IIoT-enabled and Data-driven Sustainability Evaluation Framework for Textile Supply Chain

Tan Wei Chit
Virtual Manufacturing Group
*Advanced Remanufacturing and Technology Centre, A*STAR*
Singapore
tan_wei_chit@artc.a-star.edu.sg

Liu Ning
Virtual Manufacturing Group
*Advanced Remanufacturing and Technology Centre, A*STAR*
Singapore
liu_ning@artc.a-star.edu.sg

Noel Antony Paliath
School of Mechanical and Aerospace Engineering
Nanyang Technological University
Singapore
noelantony.95@gmail.com

Yuan Miao Long
Digital Manufacturing Group
*Advanced Remanufacturing and Technology Centre, A*STAR*
Singapore
myuan@artc.a-star.edu.sg

Humza Akhtar
Virtual Manufacturing Group
*Advanced Remanufacturing and Technology Centre, A*STAR*
Singapore
akhtarh@artc.a-star.edu.sg

Yang Shanshan*
Virtual Manufacturing Group
*Advanced Remanufacturing and Technology Centre, A*STAR*
Singapore
yangs@artc.a-star.edu.sg

***Abstract*—Global ecolabelling scheme for consumer products could be beneficial to the world by increasing the public awareness about the environmental impact that might be caused by the manufacturing production along the supply chain activities, i.e., carbon footprint emission. By putting the conventional life cycle assessment (LCA) in tandem with the latest Industrial Internet-of-Things (IIoT) technologies, heterogeneous input and output data sources can be accumulated in real-time manner, towards a data-driven sustainability metric evaluation to produce the ecolabels to promote the eco-friendly consumer products in supply chain.**

In this paper, we present a high-level technical overview architecture to showcase how we utilize the IIoT technologies to enhance the sustainability evaluation metric along textile supply chain. The input and output data collection along all stages in the textile supply chain thus can be qualified and quantified to yield a guideline for LCA practitioners.

Keywords— sustainability, Internet-of-Things (IoT), textile supply chain, ecolabelling

I. Introduction

Businesses today are shifting from considering just profit, to also considering social and environmental impacts as part of their business performance, driven by shifting consumer behaviors to be eco-friendlier and more ethical. There are numbers of fashion and textile ecolabels available in the market. These ecolabels could provide standards to help businesses effectively and accurately describe their products in a way that instills loyalty and trust, support consumers with clear and accurate information for purchase decision, as well as support regulators to establish measure criteria for environmentally related incentive schemes. To reach a reliable ecolabel index, accurate data extraction and evaluation plays a key role. The data extraction process is currently being done via manual data collection, like interview or questionnaire-based data input, which is quite labor-intensive. This kind of data is captured via different input sources of the ecosystem which could be massive, dynamic and heterogenous in nature. Subsequently, there are also several technical challenges to extract the insights from the collected data.

Recent development of Industry internet of things (IIoT) and cloud computing has enabled deeper and wider data connectivity in manufacturing, logistics and even to consumer side. Products and its components are becoming smarter, with a higher degree of connectivity, tapping on the use of embedded sensor, software and cloud system for storing and analyzing product data. This has brought new technological solutions and data interpretation for environmental ecolabelling. This paper proposed a new IIoT-enabled and data-driven sustainability evaluation framework for textile supply chain by linking those emerging supply chain data visibility solutions (e.g., arc.net™), cloud computing, digitalized manufacturing and shop floor data gathering (e.g., arc.ops™ and arc.lite™) with the existing life cycle assessment (LCA) framework.

II. Literature Reivew

A. Ecolabeling

Product labelling is important to set standards and aid in public policies that can improve the environmental performance, quality of products for consumers, and the overall quality of the products [1]. Ecolabelling is a type of product labelling that is a proven method of environmental efficiency evaluation, certification, and labelling preferred by many organizations [2].

The International Organization for Standards (ISO) has outlined standard practices to govern the ecolabelling practices under the ISO 14020 to 14025 series of standards [2]. ISO proposes three types of ecolabels based on the rigor of each standard types and the degree of governance. Table 1 outlines the unique traits of each of the three types of ecolabels under ISO standards [3].

These ecolabels play a vital role in helping inform consumers of the environmental impacts of their purchase decisions. In doing so, this helps environmentally conscious businesses distinguish themselves and gain a market advantage. Mainly driven by fuel and energy consumption, the first of these ecolabels, i.e., the Blue Angel [8], was introduced in Germany in 1978. Today there are several well-known governmental ecolabels such as the EnerGuide for vehicles below 8500lb by the Canadian government [9], the Appliance Standard Program by the government of the United States of America (US) [10], and the EU Ecolabel to promote products and services with a reduced environmental impact by the European Union (EU) [11]. There are also multiple international ecolabelling organizations like the Global Ecolabelling Network – a Non-Governmental Organization (NGO) which focuses on type I ecolabelling [12] and the International Social and Environmental Accreditation and Labelling Alliance (ISEAL) [13].

TABLE 1. ISO STANDARD FOR ECOLABEL

Standards Types	ISO Schema	Description	Time to Market [4]	Cost to Organisation [4]	Examples [4]
Type I	14024: 2018	A voluntary declaration with multiple attributes, that is **developed by a 3rd – party** and within a product category, showing preference to a more environmentally efficient product in comparison [5].	Long	Medium	Blue Angel Eco-flower Swan TCO
Type II	14021: 2016	A **self-declared** claim of a particular environmental trait of a product or service that is backed by evidence (e.g., 100% recycled material) [6].	Short	Low	NITO ECMA TR/70
Type III	14025: 2006	An extension of the product Life Cycle Assessment (LCA) in accordance to ISO 14040. An interested party must **peer review this assessment,** and the organisation must include the results of the peer review in the public documentation of the study conducted [7].	Very Long	High	Volvo Electrolux Ericsson Ricoh

B. Life Cycle Assessment

Life Cycle Assessment (LCA) is outlined in the ISO 14040 standard [14]. It is a systematic method of evaluating the environmental performance of a product or service [15]. Consisting of 4 stages – namely Goal and Scope Definition (ISO 14040) [14], Inventory Analysis (ISO 14041) [16], Impact Assessment (ISO 14042) [17] and Interpretation (ISO 14043) [18] – LCA is an iterative and continuous process. LCA databases like GaBi and SimaPro are often used to address the primary data availability gaps [19].

In practice, the complexity of supply chains (e.g., web-like structure and multiple stakeholders with varying interests) directly affects the complexity of conducting LCA. On a more granular scale, each stage of the LCA has various limitations, which increases the uncertainty of the LCA and degrades its accuracy. A study was conducted to systematically identify and understand the severity of existing unsolved problems of LCA and the results of this study are summarized in Table 2 [20]. Studies have identified a lack of data and poor data quality as root causes to the aforementioned problems [21]. It was also recognized that limited progress has been made towards solving these problems across multiple industry sectors [21-27].

TABLE 2. STAGE-SPECIFIC UNRESOLVED PROBLEMS OF LCA

LCA Stages	Most Severe Problems
Goal and Scope	- Decisions of inclusion and exclusion - Selection of system boundary - Definition of function unit
Inventory Analysis	- Allocation for multi-flow processes
Impact Assessment	- Truncation or 'Cut-off' - Assumption about global homogeneity of processes (Ignoring local uniqueness) - Assumption about steady state
Interpretation	- Subjectivity of aggregation by weighing/valuation - Cumulation of inaccuracies from the prior stages

C. Supply Chain (SC) Sustainability

With the advent of Internet of Things (IoT) technologies, numerous components, machines and devices are being connected in the edge or cloud network by different communication means to allow stakeholders to do more dynamic decision making [28, 29]. Furthermore, cloud computing and the Internet may be utilized to enhance digital SC lines by connecting multiple locations [30]. Even though technology diffusion speed of IoT has almost doubled from 2014 to 2019, studies on SC sustainability using IoT have not been focused on and this area has been identified as a research gap [31].

D. Life Cycle Assessment (LCA) in the Textile industry

The global textile industry uses more than 15 000 different types of chemicals: including over 10 000 types of dyes and pigments along with more than 5000 other secondary chemicals [32]. Less than 7% of the 9.548 billion tons of water consumed by this industry was recycled in 2010 [33]. Intense international competition and a lack of ecological balance in this multi-billion industry are demanding collective focus to curb the environment impacts and extensive resource utility of this industry [34, 35]. Obtaining Life Cycle Inventory (LCI) data has been identified as an unresolved problem due to the complexity of the manufacturing SC system in this industry [36, 37]. This makes it difficult to conduct the LCA for this industry [38, 39]. Van Der Velden et al. have also identified that further studies need to be done urgently to lower the high levels of uncertainty in the LCA conducted on the textile industry [40].

The European Commission has outlined a set of Product Environmental Footprint Category Rules (PEFCR) for t-shirt SC system. These are life-cycle-based rules to provide product-specific methodological guidance in understanding the environmental footprint of an organizations within the t-shirt SC. This T-shirt PEFCR study is segmented into 3 situations based on data availability levels with multiple options within each situation. The most data reliant situation-option combination in the t-shirt PEFCR has been selected as a benchmark to base this study [41].Overall, the proposed research work aims to explore how IoT can be used to improve the quantity and quality of data collected in the textile industry – leveraging on the framework provided by the PEFCR – to reduce the levels of uncertainty in the LCA results. In doing so, it is aimed to gain a more accurate understanding of the environmental performance of the textile industry. Incorporating IoT into the textile SC also has the added benefits of conducting LCA continuously and providing stakeholder with more operational performance information.

III. METHDOLOGY AND IIOT FRAMEWORK

In the proposed solution, we aim to integrate the IIoT capabilities into the LCA modelling framework to reduce the uncertainty of primary source data from the textile industry. It consists of four layers, i.e., process layer, data layer, arc.net™ layer and ecolabelling layer.

The technological infrastructures required at each layer was co-developed in conjunction with Arcstone Pte. Ltd. to fulfill the unique requirements for a fully connected and automated IIoT-enabled LCA data acquisition network. Special attention was paid to ensure that the four layers are interconnected seamlessly to achieve a high level of automation. For a holistic approach, we provide an overview of technical architecture for the textile SC use case by using Arcstone products and solutions as the middleware platform, as shown in Fig. 1.

A. Process Layer

Interfaced to the physical world, the process layer serves the purpose of collecting material and energy flow raw data. To establish LCA modelling for textile SC, a simplified version based on system boundary consideration was given – with reference to literature [32,42] – as shown in Fig. 1.

The primary data collection at the Raw Material Production stage is constrained by its IIoT-enabled capability due to the complexity of agricultural systems. Therefore the LCA modelling of Cradle-to-Farmgate [43] would either reply on check list based data collection via arc.lite™ solution, or presume the inputs from existing secondary database for the final sustainability evaluation.

At the Product Manufacturing stages of the SC, IoT sensors are utilized to collect the flow data at each node. The types and number of sensors used at each node are to be determined based on the goals and scope of the LCA (as per ISO 14040).

However, it is not always feasible to incorporate IoT sensors into products. Therefore, at the Gate-to-Grave stage of the SC, user-input product utility data can be leveraged to derive the information required to conduct LCA. LCI databases may also be used in conjunction with the data collected to add context to the data.

B. Data Layer

The operational data at the Raw Material Production stage can be collected with a free-to-use Manufacturing Execution System (MES) called arc.lite ™. arc.lite™ interfaces with the arc.net™ layer in this model using a Supplier Web API. This allows material producers to communicate production information with the SC partners.

The IoT data collected from the machineries, devices and components at the Product Manufacturing stages need to be pre-processed and streamed into the MES. This is done by co-developing a real-time data streaming interface called arc.quire™. arc.quire™ is designed to integrate data from a wide range of existing IIoT hardware and software solutions available in the market today, in accordance with the available Industry 4.0 standard communication protocols, such as OPC UA and MQTT. To allow for ease of integration across different layers, Arcstone's extensive MES – called arc.ops™ – was selected. arc.ops™ is also preferred for connecting easily to the arc.net™ layers. Hence, the OT/ IT convergence where the operational technology (OT) and the information technology (IT) can be unified through MES (full-fledge arc.ops™) and IIoT (arc.quire™) platforms by Arcstone Pte. Ltd.

Furthermore, a wide range of Web APIs and Logistic APIs may be used to collect data from distributer centers along the way to the end-customers into the arc.net™ layer for the information retrieval of the Gate-to-Grave stages of the SC.

C. Arc.net Layer

The arc.net™ layer was designed with a dedicated intend of digitalizing the SC. This is done through a matrix-like and flexible structure that allows for seamless and secure data sharing between all SC nodes, from cradle to grave. It also interfaces with other layers to meet all the aforementioned unique data requirements and limitations from different SC stages. Consequently, arc.net™ enables to connect the product end users by forming a consortium of manufacturing partners and suppliers, which promotes end-to-end SC traceability.

Each SC node contributes to the LCA database. Each node has its own full control of the types and amount of data it shares due to a multi-level blockchain design of arc.net™. Each SC node is allocated with an individual blockchain so that data are not opened and accessed by other nodes on the same blockchain. This allows for privacy of data and promotes a mutual trust between SC partners where each data transaction is being hashed, encrypted and decrypted. Furthermore, due to the immutable nature of data on the blockchain, entries can only be updated if the transactions are validated by the network consensus mechanism. This ensures the security and authenticity of the stored data.

The multi-level blockchain architecture of arc.net™ is pivotal in ensuring access to reliable real-time SC-level LCA data. The live feed of data allows stakeholders to make decisions pertaining to the environmental performance of the SC swiftly. This reduces latency between event and decision-making allows for lesser deviation from the global-optimal environmental performance of the SC.

D. Ecolabelling Layer

The parametric data collected at each stage of the SC is fed into a LCA software engine. This engine processes the LCA data with data from LCI databases to produce nodal LCA results, which is stored in arc.net™.

The cumulative nodal LCA data is used to determine the environmental impact up till each stage of the SC, from cradle to gate. The product utility and reverse logistic data via the respective use APIs is used to determine the gate to grave environmental impact of the product. Together this information allows SC partners to determine the total footprint associated to the product. This total footprint could be benchmarked against industry standards using ecolabelling, and the sustainability index of the products can also be determined.

.

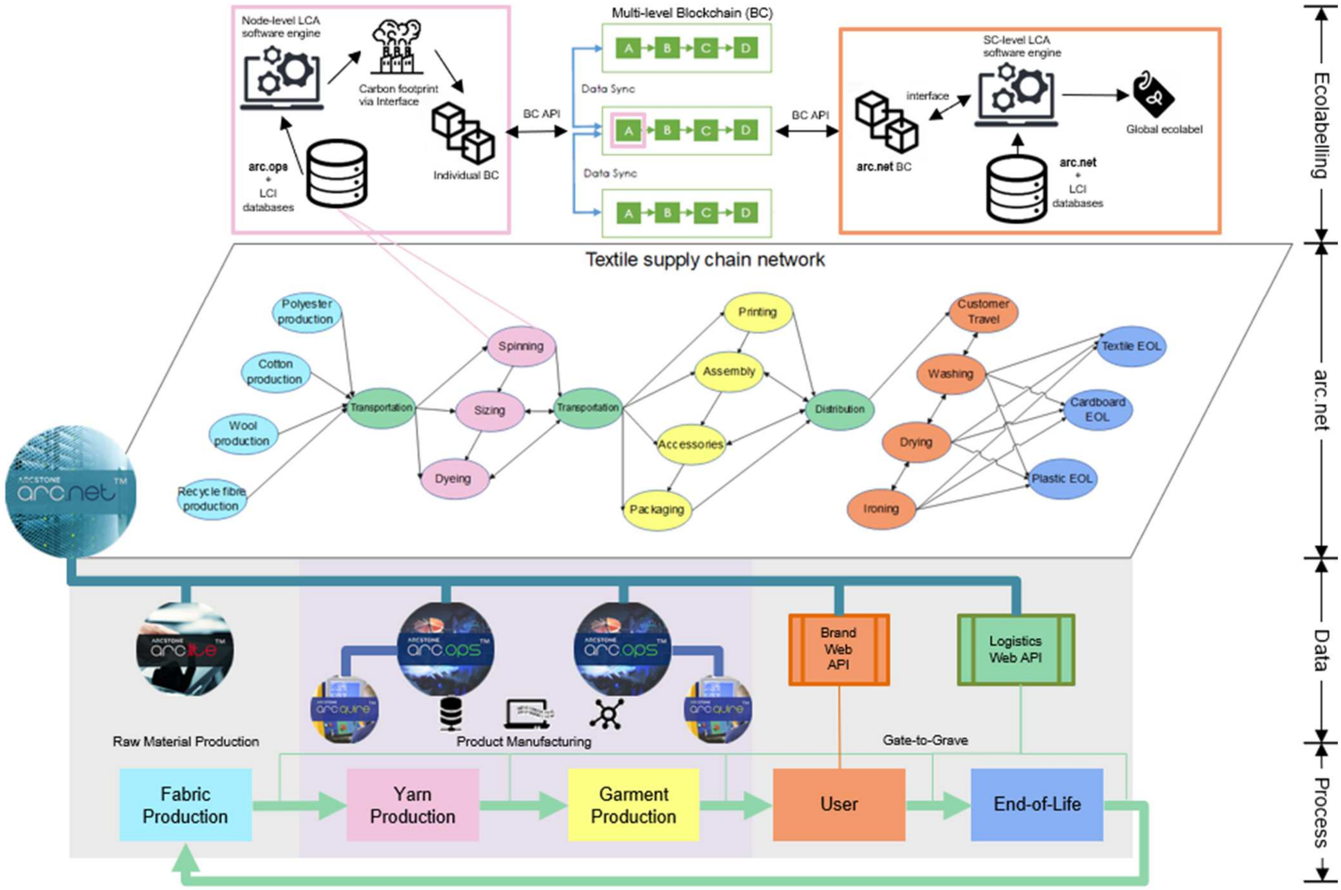


Fig. 1. Established T-shirt SC

IV. Use Case

In this section, the established textile SC is firstly presented and subsequently examined in terms of data quality rating (DQR). Then, textile dyeing process is selected as a use case to demonstrate how the proposed framework could facilitate the ecolabelling in the textile sector.

A. Textile SC

Textile industry is generally believed to have a paramount role in modern economy with huge environmental impacts [44, 45]. As such, sustainability evaluation (ecolabelling) of the textile SC has both academic and industrial importance. Across the entire textile SC , there exist a considerable amount of processes, e.g., raw material preparation, textile production, distribution, use, and end-of-life disposal. The unit process boundaries are defined based on product environmental footprint category rules (PEFCR) guidance [41], and the entire textile SC together with the input/output flows of each unit process are visualized in Annex 1.

B. Textile SC DQR analysis

The data collected from these unit processes/stages may significantly differentiate from each other in their technological/geographical/time-related representativeness and precision, resulting in various DQR. Generally, the collected data can be categorized into two types, primary data collected directly from manufacturing sites and secondary data from software/database or best available technology reference document (BREF) [45].

The PEFCR for t-shirt SCs was used as a baseline standard for designing the IoT-embedded LCA model. The LCI datasets and guideline report provided by the European Commission was analyzed to identify the situation-option combination that most rely on primary data. This combination data was segmented and analyzed to understand the primary and secondary data dependencies of each stage in the supply chain. Firstly, based on the established textile SC, material and energy input/output requirements of each stage are identified and classified in a table, as well as the additional information required for LCA, e.g., specific technology used, location parameters and the primary material used. Secondly, the consolidated information is codified to understand the DQR levels at each stage of the SC. This was done by allocating a Primary-Secondary Data Dependency Value (PSDDV) between 0 and 5 based on the main type of data used in a specific grid, with a higher PSDDV number indicating a higher DQR. A stage specific average PSDDV and an average Life Cycle Stage (LCS) based on the PEFCR classification was also calculated. Finally, the PSDDV heatmap was constructed, showing the DQR of each stage with better visualization effect. The results are shown in Annex 2**.** As can be seen, the lowest DQR is observed at EOL stage, with an average value of 1.95 and the lowest value of 1.57. This poor DQR is possibly due to the extremely limited information transparency in its material and energy inputs/outputs. By sharp contrast, the 2nd life cycle stage, i.e., production of T-shirt, are labelled with a much higher average DQR of 3.11. For processes like sizing, dyeing, printing, and finishing, the highest DQR values of 4.14 are observed, possibly benefitting from higher mechanisation degree and better resource management. Therefore, these processes are suitable for the implementation of the proposed IIoT framework.

C. Implementation demonstration: dyeing process

In terms of DQR, production of T-shirt stage is zoomed in for potential framework implementation. Among these involved processes, dyeing process is the most appropriate for the proposed IIoT-enabled and data-driven sustainability evaluation framework to be implemented due to the following reasons. Firstly, its complicated techniques and requirements have made the dyeing process the most crucial process across the entire textile SC [46]. Secondly, textile dyeing is known as a heavy polluting and water/energy-intensive sector, not only consuming lots of chemicals, energy and water, but also generating huge amounts of wastes. More importantly, modern textile dyeing factories have a high degree of mechanization, where the IIoT sensors could easily be integrated with the automated manufacturing system for real-time data collection. This feature will significantly benefit the energy output data gap whose current DQR value is as low as 1, as shown in the heat map in Annex 2**.**

With the proposed framework successfully implemented, the manufacturing data can be automatically collected in a real-time manner with the real-time data streaming interface, i.e., arc.quire^{TM}, and can then be accessed from Arcstone's extensive MES, i.e., arc.ops^{TM}. The collected data can then be used to align with the manufacturing activities specified in the manufacturing checklist provided by dyeing manufacturer. Subsequently, the aligned data can be fed into the arc.net^{TM} layer for seamless and secure data sharing, and finally contributes to the LCA database for the purpose of calculating ecolabelling. In this way, the data transparency and accuracy of the textile SC thus can be improved significantly. With data of higher DQR, the accuracy of the total footprint calculation can also be effectively improved. What's more, taking real-time parametric data as input, the ecolabelling can also be achieved in a real-time manner, which significantly advance the state of the art for the global ecolabelling.

V. Conclusion

In this paper, we proposed a framework for IIoT-enabled and data-driven sustainability evaluation for textile supply chain. Furthermore, we designed a four-layer based solution to integrate the IIoT capabilities into the LCA modelling by linking different data collection techniques and easy-to-use Arcstone MES and supply chain visibility platforms. A dyeing process of T-Shirt use case in textile supply chain has been identified to demonstrate the automatic manufacturing data collection in a real-time manner to the LCA database for the purpose of calculating ecolabelling.

With the availability of big data in manufacturing and advanced intelligent solutions, smart manufacturing must embrace big data in manufacturing and supply chain system. It will support smart decision-makings in digital supply chain and optimally balance the supply and demand cycle of manufactured products. Due to the high dimension of the heterogeneous manufacturing data captured from various resources, in future, the research work will also focus on the applications of AI techniques such as feature engineering, data fusion, efficient machine learning and deep learning solutions to analyze the data collected from different nodes in the supply chain and extract insights to improve the sustainability performance in supply chain system.

Acknowledgment

This research is supported by the RIE2020 under its INDUSTRY ALIGNMENT FUND – INDUSTRY COLLABORATION PROJECTS (IAF-ICP) (I2001E0061) and administered by the Agency for Science, Technology and Research.

References

[1] F. Iraldo, R. Griesshammer, and W. Kahlenborn, "The future of ecolabels," ed: Springer, 2020.

[2] V. P.-Sandoval, J. A. Alfaro, A. M.-Villa, and M. Ormazabal, "ECO-labels as a multidimensional research topic: Trends and opportunities," Journal of Cleaner Production, vol. 135, pp. 806-818, 2016.

[3] Z. Rezaee and R. Elam, "Emerging ISO 14000 environmental standards: a step-by-step implementation guide," Managerial Auditing Journal, 2000.

[4] F. Hermann, H.-P. Urbach, and H. Wendschlag, "Eco-labelling and the information technology (IT) industry," in Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment. 2001 IEEE ISEE (Cat. No. 01CH37190), 2001: IEEE, pp. 1-3.

[5] I. O. f. Standardization, Environmental Labels and Declarations--Type I Environmental Labelling--Principles and Procedures. International Organization for Standardization, 1999.

[6] I. O. f. Standardization, Environmental Labels and Declarations: Self-declared Environmental Claims (type II Environmental Labelling). International Organization for Standardization, 1999.

[7] I. O. f. Standardization, "Environmental labels and declarations—Type III environmental declarations—Principles and procedures. ISO 14025," ed: ISO Geneva, 2006.

[8] P. Watanatada, "Questioning and evolving the eco-label," Retrieved June, vol. 23, p. 2014, 2011.

[9] F. C. Guide, "Government of Canada," ed: Ottawa, 2009.

[10] G. Hustvedt, "Review of laundry energy efficiency studies conducted by the US Department of Energy," International journal of consumer studies, vol. 35, no. 2, pp. 228-236, 2011.

[11] G. L. Baldo, M. Marino, M. Montani, and S.-O. Ryding, "The carbon footprint measurement toolkit for the EU Ecolabel," The International Journal of Life Cycle Assessment, vol. 14, no. 7, pp. 591-596, 2009.

[12] M. F. Teisl, "Global Ecolabelling Network," in Handbook of Transnational Economic Governance Regimes: Brill Nijhoff, 2010, pp. 889-897.

[13] A. Loconto and E. Fouilleux, "Politics of private regulation: ISEAL and the shaping of transnational sustainability governance," Regulation & Governance, vol. 8, no. 2, pp. 166-185, 2014.

[14] I. S. Arvanitoyannis, "ISO 14040: life cycle assessment (LCA)–principles and guidelines," Waste management for the food industries, pp. 97-132, 2008.

[15] J. Guinée and R. Heijungs, "Introduction to Life Cycle Assessment," in Sustainable Supply Chains: Springer, 2017, pp. 15-41.

[16] H.-J. Klüppel, "ISO 14041: Environmental management--life cycle assessment--goal and scope definition--inventory analysis," The International Journal of Life Cycle Assessment, vol. 3, no. 6, 1998.

[17] S.-O. Ryding, "ISO 14042 Environmental management* Life cycle assessment* life cycle impact assessment," The International Journal of Life Cycle Assessment, vol. 4, no. 6, p. 307, 1999.

[18] H. Lecouls, "ISO 14043: Environmental management· life cycle assessment· life cycle interpretation," The International Journal of Life Cycle Assessment, vol. 4, no. 5, p. 245, 1999.

[19] GaBi Education, "Handbook for Life Cycle Assessment (LCA), Using the GaBi Education Software Package," 2009.

[20] J. Reap, F. Roman, S. Duncan, and B. Bras, "A survey of unresolved problems in life cycle assessment," The International Journal of Life Cycle Assessment, vol. 13, no. 5, pp. 374-388, 2008.

[21] S. Ross, D. Evans, and M. Webber, "How LCA studies deal with uncertainty," The international journal of life cycle assessment, vol. 7, no. 1, pp. 47-52, 2002.

[22] M. Abrahamsson et al., "Life cycle assessment on silicon and gallium arsenide transistors," Chalmers University of Technology, Gothenburg, p. 17, 1999.

[23] K. Andersson and T. Ohlsson, "Life cycle assessment of bread produced on different scales," The International Journal of Life Cycle Assessment, vol. 4, no. 1, pp. 25-40, 1999.

[24] M. Aresta and M. Galatola, "Life cycle analysis applied to the assessment of the environmental impact of alternative synthetic processes. The dimethylcarbonate case: part 1," Journal of Cleaner Production, vol. 7, no. 3, pp. 181-193, 1999.

[25] A. Azapagic and R. Clift, "Life cycle assessment as a tool for improving process performance: a case study on boron products," The International Journal of Life Cycle Assessment, vol. 4, no. 3, pp. 133-142, 1999.

[26] K. Kadam et al., "Environmental life cycle implications of fuel oxygenate production from California biomass," National Renewable Energy Lab., Golden, CO (US), 1999.

[27] J. B. Legarth, S. Åkesson, A. Ashkin, and A.-M. Imrell, "A screening level life cycle assessment of the ABB EU 2000 air handling unit," The International Journal of Life Cycle Assessment, vol. 5, no. 1, pp. 47-58, 2000.

[28] M. Rezaei, M. A. Shirazi, and B. Karimi, "IoT-based framework for performance measurement: A real-time supply chain decision alignment," Industrial Management & Data Systems, 2017.

[29] X. Li, D. Li, J. Wan, A. V. Vasilakos, C.-F. Lai, and S. Wang, "A review of industrial wireless networks in the context of industry 4.0," Wireless networks, vol. 23, no. 1, pp. 23-41, 2017.

[30] B. T. Hazen, J. B. Skipper, J. D. Ezell, and C. A. Boone, "Big data and predictive analytics for supply chain sustainability: A theory-driven research agenda," Computers & Industrial Engineering, vol. 101, pp. 592-598, 2016.

[31] E. Manavalan and K. Jayakrishna, "A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements," Computers & Industrial Engineering, vol. 127, pp. 925-953, 2019.

[32] S. Roos, C. Jönsson, S. Posner, R. Arvidsson, and M. Svanström, "An inventory framework for inclusion of textile chemicals in life cycle assessment," The International Journal of Life Cycle Assessment, vol. 24, no. 5, pp. 838-847, 2019/05/01 2019, doi: 10.1007/s11367-018-1537-6.

[33] J. Wang, J. Yu, X. Wu, and X. Lv, "Energy and emissions reduction of printing and dyeing industry," Energy and Emissions Reduction of Printing and Dyeing Industry, 2011.

[34] A. Baban, A. Yediler, and N. K. Ciliz, "Integrated water management and CP implementation for wool and textile blend processes," CLEAN–soil, air, water, vol. 38, no. 1, pp. 84-90, 2010.

[35] A. Tanapongpipat, C. Khamman, K. Pruksathorm, and M. Hunsom, "Process modification in the scouring process of textile industry," Journal of Cleaner Production, vol. 16, no. 1, pp. 152-158, 2008.

[36] A. Beck, M. Scheringer, and K. Hungerbühler, "Fate modelling within LCA," The International Journal of Life Cycle Assessment, vol. 5, no. 6, pp. 335-344, 2000.

[37] N. Terinte, B. K. Manda, J. Taylor, K. Schuster, and M. K. Patel, "Environmental assessment of coloured fabrics and opportunities for value creation: spin-dyeing versus conventional dyeing of modal fabrics," Journal of cleaner production, vol. 72, pp. 127-138, 2014.

[38] K. Hitchcock, J. Panko, and P. Scott, "Incorporating chemical footprint reporting into social responsibility reporting," Integrated environmental assessment and management, vol. 8, no. 2, pp. 386-388, 2012.

[39] A. Laurent, S. I. Olsen, and M. Z. Hauschild, "Limitations of carbon footprint as indicator of environmental sustainability," Environmental science & technology, vol. 46, no. 7, pp. 4100-4108, 2012.

[40] N. M. van der Velden, M. K. Patel, and J. G. Vogtländer, "LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane," The International Journal of Life Cycle Assessment, vol. 19, no. 2, pp. 331-356, 2014.

[41] S. Pesnel and J. Payet, "Product Environmental Footprint Category Rules (PEFCR)—T-Shirts," CYCLECO: Amberieu en Bugey, France, p. 130, 2019.

[42] A. M. H. Almanza and B. Corona, "Using Social Life Cycle Assessment to analyze the contribution of products to the Sustainable Development Goals: a case study in the textile sector," The International Journal of Life Cycle Assessment, vol. 25, no. 9, pp. 1833-1845, 2020.

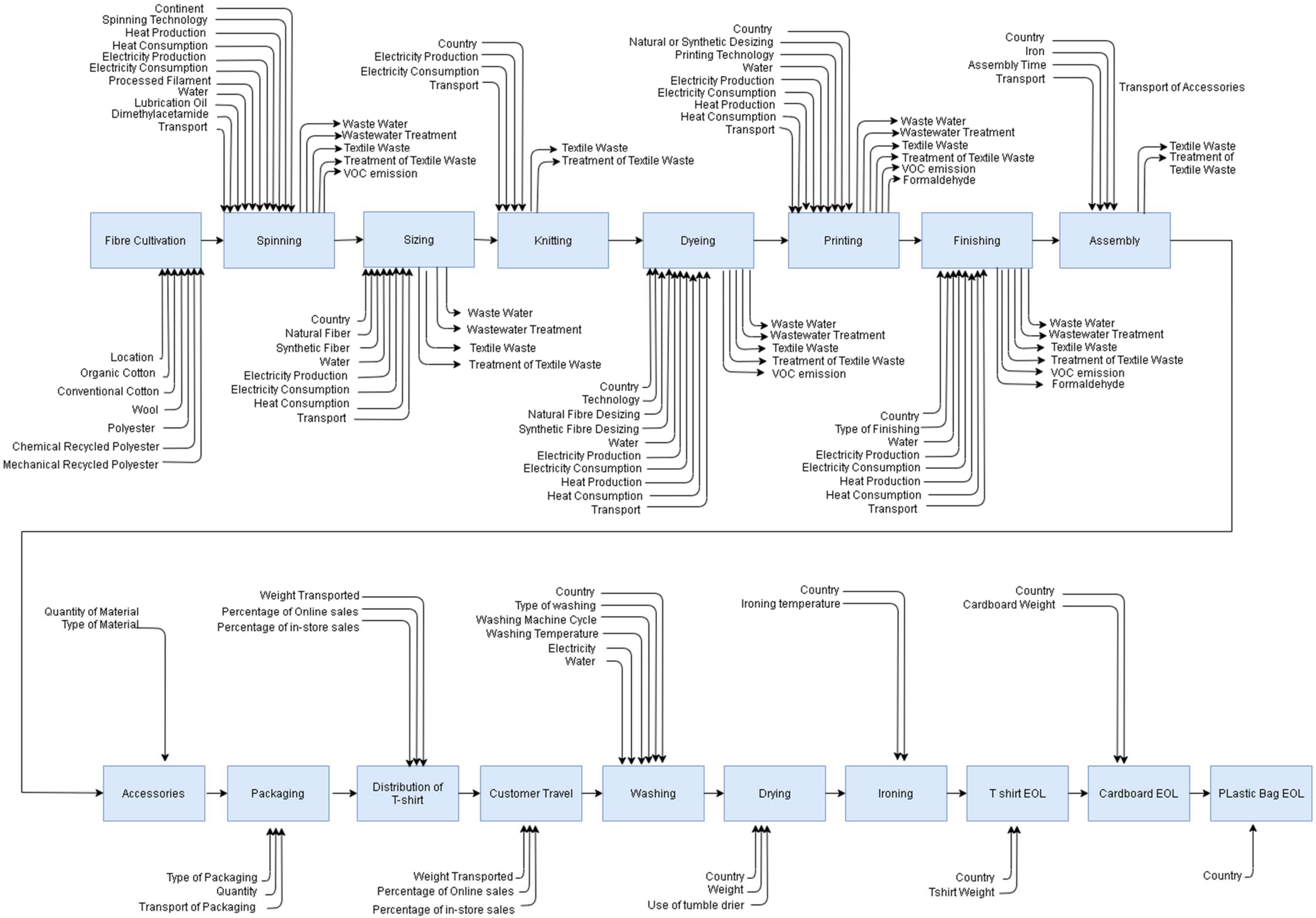
[43] PE INTERNATIONAL (2014) Life Cycle Assessment (LCA) of Organic Cotton – A global average.

[44] A. M. Morita, C. C. S. Moore, A. R. Nogueira, L. Kulay, and M. A. da S. S. Ravagnani, "Assessment of potential alternatives for improving environmental trouser jeans manufacturing performance in Brazil," J. Clean. Prod., vol. 247, 2020, doi: 10.1016/j.jclepro.2019.119156.

[45] M. Bevilacqua, F. E. Ciarapica, G. Giacchetta, and B. Marchetti, "A carbon footprint analysis in the textile supply chain," Int. J. Sustain. Eng., vol. 4, no. 1, pp. 24–36, 2011, doi: 10.1080/19397038.2010.502582.

[46] W. Jiang, Z. Yuan, J. Bi, and L. Sun, "Conserving water by optimizing production schedules in the dyeing industry," J. Clean. Prod., 2010, doi: 10.1016/j.jclepro.2010.07.004

ANNEX



ANNEX 1. Input and output flows of T-shirt SC.

Life Cycle Stage		Fibre Cultivation	Spinning	Sizing	Knitting	Dyeing	Printing	Finishing	Assembly	Transport per Process	Accessories	Transport of Accessories	Packaging	Transport of Packaging	Distribution of T-shirt	Customer Travel	Washing	Drying	Ironing	T-shirt EOL	Cardboard EOL	Plastic bag EOL
INPUT	Locational Parameters	5	4	5	5	5	5	5	5	1	1	1	1	1	5	1	5	5	5	5	5	5
	Primary Material Parameter	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	1
	Technology Selection Input (if any)	5	5	5	1	5	5	5	5	1	1	1	1	1	1	1	5	5	5	1	1	1
	Material Input	1	4	4	1	4	4	4	1	1	4	1	4	1	5	5	1	1	1	1	1	1
	Energy Input	1	4	5	5	5	5	5	5	4	1	4	1	4	2	2	1	1	1	1	1	1
OUTPUT	Energy Output	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Material output	1	4	4	4	4	4	4	4	1	1	1	1	1	1	1	1	1	1	1	1	1
	Life Cycle Stages	LCS1 Production of Material	LCS2 Production of T-shirt												LCS3 Distribution	LCS4 Transport by Customer	LCS5 Use Stage			LCS6 End-of-life		
	Average Available Data type	2.71	3.11												2.86	2.29	2.71			1.95		
		2.71	3.86	4.14	3.14	4.14	4.14	4.14	3.71	2.00	2.00	2.00	2.00	2.00	2.86	2.29	2.71	2.71	2.71	2.14	2.14	1.57

LEGEND

Level	Level of Data Used
1	No Data
2	Only Secondary Data
3	Mostly Secondary Data & Some Primary Data
4	Mostly Primary Data & Some Secondary Data
5	Only Primary Data

ANNEX 2. DQR heatmap analysis of the TEXTILE SUPPLY CHAIN