Cloud-based Collaborative Footprint Assessment for Green Supply Chain Management

Ke Xing, Wei Qian
University of South Australia, Adelaide, South Australia, Australia
ke.xing@unisa.edu.au, wei.qian@unisa.edu.au

Short abstract
Managing life-cycle information presents a critical challenge for supply chain footprint assessment and performance measurement. Extant literature and supply chain collaboration models fall short in providing an interactive platform to enable cross-organisational life-cycle information gathering, sharing and management. This paper proposes a cloud-based model for life-cycle information and assessment collaboration that can enable dynamic life-cycle data collection and exchange, and supports supply chain collaboration for environmental footprint assessment. This integration is aimed at increasing the accuracy and timeliness of life-cycle information and allows information directly relevant to the characteristics of a particular operation system to be identified and traced.

Keywords: Green supply chain management, Life-cycle assessment, Cloud computing

Topics: Sustainability, Supply chains

Methodology: Theory and/or research framework

Introduction
With growing public awareness and legislative pressure on sustainability performance, businesses today are keen to incorporate environmental considerations into their supply chain models and management decisions. Whilst measuring and sharing information including environmental information between supply chain entities have been discussed extensively in previous literature (see e.g. Bailey & Francis, 2008; Wang et al, 2005; Wu & Cheng, 2008), collaborations amongst supply chain members for measuring environmental footprints and managing relevant environmental risks and opportunities are still new phenomena in Green Supply Chain Management (GSCM). In particular, managing life-cycle inventory (LCI) data for life-cycle assessment (LCA) and life-cycle management (LCM) of products and services in supply chains are major technological as well as financial challenges for GSCM. The data and information stored in established databases are often compiled from limited sources representing average industry practices only. They are inadequate for supporting life-cycle environmental performance evaluation and management, especially when the supply chain networks are complex, dynamic, and composed of involve divergent and frequently changing process and resource flows (Browne & Allen, 2004).

Despite some prior studies suggesting that improved supply chain collaboration will improve information availability and quality (e.g. Hagelaar & van der Vorst, 2002; Kuo et al., 2012; Nakano & Hirao, 2011; Samaddar & Kadiyala, 2006; Verdecho et al.,
there is no platform currently available that enables cross-organisational life-cycle information collection, sharing and management in supply chains. Recent developments in information and communication technologies (ICTs), such as Cloud Computing, Web 2.0 and XML, and Internet of Things, and their applications in manufacturing and service industries enable effective and efficient processing, storage, and exchange of data of diverse sources and heterogeneous formats. These bring promising new technological solutions to improve business information management and supply chain performance (Chen & Ma, 2011). In this paper, we link LCI analysis and supply chain footprint assessment with emerging Cloud Computing and Cloud Manufacturing paradigms to propose a new model for facilitating cross-organisational life-cycle information sharing and LCA collaboration in a multi-structural cyber-physical supply chain networks.

The paper is structured as follows. Section 2 discusses the necessity and features of life-cycle information management for supply chain footprint assessment, which then leads to the importance as well as limitations of information sharing and collaboration models for GSCM explored in Section 3. Section 4 analyses current applications of Cloud Computing in manufacturing and supply chain information management. Based on this analysis, Section 5 presents a hybrid cloud-based model to enhance collaborative LCA in GSCM. The paper concludes in Section 6 with limitations and future research discussed.

**Life-cycle Information for Supply Chain Footprint Assessment**

Using life-cycle cost and impact information, as well as LCA tools to assess and improve environmental performance of supply chains, is of growing importance for companies to obtain green certification or labelling for their products and services (Wang, 2009). In particular, incorporating LCA in GSCM for tracing and mitigating greenhouse gas (GHG) emissions has been increasingly applied in carbon footprint management (CFM) in supply chains (e.g. Abdallah et al., 2011; Chaabane et al., 2012; Sundarakani et al., 2010). Within the three scopes of GHG emissions from industrial operations, Scope 1 and Scope 2 emissions only account for direct GHG emissions from a company’s production operations and indirect emissions from related electricity and thermal energy usage. Scope 3 emissions comprise of all other indirect emissions from supply chains including transportation of supplies, goods delivery, and waste disposal (Greenhouse Gas Protocol, 2011). Studies on carbon footprints of US industries reveal that Scope 1 and Scope 2 emissions capture only about 26% of total emissions, leaving the majority of emissions unmeasured within Scope 3 (Lee, 2011). This indicates the significance of taking the supply chain and life-cycle perspectives into account for measuring and managing carbon emissions and relevant carbon footprints.

Despite recent research and attempts by business to manage environmental footprints in supply chains (such as GHG emissions, solid waste, water, abiotic resource depletion, land degradation, acidification, etc.), it remains a challenge for manufacturing and service companies to effectively measure and control environmental impacts of activities in upstream and downstream supply chain stages (Abdallah et al., 2011; Chaabane et al., 2012; Lee, 2011; Ramudhim et al., 2009). This is especially so if the supply chain is coupled with global outsourcing and distribution, as the complexity and diversity of processes increases.

Most existing supply chain footprint assessment models for GSCM are based on combining business in-house data of production processes and machine use with secondary external data from either established LCA databases/packages or documented information provided by supply chain partners (Browne & Allen, 2011). Although in-
house data from a company’s own processes are likely to be of higher accuracy and quality, collecting and processing such data are time and resource consuming, and require sufficient LCA expertise. Locally operated small and medium sized enterprises (SMEs) usually lack resources and technical capability to perform LCI analysis for their own operation activities. Given an increasingly significant role that SMEs are playing in supplying materials, components, and logistics services, any new method for supply chain footprint assessment needs to enable SMEs to collect and access relevant life-cycle information. Established national or industry-specific LCI databases may contain useful secondary data covering a wider range of goods, services, and energy production and consumption. However, the information recorded in these databases is largely retrospective in reporting environmental impacts, limited in the number of sources, and often statistics-based or aggregated to reflect industry average only (Moreno et al., 2011). Obtaining footprint information from supply chain partners through contractual obligations such as green procurement policies may generate context-relevant and specific data required for performance measurement. But the scope of information held by a small group of supply chain partners is often narrow and limited by contractual conditions, making it hard to use such data to compare and identify differences in environmental impacts between alternative supply chain options. Therefore, as pointed out by Hagelaar and van der Vorst (2002), the concept of combining in-house and external data sources should be replaced by close collaboration among supply chain members to share and integrate sector-specific information. To do so, there requires an efficient and effective technological platform for collaboration in information collection and sharing.

Information Sharing and Collaboration for GSCM

Information sharing and collaboration are at the forefront of discussion recently, particularly in supply chain studies (Bailey & Francis, 2008; Mourtzis, 2011). Previous research demonstrates that improved information sharing and collaboration can help to reduce inventory costs for distributors and manufacturers (Wu & Cheng, 2008), improve efficiency and effectiveness of product and process designs (Dekker et al., 2012), and enhance product as well as supply chain environmental performance (Albino et al., 2012; Green et al., 2012; Morose et al., 2011; Sarkis, 2012; Yu et al., 2010). In GSCM, however, the topic is less discussed. For example, Hagelaar and van der Vorst (2002) provide a comprehensive discussion about theoretical and practical roles of LCA in structuring supply chains. The study highlights the usefulness of integrating and sharing different types of LCI data in supply chains, although it remains unclear as to what techniques can be used to consolidate life-cycle information and maximise the desired benefits of LCA.

Based on a review of the recent development of GSCM, Green et al. (2012) establish a boundary-and-flow framework to identify barriers to interdisciplinary GSCM. They indicate that information availability and sharing, in particular availability and sharing of environmental information, have become more problematic in today’s GSCM. This is owing to increasing informational dynamics arising from continuous development of new products and materials and introduction of new processes in supply chains, whilst current life-cycle information is still largely retrospective and static. The study points to the need for collaborative methods and platforms to facilitate real-time information acquisition, recording, sorting and sharing.

Firms need to be aware of not only environmental implications of their own processes and operations, but also related environmental implications from and to their suppliers and product users. This requires new life-cycle information being made
available continuously and visible to every supply chain participant. Clearly, there is a need to establish a collaborative life-cycle information sharing platform to enable the incorporation and assessment of entire supply chain footprints. Research has started to develop and apply new ICT solutions, in particular Cloud Computing and web-based technologies, to assist in establishing such collaborative platform.

**Emerging Cloud in Manufacturing and Supply Chain Management**

Cloud Computing has recently been proposed as a new solution to mass data management and sharing in manufacturing and supply chains (Chieu et al., 2010; Zhao & Liu, 2009). In a Cloud Computing environment, functions, services and resources are configured and delivered by a system of independent, self-serviced, heterogeneous Clouds, which can be generally categorised into four categories according to their formations and boundaries (Chang et al., 2010; Briscoe & Marios, 2009; Celesti et al., 2010):

- **Private Cloud**: a proprietary computing architecture that provides hosted services to limited internal users behind a firewall, with the highest level of privacy and data security.
- **Public Cloud**: resources available to the general public beyond the firewall of an organization and over the Internet. The level of privacy and data security will be a main concern for users.
- **Community Cloud**: ICT resources and infrastructures from several organisations with similar interests or needs are shared to realise common benefits. It may have a higher level of data security than public cloud.
- **Hybrid Cloud**: a mix of both Public and Private Clouds to swap processing and spread applications across those boundaries, including federated Clouds that have multiple external and internal Cloud Computing services deployed and managed to match business needs.

A Cloud Computing system is inherently service-oriented and highly agile and scalable in providing/re-providing near real-time functions and resources to a large number of divergent users (Damodaram & Ravindranath, 2010; Marston et al., 2011; Tsao et al., 2010). Therefore, it is considered as particularly suitable for cross-service collaboration in manufacturing as well as cross-organisational collaboration in supply chains (Cegielski et al., 2012; Chen & Ma, 2011; Demirkan & Delen, 2012; Li et al., 2010). Cloud Manufacturing is an example of using Cloud-based technologies to enable a collection of distributed manufacturing resources and capabilities accessed and operated through centralised production management with intelligent search mechanism on a cloud platform (Li et al., 2010; Wu & Yang, 2010; Zhang et al., 2011). Yang et al. (2013) investigate the use of cloud technologies to adapt large equipment manufacturers for collaborative manufacturing service operations. Integration and coordination of federated resources to provide scalable and adaptive service solutions are enabled through a cloud manufacturing service platform. Manufacturing clouds encapsulate virtualised manufacturing resources and capabilities and assemble them into a virtual manufacturing environment or enterprise to provide production solutions on-demand (Li et al., 2010; Ning et al., 2011; Valilai & Houshmand, 2013; Xu, 2012; Yang & Li, 2011). However, there is still a paucity of research applying cloud technology into other processes and stages of a supply chain beyond manufacturing, particularly for supply chain footprint assessment and control. As part of initial developments include, Demirkan and Delen (2012) develop a conceptual framework of service-oriented decision support system to improve agility of the system and propose the idea of putting analytics and large data into the Cloud. Chen and Ma (2011) mainly focus on the
potential of using Cloud concepts in managing supply chain information. Both studies argue that Cloud Computing provides potential solutions to better coordination and co-management of environmental information and resources in networked supply chain processes, although their studies have not adequately pursued these solutions.

By extending the Cloud Manufacturing paradigm and previous limited studies of Cloud applications in supply chain management, this paper proposes that a multimodal and multilevel cloud environment to support hybrid cloud platforms needs to be established to enable supply chain members to access and share real-time life-cycle information and help assess their environmental performance.

**Hybrid Cloud Collaboration Platform for GSCM**

This study posits that a broader configuration of a Cloud service environment, which links different Cloud applications and platforms, is capable of facilitating cross-organisational life-cycle information sharing and collaboration in a multi-structural cyber-physical supply chain networks. Extended from the Cloud Manufacturing paradigm and to cope with the dynamic and heterogeneous nature of supply chains, resource integration and process collaboration need to operate on a flexible and scalable platform which can lead to a federation of different Clouds and Cloud services, or ‘a Cloud of Clouds’. Therefore, a hybrid cloud platform with a mixture of public, private and community Clouds needs to be created to provide support for collaborative LCA. Figure 1 illustrates the hybrid cloud-based model for LCA collaboration in GSCM. There are three main types of Clouds contained the model, namely Life-cycle Assessment Cloud (LCAC), Enterprise Cloud (EC), and Green Supply Chain Cloud (GSCC).

![Figure 1 – Hybrid Cloud Model for LCA Collaboration](image)

**Life-cycle Assessment Cloud (LCAC)**

LCAC is a service-oriented Cloud offering LCA resources and capacities to users. LCA resources and capacities are built upon a Cloud platform because localised LCA
platforms can be costly and lack accessibility. There are an increasing number of LCA or similar environmental assessment software available in the market, such as SimaPro, Gabi, LCAiT, TEAMS, PEMS, and the like. These software may have embedded modules allowing users to conduct self-study of LCA. However, in many cases, LCA software platforms for product system life-cycle modelling and impact assessment need to be installed within local computer systems and use life-cycle datasets downloaded to local databases or included in LCA software packages. Mounting software license fees are clearly a major concern for local users, especially SMEs. Also, data quality and generalisability are issues in secondary databases which can hinder life-cycle information sharing in supply chains (Moreno et al., 2011).

In recent years, more Internet-based LCA services appear to provide online access to established LCI databases and for LCI data analysis. For example, the Europe Union (EU) LCA InfoHub (https://infohub.konicaminolta.eu) provides online resources on life-cycle reference data, tools and services. The CASCADE and DEPUIS projects funded by the EU have developed Web Ontology Language (OWL) to support online life-cycle information transfer between different LCA systems (Moreno et al., 2011). The widely used EcoInvent system supports web-based LCI analysis and data exchange using XML technology and schemes (Frischkneckt & Rebitzer, 2005). These online LCA services and applications go beyond localised LCA platforms and provide opportunities as well as technological support for real-time life-cycle information sharing and management. To realise such information sharing and management, online LCA software and technological applications can be built on a service-oriented LCA Cloud platform. As argued by some researchers (e.g. Marston et al., 2011; Demirkan et al., 2010; Xu, 2012), Cloud services can be supported and realised through applications and software built and deployed for the Cloud on the Internet (known as Software-as-a-Service or SaaS), through some middleware, Application Programming Interfaces (APIs), and information for users to develop Cloud applications (known as Platform-as-a-Service or PaaS), or through providing and ensuring computing power when it is needed, using virtualisation techniques to achieve cost savings and more efficient use of resources (known as Infrastructure-as-a-Service or IaaS). Since services supplied in LCAC are supported through LCA software and applications, LCAC can be designed as a SaaS Cloud providing flexible, accessible, and dynamic LCI data and impact assessment services for supply chain footprint evaluation. Once LCAC is constructed and modulated, it provides solid foundation for interaction with the other two Clouds, i.e. EC and GSCC.

**Enterprise Cloud (EC)**

In a multi-echelon supply chain network, each supply chain member needs to have its operation system and resources virtualised and managed in an EC. There may be different ECs set up for respective supply chain stages, e.g. material and energy supply ECs, manufacturing ECs, distribution ECs, warehousing ECs, take-back ECs, recycling ECs, etc. While large companies may have their ECs built upon own ICT infrastructures, most of SMEs have to rely on third-party Cloud service providers to set up EC platforms.

In many situations, when there is horizontal collaboration between companies at one supply chain stage, such as manufacturing companies use subcontractors to complement their production capacity or slot exchange between different shipping carriers, interactions among corresponding ECs for sharing virtual resources, infrastructures, and capabilities in the form of a ‘Cross-Cloud Federation’ are instigated (Celesti et al., 2010). In a Cloud environment, such cross-EC communications and collaborations are
enabled through the applications of Agent Technology and Multi-Agent Network, popular approaches used in Collaborative Manufacturing (Liu et al., 2011; Zhou et al., 2010). Adapted from the architecture of Cloud Manufacturing developed by Ning et al. (2011), the structure of EC is designed as Figure 2 where life-cycle information tracking occurs first inside local Clouds and then is governed by the mechanism of EC.

![Figure 2 – Structure of Enterprise Cloud (adapted from Ning et al., 2011)](image)

**Virtual Resources Layer** is the foundation layer that consists of two functional modules. The Resource Interface module interacts with the Actual Resources of machinery, equipment, devices, and ICT infrastructures possessed by the organisation through advanced sensor networks, RFIDs and smart tags, as well as Virtual Machine Monitors run on identified hardware equipment. Information and data signals of equipment operations and states are extracted and delivered to the Virtual Machines module, which maintains the virtual representations of the facilities equipment capacities are maintained. Virtual machines and resources can be decomposed, reconfigured, and regrouped to produce results based on internal and external demands.

**Core Service Layer** is a function layer responsible for service request processing, request queuing and prioritising, and defining the formats for receiving and dispatching the data. In this layer, the Service Interface module contains various Task Agents to directly communicate with external and internal applications (e.g. life-cycle design, product life-cycle management, green labelling, etc.) and stakeholders. Task Agents are defined as autonomous intelligent agents that operate on behalf of their host ECs to achieve a particular goal, but without interference from their ownership entities. They
are capable of developing and adjusting their agenda according to the changes they sensed from the interaction with other agents in the green supply chain networks (Franklin & Graesser, 1997; Mishra et al., 2011). The Service Management module handles service requests from internal and external sources through identifying and managing corresponding virtual machines and capabilities to form adaptive processes and perform on demand. The Service Management module also interacts with internal databases to retrieve accurate information for planning and control of virtual resources.

Enterprise Data Repository Layer consists of databases that store information of parts, materials, processes and input-output flows, and resource requirements related to each product or service portfolio. Various forms of application-specific data and information used by different virtual machines and computer-aided application software programs, or CAx Apps, for internal and external service requests need to be translated into standardised representations for data storage, and vice versa. The layer communicates with the other two layers through Loading, Extracting, Converting, and Transferring (LECT) channels, which perform data management functions to obtain, sort, transform, and move product and process data into or from respective data bins of Enterprise Data Repository (Demirkan & Delen, 2012). Meanwhile, Data Security Layer interacts with all other layers in an EC. It provides a security envelop for the system to protect safety and integrity of both inter-Cloud and intra-Cloud data processing and exchange.

When Service Interface receives a task request from an internal or external source regarding a certain product or service processing, a cluster of virtual machines will be identified, integrated and activated by Service Management. The primary process input-output data about material and energy consumption, process emissions and operating status of corresponding equipment and facility use can be traced and gathered from Actual Resources through technologies such as RFIDs and smart tagging. At Resource Interface, the process-flow information collected are sorted and modulated into compatible and operable formats. These formats are defined by respective CAx (e.g. computer-aided design, computer-aided planning, and computer-aided manufacturing, etc.) applications run through Virtual Machines. When a virtual resource from another EC is called upon through Cross-Cloud Federation, copies of the process-flow data related to that particular resource will be requested and conveyed via communications between agents in Service Interface of a corresponding EC. Then, the product or service-specific process-flow data will be compiled and converted into a uniform data structure through Data LECT channels and deposited into pertinent data bins in Enterprise Data Repository. This Enterprise Data Repository can be connected to and used by ERP systems.

Life-cycle Data Representation and Exchange in EC

To exchange and share product/service life-cycle information within an EC environment, it has to be firstly ensured that the meaning and measurement of process and flow properties are consistently and unambiguously defined. Consistent LCI data representation is important not only for cross-organisational collaborations among multiple ECs but also for a single EC using different software and information management platforms. As indicated by Swindells (Swindells, 2009), direct data transfer between two software systems will fail if the data are represented and interpreted by dissimilar internal data models at the source and at the receiving end. In this regard, life-cycle data structures need to be represented independently from proprietary ICT systems to ensure data compatibility and interoperability. For this purpose, standardised, system-neutral mechanisms are needed to define specifications of
computerised information about products, processes and their properties. We apply Product Data Technology (PDT) to standardise life-cycle data representation and exchange in an EC.

PDT provides a means to specify product and process information so that it can be communicated and exchanged efficiently among computerised operations at different product/service life-cycle stages (Moreno et al., 2011). PDT has experienced rapid expansion in different industry sectors through developing various PDT standards, such as ISO 10303, otherwise known as STEP (Standard for the Exchange of Product Model Data), application protocols (APs), ISO 13584 Parts Library (for part and material suppliers), ISO 15926 (with a particular emphasis on the oil and gas industries), as well as ISO 14048 for the format of LCI data (Frischkenckt & Rebitzer, 2005; Swindells, 2009). This paper uses PDT to facilitate system-neutral life-cycle data tracking, conversion and exchange within a Cloud environment. This is built upon recent work of Taghaboni-Dutta et al. (2010), Moreno et al. (2011) and Valilai and Houshmand (2013). According to these studies, applying PDT among supply chain members operating in different industry sectors needs to follow the criteria below:

- Various product and process information relevant to different life-cycle stages are collected and represented in a standard data format which supports computer-aided applications and can be transferred between heterogeneous software systems; and
- Process-flow information from different data models and product databases are interpreted and converted into ISO 14048-based XML format to allow data sharable in the Semantic Web and processable by different LCA systems.

Based on these procedures and criteria, LCAC and EC structures are expanded to include the use of PDT to represent and exchange life-cycle information in ECs, which is illustrated in Figure 3. The figure demonstrates that first, through applying Virtual
Machine Monitors, RFIDs or advanced sensors on physical resources, the production equipment and systems are virtualised, and the operation information about resource usage, material and energy flows, temperature, pressure, toxic chemicals, or possibly, harmful agents can be captured. Second, the process-flow information captured by different devices needs to be modulated (at Resource Interface in EC) into a format that meets the specifications of respective CAx applications and be delivered as an input to virtual machines and CAx modules. As indicated previously, for a product or service, information about its virtual resource use and input-output flows be packaged and transferred to product databases in Enterprise Data Repository through Data LECT channels. At this stage, the product and process-flow data will be converted from an application-specific format into a standard industry-relevant data structure. For manufacturing firms, schemas of some ISO 10303 APs (STEP APs), such as AP209 for composite and metallic structural design, AP210 for electronic assembly and packaging design, AP221 for process plant representation, and AP239 for product life cycle support, are applied to represent modular data structure of the product and process information in respective life-cycle stages (Moreno et al., 2011). The data format conversion mechanism in this process is similar to that of LAYMOND platform for collaborative manufacturing (see Valilar & Houshmand, 2013).

Subsequently, the translated product and process data in STEP standard are dispatched to the product databases in the Enterprise Data Repository for storage. The STEP standard data can be conveniently transferred to and processed by CAx in other ECs, irrespective of what types of software platforms they use. This is especially useful when virtual resources from external ECs are engaged via Cloud federation as a result of production/service outsourcing and when process-flow information from different production resources need to be integrated for LCI analysis.

Upon receiving the requests for life-cycle information, the STEP AP data need to be extracted from relevant databases and directed to the LCI Analysis function in the Service Management module. Product-specific process and flow information are received at the Life-cycle Process-Flow Information Interpretation module where data structures are translated into ISO 14048 Environmental Management and LCA data documentation format. The LCI Analysis module communicates with the LCA system, which can be located in the LCAC and act in the SaaS mode, via a web-based software interface. As illustrated in Figure 2, raw product and process data are delivered to a LCAC through LCA Platform Interface which evokes the LCI analysis process inside the Cloud for dataset verification, dataset categorisation and inventory result computation. The processed system-specific LCI data are then conveyed back to the EC and stored in local LCI libraries in ISO 14048 format to support life-cycle modelling and environmental performance assessment.

To achieve speedy communications and efficient data exchange among different Clouds over the Internet, XMLize/DeXMLize operations are incorporated (Taghaboni-Dutta et al., 2010). These operations enable PDT standard data structures to be converted to (XMLize) or from (DeXMLize) XML document format when data are sent or received through different data exchange interfaces. Specifically, for LCA data conversion, a formal ontology using Web Ontology Language (OWL) (developed under the CASCADE and DEPUIS projects of the European Union) is applied. The format of the ontology is derived from ISO 14048 and compatible with the format of engineering data transfer between enterprise information systems. Moreno et al. (2011) postulate that the ontology can be conveniently applied to translate PDT data into the XML format to facilitate LCI analysis. Also, through using data exchange Task Agent, the Life-cycle Data Exchange Interface can provide a communication platform for inter-
organisational information collaboration, which contains modules for processing/issuing data requests, uploading/downloading XML data files selected and controlling the security of data access (Taghaboni-Dutta et al., 2010).

**Green Supply Chain Cloud (GSCC) for LCA Collaboration**
The data exchange among supply chain members are managed in a broader supply chain Cloud. We construct this as a *Green Supply Chain Cloud* (GSCC). GSCC is a Community Cloud representing product-specific, supply-demand-based, and solution-oriented supply chain partnership. The formation of a GSCC may change when EC members change, i.e. withdrawal of existing EC members or signing of new ECs. In addition, an EC may simultaneously communicate and collaborate with a number of GSCC platforms if an EC member has multiple product/service portfolios and is involved in different supply chain networks.

![Figure 4 – Virtual Green Supply Chain Cloud System](image)

Extended from the current Cloud Manufacturing paradigm, GSCC has a construct of a hybrid Cloud and functions as an extended virtual enterprise that integrates the virtual resources and capabilities encapsulated in individual ECs of supply chain members. As illustrated in Figure 4, the basic architecture of GSCC is consistent with that of EC, but with broader functional scopes to ensure that information sharing and collaboration among supply chain members can successfully accomplish key GSCM tasks. These include identifying and defining GSC strategy and structure to achieve common GSC interests and goals, selecting and prioritising environmental footprint performance measures and targets that are in line with the GSC strategies and goals defined, identifying the information needs and methods for conducting LCA process to provide and share environmental footprint data, and managing and improving overall sustainability performance of a GSC (Hagelaar & van der Vorst, 2002).
GSCC has to bring together different types of physical-cyber resources along the chain. This includes incorporating virtualised resources from stages of Material Supply, Production, Distribution, Product Use and Recycling. Often, Service-Oriented Architecture (SOA) and Internet of Things (both physical and virtual objects) are used to link together these different forms of resources. When physical-cyber resources are represented in forms of Virtual Resources, they are organised and managed through Agent-based Interfaces embedded in the Service Interface layer of ECs at different supply chain stages. Agent-based Interfaces will ease communications and coordination among heterogeneous supply chain ECs because interactions between diverse agents in supply chain ECs can be supported by multi-agent system techniques (Zhou et al., 2009; Kishorea et al., 2006) or through agent-based supply chain coordination models (e.g. Kim & Cho, 2010; Mishra et al., 2011; Sadeh et al., 2001). In this regard, GSCC is essentially an Agent-based Virtual GSC upon which an agent-based information collaboration and management platform can be built. Figure 5 further elaborates how GSCC provides an agent-based platform for life-cycle information sharing and LCA collaboration.

Figure 5 – GSCC Platform for LCA Collaboration

In the GSCC platform designed, LCA collaboration is facilitated by a Supply Chain Champion (often the dominant member in the supply chain). By using the middleware
and APIs provided and maintained by a Cloud Service Provider via PaaS, coherent protocols and standard interfaces are established for both GSCC Collaboration Platform and ECs of supply chain members (including Supply Chain Champion) to support communication among various Task Agents representing respective supply chain tiers and roles to ensure quality, consistency and compatibility of life-cycle information exchange and sharing.

The process of LCA collaboration can follow the patterns as suggested by Nakano and Hirao (2011), which includes a mixture of collaboration and local tasks. First, the LCA project scope and system boundary (1) and information sharing needs (2) are negotiated and determined through agent communication. These Collaboration Tasks are to define consistently what and how system boundary, functional unit, level of detail, data format and terminology, modelling method, and impact allocation need to be applied in a supply chain (Chen & Ma, 2011). Second, each Task Agent feeds the information back to its local EC to evoke service requests internally through the Service Management module in respective EC. Relevant product and process data will be extracted from local databases and sent to LCAC for LCI analysis (3) and conducting partial LCA (4). Local Tasks of (3) and (4) only compute environmental footprint measures related to the respective life-cycle stage in accordance with identified system boundaries. Third, the locally obtained LCI and LCA information from supply chain ECs are conveyed back to the GSCC platform through Task Agents for shared access and for result synthesis as well as interpretation at the supply chain level. This means Local Tasks return to Collaboration Tasks. After the interaction with LCAC, supply chain LCA is conducted and footprint performance is evaluated against GSC performance targets (5). The weak spots in supply chain processes, the processes and/or parts that significantly contribute to supply chain footprints, and alternatives for improvement are also identified through scenario analysis (6). Finally, the evaluation outcomes and improvement strategies are communicated back to respective local ECs for necessary off-line changes made on production and service systems held by supply chain members (7). Up to this stage, one communication cycle for LCA collaboration using GSCC platform is completed. The effective application of GSCC platform may largely hinge upon continuous communication among Task Agents and their real-time as well as dynamic exchange and processing of life-cycle information within and between ECs.

Discussion and Conclusion
A major technological and financial challenge for GSCM involving a large network of dispersed manufacturing facilities and SMEs is the lack of resources and ability in those companies to access, assess, and manage environmental impact data of their operations. Extant literature and GSCM collaboration models acknowledge the issue but fall short in providing an interactive platform to enable life-cycle information collection and exchange and to support collaboration for LCA and supply chain footprint assessment.

Based on the Cloud Manufacturing paradigm and web-based technology applications, this paper proposes a multimodal and multilevel cloud-based model to support collaborative LCA. The architecture and data exchange mechanisms used for this hybrid cloud model provide a technological platform to support dynamic life-cycle information sharing and real-time footprint assessment in supply chains. The implementation of this platform can be done by either the champion of the supply chain or a third-party business intelligence service provider to set and maintain protocols for life-cycle data collection and communication, to check LCI data quality and consistency, to ensure system accessibility, reliability, and security, to conduct data synthesis and the whole-
of-supply-chain environmental footprint evaluation, and to produce LCA report for the supply chain as well as external stakeholders.

In comparison with other extant models for supply chain collaboration, which largely focus on business and operations strategies for cross-organisational information sharing, a main strength of this model is the integration of RFID and data management technologies with an enterprise Cloud platform for tracking process-flow information of production and logistic activities. This integration increases the accuracy and timeliness of life-cycle information obtained and allows information directly relevant to the characteristics of a particular operation system to be identified and traced. In addition, by creating the interconnected LCA, Enterprise and GSC Cloud environments, the model enables companies, particularly SMEs, to access and exchange life-cycle information with other members of the entire supply chain network, and to conduct footprint assessment and management based on real-time life-cycle data. The service-oriented architecture of the GSCC platform and agent-based communications established in XML data format also facilitate more flexible and scalable LCA collaboration for different types of ECs. One of the major opportunities derived from Cloud-based LCA and GSCM is to encourage existing LCI and LCA service providers to develop and adopt new business portfolios for online life-cycle information management and footprint management based on SaaS and PaaS. This may create new profit centres for companies willing to become life-cycle information service providers.

However, the proposed Cloud-based model is still at the conceptual design stage. Therefore, a detailed model construct and operational mechanism to support data conversion, data exchange and data synthesis within and across the three Clouds (i.e. LCA Cloud, Enterprise Cloud, and Green Supply Chain Cloud) are yet to be further developed. Also, like many Cloud-based systems and applications, the costs of investing in developing in-house IT capabilities and maintaining operations of hardware and software systems may be high if companies operate their own private Clouds. For most supply chain members, especially SMEs, it is more viable to subscribe Cloud data or platform services provided by third parties on a pay-per-use basis. Meanwhile, the stability and quality of mission-critical Cloud services for life-cycle process-flow data gathering, management and exchange need to be addressed and guaranteed through Service Level Agreement with Cloud service providers. Applying the model developed in this paper will not be feasible without developing and managing mutual trust and partnership among supply chain members for collective GSCM benefits. In the future work, it is necessary to incorporate the Cloud-based model implementation with a cross-organisation communication framework for co-defining system boundary and functional unit, the level of detail for data sharing, and common strategies for footprint management. Future research may also benefit from incorporating other GSCM functions, such as life-cycle design and life-cycle management, into Cloud-based models. Linking Cloud technology with the ERP system to enhance business analytics are also areas worth further investigation in future studies.

References


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