table 4.1 Sample Transmission Data without Encipher

Date	Sender	Receiver	Quantity	Unit	Material	Carbon
Jan-18	Part_0002	Manuf_0002	12	Dollar	Material 1	76.31688
Feb-18	Part_0002	Manuf_0002	12	Dollar	Material 1	76.31688
Mar-18	Part_0002	Manuf_0002	12	Dollar	Material 1	76.31688
Apr-18	Part_0002	Manuf_0002	12	Dollar	Material 1	76.31688
May-18	Part_0002	Manuf_0002	12	Dollar	Material 1	76.31688
Jun-18	Part_0002	Manuf_0002	12	Dollar	Material 1	76.31688
Jul-18	Part_0002	Manuf_0002	12	Dollar	Material 1	76.31688

Table 4.2 Sample Transmission Data with Encipher

Date	Sender	Receiver	Quantity	Unit	Material	Carbon
Jan-18	Bgrws2dNbee6q6aIaOsf	FzYNXJMtz0UbrAyDvrij	O4UKAYzZuA	Dollar	YpMJUyhQEq	76.31688
Feb-18	Bgrws2dNbee6q6aIaOsf	FzYNXJMtz0UbrAyDvrij	TOx3cUVgxl	Dollar	zVjKPSjWVB	76.31688
Mar-18	Bgrws2dNbee6q6aIaOsf	FzYNXJMtz0UbrAyDvrij	rFxnZB7ucf	Dollar	osIg5wtyXP	76.31688
Apr-18	Bgrws2dNbee6q6aIaOsf	FzYNXJMtz0UbrAyDvrij	tMSkZ1BL7x	Dollar	2qWqlOpiiJ	76.31688
May-18	Bgrws2dNbee6q6aIaOsf	FzYNXJMtz0UbrAyDvrij	n7XXrxdorE	Dollar	QWWMvygVbs	76.31688
Jun-18	Bgrws2dNbee6q6aIaOsf	FzYNXJMtz0UbrAyDvrij	5VXDudTF7c	Dollar	lu0KP0eM6H	76.31688
Jul-18	Bgrws2dNbee6q6aIaOsf	FzYNXJMtz0UbrAyDvrij	qzNTN8oqs8	Dollar	Ev1G09lPC2	76.31688

Table 4.1 and Table 4.2 shows the result of encipher, which is manually exported and formatted from BC-LCA, based on Scenario 4. Generally, when BC-LCA network is running, the result of encipher would be stay in catcher, and not that easy to observe. The encipher and decipher operation would be run automatically. Compare Table 4.1 and Table 4.2, the name of sender and receiver is constant, though anonymous. The material name after enciphering is dynamic, which means every transaction has its unique Key to decipher, to enhance data privacy.

Another test is also performed to exam the ability of cheating prevention, based on Scenario 4. Manuf_0002 is manually set to cheat, which claims that its products have 10% lower carbon footprint than they actually have. In this case, some carbon footprint would be accumulated in Manuf_0002. And a threshold is set, to make sure that any node with higher accumulation carbon footprint high than the threshold, would be warned and kicked out.

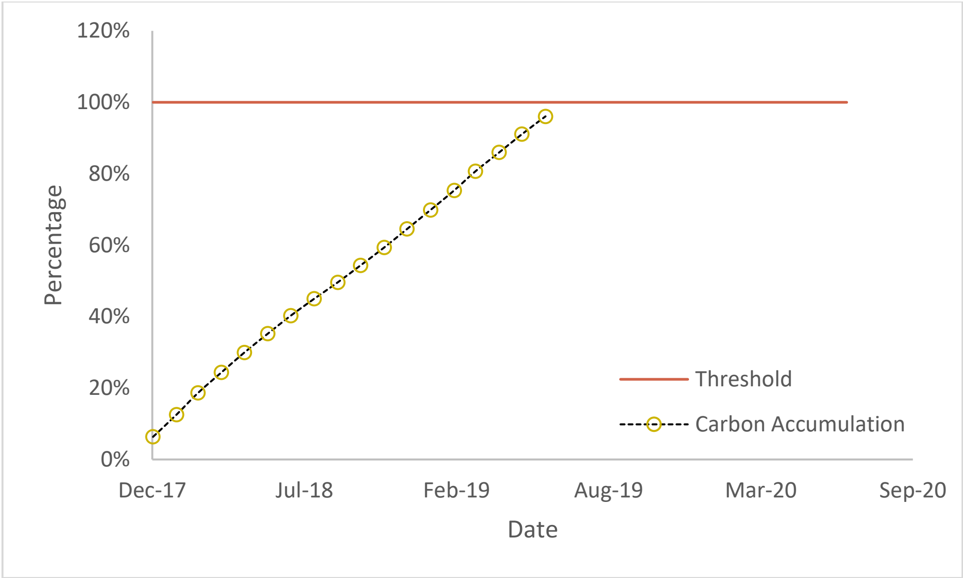


Figure 4.13 Carbon Accumulation Percentage when Cheating

Figure 4.13 shows the carbon accumulation percentage compared to threshold. The carbon footprint is always accumulated, and when it reaches the threshold at Jul-2019, Manuf_0002 is warned and kicked out of BC-LCA network. The threshold could be modified according to actual requirement.

The whole case study is programmed with Python, where a simple version of BC-LCA is developed, with limited nodes and transactions. However, this framework could be expanded to a supply chain across multiple companies, or multiple departments within one big company. The implication of BC-LCA across companies/departments would need every company/department acts as a node, contributing to data broadcasting, transaction ledging and cheating prevention. Each company/department can save some budget on LCA, as it would be unnecessary to purchase LCA software and database. But hardware and operators are needed, and BC-LCA may require a more powerful processor, due to enormous computational complexity, compared with traditional LCA software.

4.7 Summary and Future Work

BC-LCA is the combination of blockchain technology and life cycle assessment, which could significantly improve the availability, privacy, accuracy, and timeliness of LCI data, with less manual operation and time cost. The framework and mechanism of BC-LCA are both designed based on blockchain and modified according to life cycle assessment features. The whole network can automatically calculate environmental impact, transfer data, back up data and prevent cheating.

One of the properties in BC-LCA is interesting: with more nodes, which belong to the same supply chain, join in BC-LCA network, data availability and data accuracy would increase. This indicates a trend on BC-LCA development and expansion. The early stage would be tough and slow, as BC-LCA is not able to provide dramatically improvement with only one or two nodes join in. However, along with more nodes join in BC-LCA network, there would be a significant breakthrough on data availability and data accuracy, because data company/organization (e.g., ecoinvent, GaBi) would not be the only data source, and more specific data would replace generic data. Theoretically, these two points guarantee the attraction that BC-LCA would have.

The implication of BC-LCA has variate potential. Manufacturing would benefit a lot from BC-LCA, due to its strong dependence on supply chain. Transportation would also get more accurate environmental impact estimation, as tracking odometer and gas filling history is comparatively easier than back tracking supply chain. Besides, building construction, tourism and agriculture can improve their environmental performance evaluation with the help of BC-LCA, because these fields have very close relationship with supply chain as well.

Next step of this research may include an algorithm and data structure design of BC-LCA, as well as a practical demonstration to test the time and hardware cost when BC-LCA is implemented.

5. CONCLUSION

In this study, three informatic technologies are applied in LCA related field. Automatically Content Analysis is used to provide an overview and find out if there is any blank field or break through point in LCA research, web-based application is used to lower the learning curve of LCA software and provide a more user-friendly and ICT specific optimized interface, and blockchain is used to modernize LCA to improve data accuracy, data availability, data privacy and cheating prevention. The result of such modernization is positive, and practical.

5.1 Automated Content Analysis can provide an overview on LCA research

ACA is one of the large texture material analysis methods, to output quantitative description on the big picture of LCA research field. From the results of ACA, it is obvious that the topics could be ranked due to the popularity, and therefore any blank field or gap could be shown. In this study, the blank field is shown as informatic techniques application in LCA methodology.

In this study, all LCA related topic are classified into three categories: LCA application, LCA methodology and environmental impacts. In LCA application, scholars pay more attention on clean energy, manufacturing and fossil energy, all of which are very fundamental component in the whole industrial field. In LCA methodology, “economic sustainability” is the most attractive topic, and “model” is the second, both of which shows the trend of LCA development. LCA would consider more about economic sustainability and optimize the model. In environmental impact aspect, carbon emission is certainly the most popular topic, and get more and more attraction over the years. Water consumption is the second most popular topic among all environmental impacts.

5.2 Web-application can provide a more efficient and user-friendly solution to industrial application LCA

With the help of web-based application, the procedure of LCA become more user-friendly and easy-to-learn. The learning curve of EiE is comparatively lower than traditional LCA software, and the user interface is more friendly. In this study, both web-application framework and database are carefully designed, to maximize the efficiency and minimize the time complexity.

According to the feedback from current active users, the operation of EiE is success, though some modification or communication may be necessary. Most users provide strong positive feedback to EiE and are actively learning how to use EiE to estimate environmental impact. Meanwhile, with the help of iNEMI, more environmental impacts are taken into consideration.

5.3 Blockchain technology can provide some improvement on LCI data quality

The application of blockchain technology on LCA is an improvement of LCA methodology, increasing data availability, data accuracy and data privacy, and preventing cheating at the same time. BC-LCA is able to reduce manual operation and time cost, and the whole BC-LCA network can automatically calculate environmental impact, transfer data, backup data and prevent cheating.

According to the case study of BC-LCA, one property of BC-LCA raise up: the more nodes with in one supply chain join in BC-LCA network, the higher data accuracy, data availability and cheating prevention they could get. This property indicates that the early stage of BC-LCA development would be tough, as there is not much benefit. But when more and more nodes join BC-LCA network, there would be a dramatic improvement on data availability, data accuracy and data privacy.

There are many fields that BC-LCA could be applied, including manufacturing, transportation, building construction, tourism and agriculture. All these fields have very close relationship with supply chain, and with the help of blockchain technology, the backtracking of supply chain could be more efficient and accurate.

5.4 Summary

With the implication of all three informatic technologies, it is obvious that interdisplinary field could be more creative. If a method can bring benefit to one field, it would be worth trying this method in another field.

APPENDIX A. LCA ACA RELATED GRAPHS

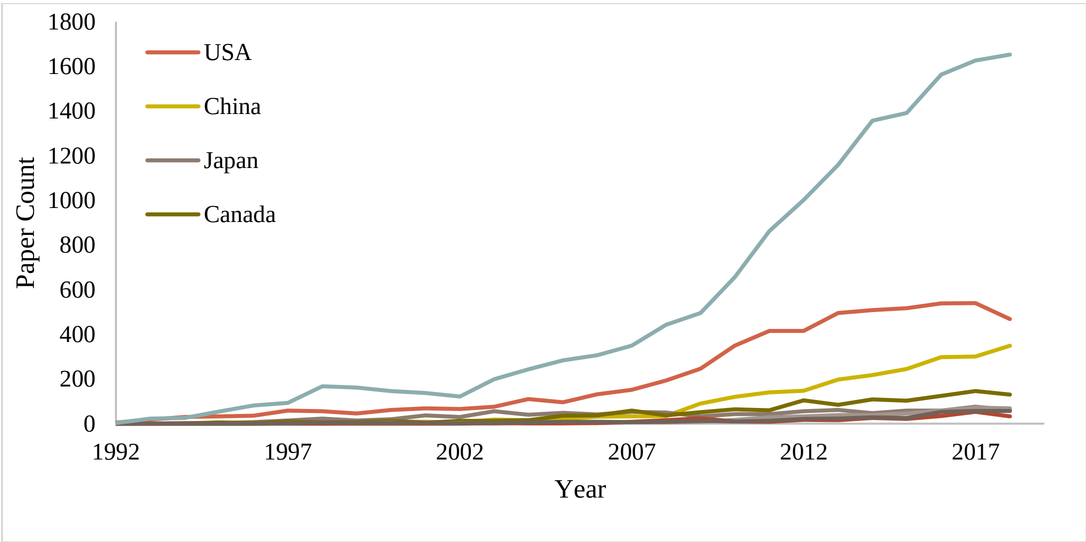


Figure A.1 LCA related paper count by countries

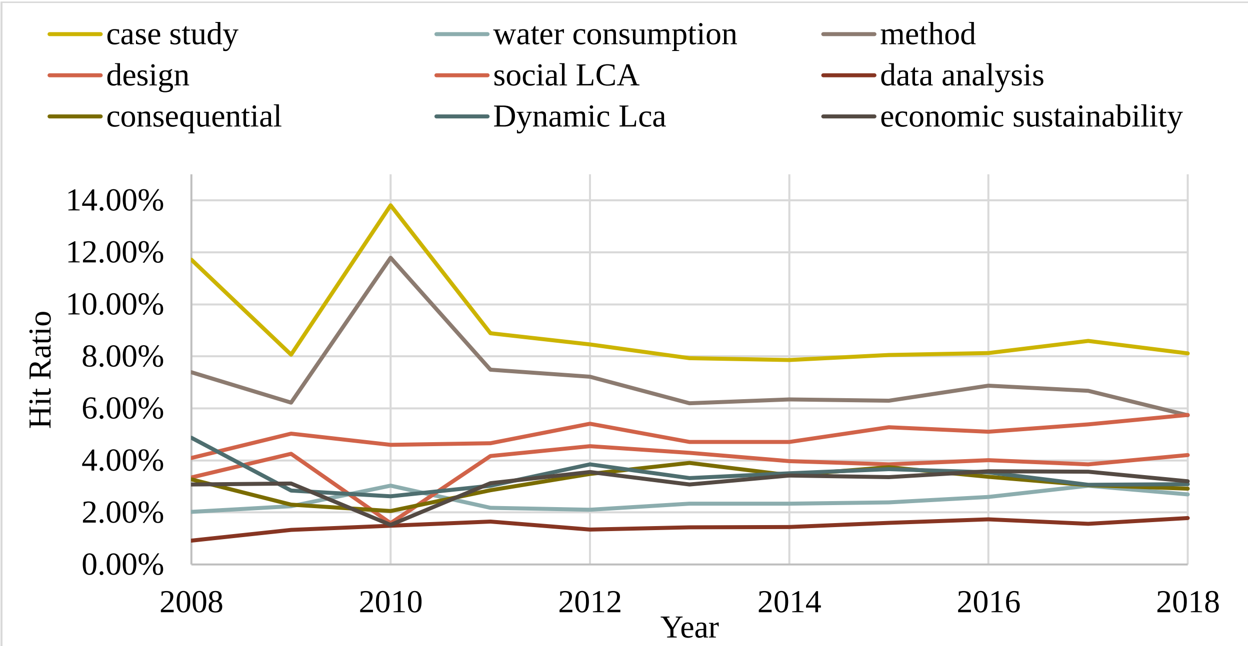


Figure A.2 LCA method related paper hit ratio

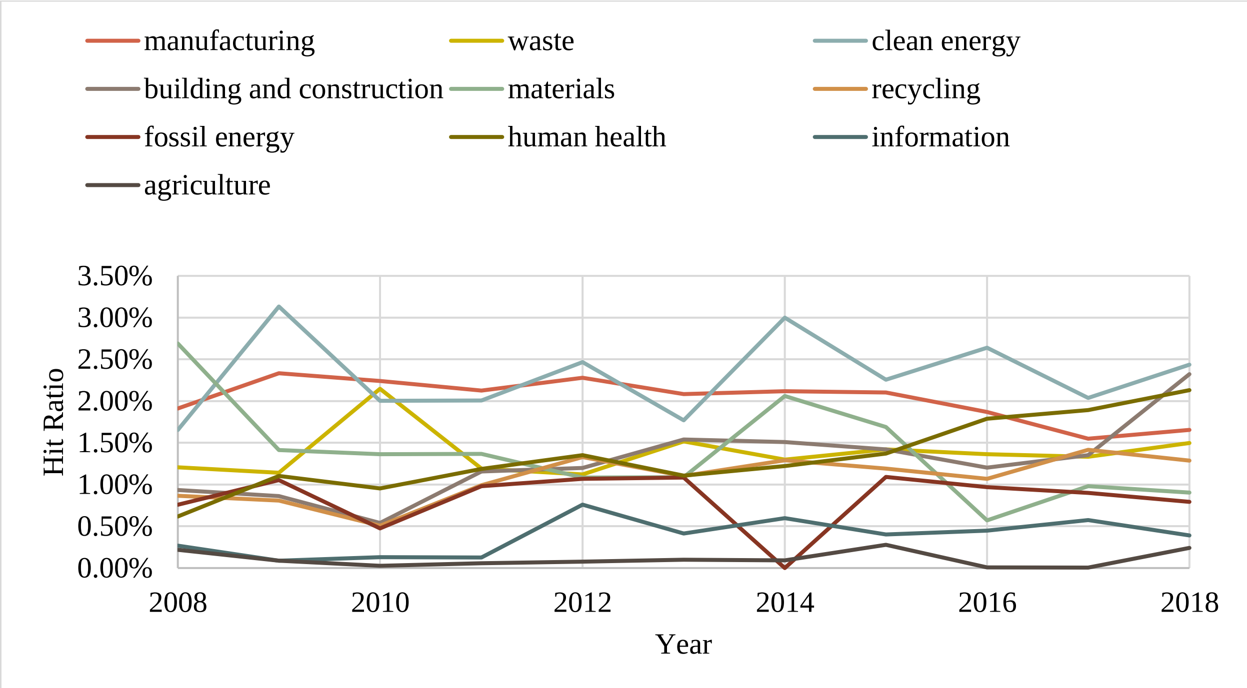


Figure A.3 LCA application field paper hit ratio

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PUBLICATIONS

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International Society for Industrial Ecology

Automated Content Analysis of Life Cycle Assessment Research from 2001 to 2018

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Background

The exponential growth of scientific literature – which we call the 'big literature' phenomenon – has created great challenges in literature comprehension and synthesis. The traditional manual literature synthesis processes are often unable to take advantage of big literature due to human limitations in time and cognition, creating the need for new literature synthesis methods to address this challenge. Automated Content Analysis (ACA) is a specific algorithm that is designed to treat large texture information and provide a visual output. It has been developed since 1990s, and the original process includes sifting, classifying and simplifying of published research. In this project, we are looking into how the research topic changes in the last 18 years, and make some expectations in the developing trend in the future.

Methodology

Data Preparation

19,354 abstracts about Life Cycle Assessment (LCA) from Scopus

Time range from 2001 to 2018

Manual Reading

50 papers

to get a comprehensive understanding about different topics in LCA

Dictionary Construction

LCA application:

Clean energy, Fossil energy, Recycling, Human health

Agriculture, Waste, Manufacturing, Building construction, Material, Packaging

Waste treatment, Economic sustainability

LCA methodology

Consequential, Dynamic LCA

Social LCA, Method, Data analysis, Information, Case study

Environmental Impacts

Ozone depletion (kg CFC-11 eq), Global warming (kg CO2 eq) •

Smog formation (kg NOx eq) • , Acidification (H+ moles eq) •

Eutrophication (kg N eq) •

Human health cancer (kg benzene eq) •

Human health noncancer (kg toluene eq) •

Human health criteria pollutants (kg PM2.5 eq) •

Eco-toxicity (kg 2,4-D eq) •

Fossil fuel depletion (Surplus MJ/yr) •

Land use (density of threatened and endangered species) •

Water use

ACA Process

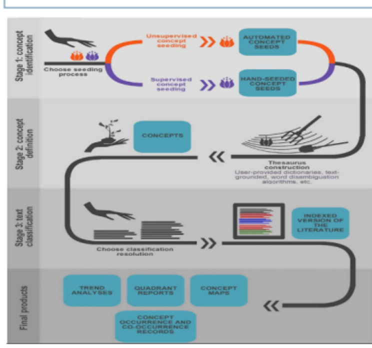

Fig. 1 The Automated Content Analysis Procedure (Nunez-Mir, 2016)

Results

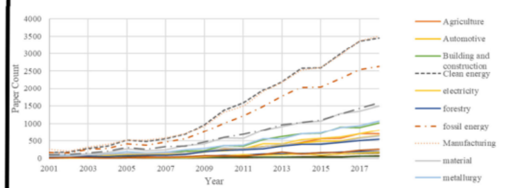

Fig. 2 Application Field

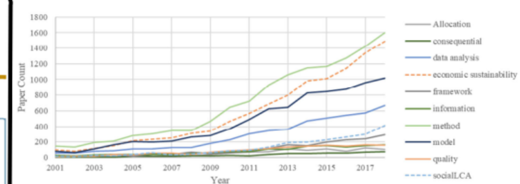

Fig. 3 Methodology Research

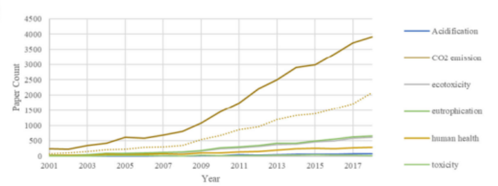

Fig. 4 Environmental Impact

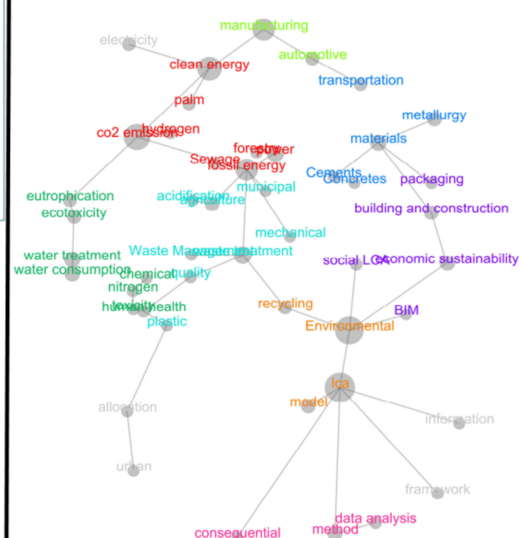

Fig. 5 Concept Cloud Map

sustainability

Article

The Application of Blockchain-Based Life Cycle Assessment on an Industrial Supply Chain

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Abstract: Life cycle assessment (LCA) is a widely recognized tool used to evaluate the environmental impacts of a product or process, based on the environmental inventory database and bills of material. Data quality is one of the most significant factors affecting the analysis results. However, currently, most datasets in inventory databases are generic, i.e., they may represent the material and energy flow of a process at a market average, instead of a specific process used by a manufacturer. As a result, stockholders are unable to track their supply chain to find out the actual environmental impact from each supplier and to compare the environmental performance of alternative options. In this paper, we developed a new framework, i.e., blockchain-based LCA (BC-LCA), where blockchain technology is adapted to secure and transmit inventory data from upstream suppliers to downstream manufacturers. With BC-LCA, more specific data can be acquired along the supply chain in a real-time manner. Moreover, the availability, accuracy, privacy, and automatic update of inventory data can be improved. A case study is provided based on an industrial supply chain to demonstrate the utilization of BC-LCA.

Keywords: life cycle assessment; blockchain; supply chain

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1. Introduction

In recent decades, environmental problems have been an increasingly global issue, affecting everyone. Typical environmental problems include global warming, chemical pollution, depletion of natural resources, and the loss of biodiversity [1]. The blooming of new technologies and demand of products brings growth of industry, but also leads to more serious environmental problems. Thus, to produce a more accurate and fast quantification of the environmental impacts caused by a certain process, a reliable tool is required, which could measure and calculate the environmental impacts in different aspects [2].

Life cycle assessment (LCA) is a widely used tool to analyze environmental impacts. The users of LCA include governments, non-governmental organizations, industrial sectors, and academic and education institutes. The results of LCA could provide customers with a reference so that they can make comparisons. LCA can also benefit decision making by providing information on several alternative products or processes so that there could be some space for trading off [3].

Blockchain, prominently implemented in cryptocurrency Bitcoin [4], could be a promising and complementary addition to LCA. Besides cryptocurrency, blockchain is widely used in financial services, health and medical services, energy rebalancing, agricultural services, and so on. Previous research shows that blockchain can also be applied to improve the sustainable performance as well as the resilience of the supply chain [5,6]. LCA has a very close relationship with the bill of material for products, which are derived from the