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Letters

# Ubiquitous Life Cycle Assessment (U-LCA): A Proposed Concept for Environmental and Social Impact Assessment of Industry 4.0

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ABSTRACT

Smart manufacturing in an Industry 4.0 setting requires developing unique infrastructures for sensing, wired and wireless communications, cyber-space computations and information tracking. While an exponential growth in smart infrastructures may impose drastic burdens on the environment, the conventional Life Cycle Assessment (LCA) techniques are incapable of quantifying such impacts. Therefore, there is a gap between advances in the manufacturing domain and the environmental assessment field. The capabilities offered by smart manufacturing can be applied to LCA with the aim of providing advanced impact assessment, and decision-making mechanisms that match the needs of its manufacturing counterpart.



## 1. Introduction: a closer look at the consequences of Industry 4.0

Since the introduction of Industry 4.0 concept in Germany [1], several conceptual and novel manufacturing paradigms have emerged as responses to advances in the Information and Communication Technology (ICT) domain. Smart manufacturing [2], cyber manufacturing [3], computer-integrated and cloud manufacturing [4,5] and cloud remanufacturing [6] are among the paradigms that call for intensive interconnectivity and interoperability of manufacturing modules and services through cyber-physical systems (CPS). Industry 4.0 is believed to shift the manufacturing paradigm toward a socially-connected [7], and service-oriented cyber-physical network. This transition is usually considered to have immediate benefits for consumers [8], as well as manufacturers, through informed and timely decision making [9] facilitated by advanced data management techniques. However, the deep and long-term environmental and social impacts of this revolution should be investigated further. A CPS requires intelligent connectivity, advanced data management, and computational capabilities [10], all of which necessitate exponential growth in the ICT infrastructure. The CPS implementation can bring prominent benefits in prognostication and machine health monitoring using the mentioned interconnectedness via similarity identification [10]. However, while the efficiency of ICT has been drastically improved over the recent years, their environmental and societal aspects are still disputable [11]. Therefore, the policies regarding the implementation of Industry 4.0 should be examined systematically from a holistic perspective, so that adequate measures can be taken to avoid future adverse impacts. Nevertheless, conventional Life Cycle Assessment (LCA) techniques are unable to properly assess smart manufacturing [12]. This paper takes the first steps in shedding light on potential environmental and social impacts of smart manufacturing and laying the ground for developing adequate tools to address this issue by identifying the shortcomings of LCA in analyzing smart manufacturing and remarking the required features of future LCAs.

## 2. Exponential growth in ICT and the corresponding environmental and societal concerns

Originally, it was believed that technological advancements in ICT had significantly decreased energy intensity [13], and probably the corresponding environmental impacts. However, later on, new opinions have been expressed on the point that environmental impacts of ICT are very complex [11]. Many empirical studies have revealed that elevating the efficiency of technologies does not necessarily alleviate their environmental impacts. Despite the substantial improvements that such systems bring into the equation with respect to efficiency, the environmental challenges corresponding to them are not intuitive. For example, although the environmental impact per unit functionality of desktop processors

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have decreased over time, the impacts of a typical processor remained the same, due to the increase in the functionality [11], which has also been historically the case for the automobile industry [11]. Another example can refer to the energy consumption required for manufacturing computers and electronic products which has been stable over time and has not decreased properly in response to drastic advancements in their corresponding technologies, compared to other manufacturing sectors (Fig. 1).

Moreover, a number of comparative studies that evaluated the impacts of the transition from conventional services to ICT based services suggested that e-services may actually impose additional environmental impacts, depending on the usage mix and behavioral patterns of users [15]. For instance, Caudill et al. [16] discussed that the transition from regular commerce to e-commerce can have negative environmental impacts if the practice does not reach its full potential. The possible environmental benefits of ICT-based services, in comparison with their conventional counterparts, are heavily dependent on the extent to which they are adopted, the users' parameters and the life span of devices [17–19]. There is often a trade-off between benefits offered by advanced technologies in reducing materials and efficient usage of resources and other adversary effects such as increasing energy consumptions. In addition, the effect of Khazzoom-Brookes postulate that describes the rebound effect regarding the increase in consumption as a result of increasing efficiency [20] should also be noted. For a comprehensive list of studies, the reader may refer to [21].

This is particularly critical in the case of smart manufacturing in big data and Industry 4.0 environments that entail ubiquitous connectivity, information transmissions, and computations. These essentials of smart manufacturing require a boost in developing the required infrastructures for sensing, cyber-space computations, and information tracking. Therefore, environmental impacts should be one of the most vital concerns related to smart manufacturing, besides other challenges such as cyber-physical threats [22] since they not only influence the environment but also have economic and societal consequences.

## 3. Limitations of Life Cycle Assessment

LCA is the assessment of environmental (and social) impacts of a product or a service throughout their entire life cycle, from the extraction of raw materials to the end of life waste management [23,24]. While LCA is the number one tool for investigating the environmental burdens of a product or service, it has certain limitations that make it incapable of studying smart manufacturing.

*Uncertainty in the definition of the functional unit:* in LCA, a system boundary should be defined such that the inputs and the outputs of system processes can be assessed. The system boundary which defines the *functional unit* helps the results of the analysis to be scalable. However, defining the system boundary is arbitrary [25], which makes different analyses of similar products or services unalike. While defining the proper functional unit has always been a challenge even in conventional LCA, the depth of impact is larger in the case of smart manufacturing since the concept of cloud, new business models, and resource and equipment sharing make it very difficult to define the physical boundary of enterprises and the scope of their responsibilities.

*Inability to address emerging systems and the lack of datasets:* LCA requires established data to assess the impacts of a process or a product. Therefore, LCA is incapable of analyzing emerging systems and technologies [26,27]. In other words, LCA is not capable of forecasting [12] since the existing LCA databases are not complete to cover emerging technologies and behaviors and the required datasets currently do not exist.

*Consideration of steady-state systems:* LCA is not prominent in analyzing temporal or spatial effects [28]. LCA usually focuses on global perspectives and assumes high levels of homogeneity. Thus, segregated systems that demonstrate high heterogeneity levels impeach the results of LCA [12].

The above-mentioned limitations impede conventional LCA's ability to comprehensively assess the possible environmental impacts of smart manufacturing in an Industry 4.0 environment. In an intensively interconnected network of manufacturing modules, defining a robust functional unit without neglecting the related processes would be unrealizable. Furthermore, the concept of Industry 4.0 is in its early stage of implementation with some unknown effects. For example, one of the critical properties of manufacturing in an Industry 4.0 setting is self-adaptiveness and self-configuration [10] that entails nonlinear and heterogeneous behavior of modules.

## 4. Capabilities offered by smart manufacturing

While the emergence of smart manufacturing may impose new challenges and constraints for LCA, it also paves the way for

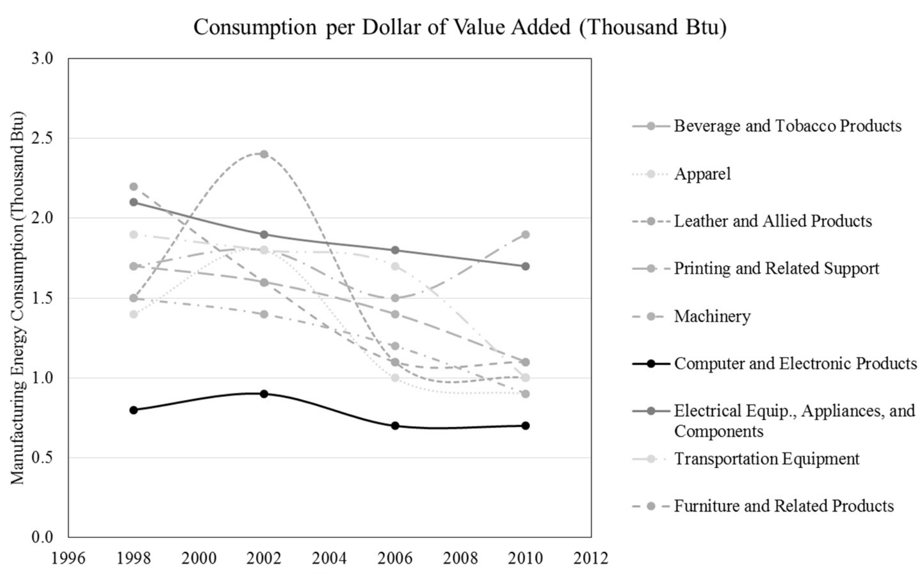


**Fig. 1.** Consumption per dollar of value added of manufacturing in the US from 1998 to 2010 [14].

developing new tools based on the capabilities it provides. Self-awareness has been suggested as one of the core properties of smart manufacturing [29]. This self-awareness is supposed to be utilized in order to closely monitor, assess and predict the machines' health status in real time. However, the concept of self-awareness can be extended even further to environmental impacts and carbon footprints. In the conceptual framework of an ever-present LCA system, each manufacturing machine or process has an interconnected environmental tracker agent that records and reports inputs (e.g., energy) and outputs (e.g., waste) in real-time. The communication protocols such as MTconnect [30] and RFID tagging facilitate recording the data such that the data can be processed in a data processing unit. The traceability of such a framework enables retrieving queries about temporal, spatial and global impacts of a desired entity.

The definition of the functional unit should be redefined in the future '*Ubiquitous Life Cycle Assessments* (*U-LCA*)'. Instead of defining physical boundaries and linearly scaling the results, the intensive interconnectedness provided by Internet of Things (IoT), will enable the cyber-space avatars of machines to tag, monitor and track any inputs or outputs, and assess the corresponding impacts, individually and in real-time. The traceability provided by IoT should enable the future LCAs to be able to evaluate the environmental impacts to any arbitrary level with respect to processes, products, regions or durations. The assumptions regarding the linearization of heterogeneous attributes such as variable power demands, feed rates, process parameters or use-phase consumers' energy consumption can be relaxed through tracking and calculating the impacts of any single product or process exclusively via specific identity data.

Moreover, U-LCA, as a transformative system, should play a more proactive role in manufacturing systems compared to the conventional LCAs that only focus on assessment of the impacts. The self-configuration scheme, which is a prerequisite of smart manufacturing [3], can be extended to include the environmental dimension of manufacturing machines and processes. Using the recorded environmental impacts data, coupled with deep learning and multi-objective optimization techniques, optimum configurations are achievable that simultaneously meet economic, environmental and even social requirements. Table 1 summarizes the features of future LCAs with respect to the capabilities offered by smart manufacturing.

**Table 1**
Features of future LCAs with respect to the capabilities offered by smart manufacturing.

| | |
|---|---|
| Smart manufacturing characteristics | • Massive data collection<br>• Real-time data analysis<br>• Possibility of waste reduction<br>• Higher automation level<br>• New business models<br>• Flexible and local supply chains, less transportation<br>• Increase of information flows and decrease of material flows<br>• Higher consumption, new markets |
| Features of future LCAs | • New databases<br>• New definition for functional units, new boundaries<br>• Methods that consider heterogeneity<br>• Sub-product level impact assessment<br>• Sub-process level impact assessment<br>• Proactive impact assessment<br>• Temporal, spatial and global impact assessment<br>• Low uncertainty w.r.t result generalization |
| Capabilities of smart enterprises | • Ability to collect data from all sources<br>• Real time computation and assessment of impacts via cloud computing<br>• Ultimate traceability of product and process paths via IoT<br>• Product identity data tracking for accurate and exclusive impact assessment<br>• Simultaneous self-configuration w.r.t economic and environmental requirements |

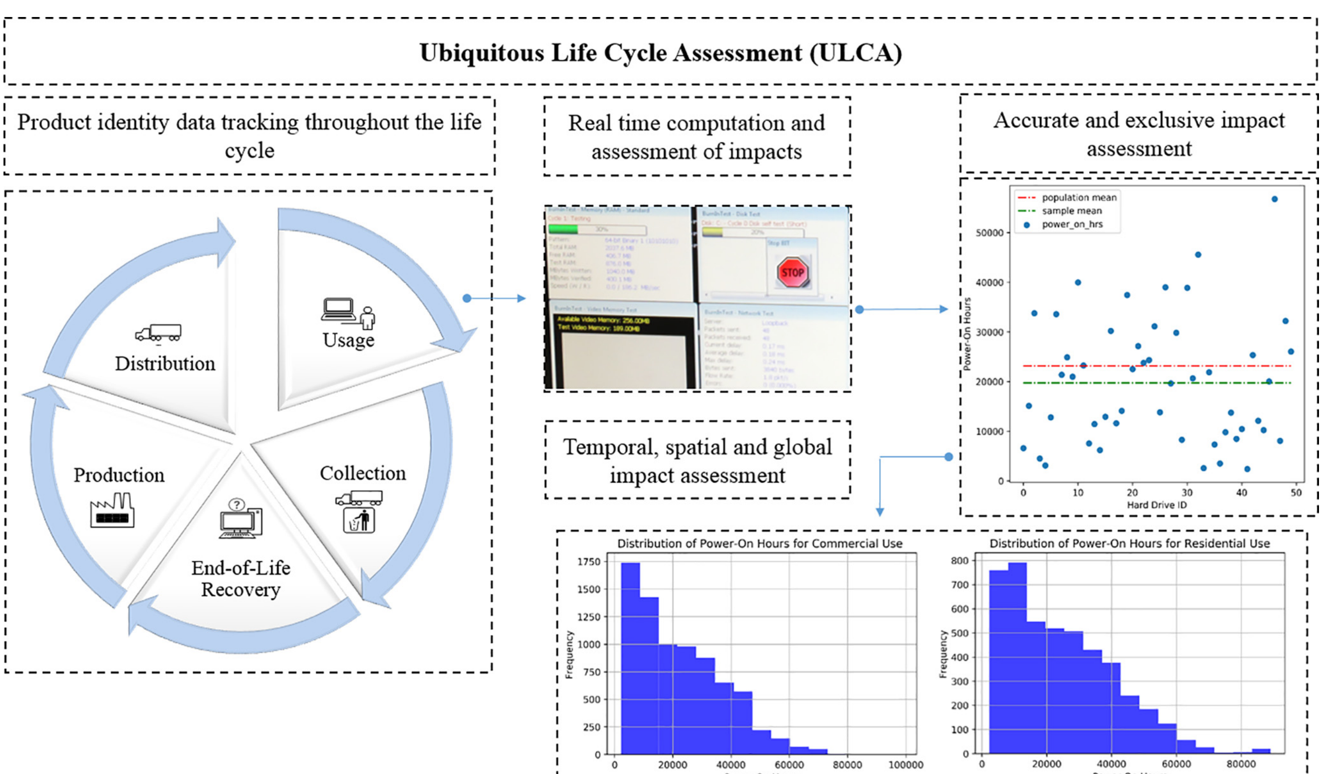


**Fig. 2.** Schematics of implementation of the U-LCA for usage phase of hard disk drives.

## 5. Implementation of U-LCA using product identity data

The implementation of U-LCA concept facilitates more accurate and exclusive impact assessments using product identity data. For certain ICT products in which the usage phase contributes significantly to the life cycle environmental impacts, assuming static and average-oriented usage mixes can potentially skew the results of LCA analyses [12,31]. Fig. 2 illustrates an overview of the implementation of U-LCA concept for an example of Hard Disk Drives (HDDs). Self-Monitoring, Analysis and Reporting Technology (S.M.A.R.T) provides the opportunity to track and monitor power-on hours of individual HDDs during their usage phase. The data presented in Fig. 2 have been provided by PC Rebuilders & Recyclers, a remanufacturing facility located in Chicago, IL. The individual-based and exclusive product tracking provides more accurate information about the distribution of power-on hours, the electricity consumption, and the corresponding impact estimations using product identity data. Moreover, the tractability provides capabilities to retrieve sub-level impact queries with respect to various factors such as product model, and usage type (e.g., commercial use vs. residential use).

## 6. Conclusions

This paper discusses the possible environmental burdens that can be imposed by the implementation of smart manufacturing in an Industry 4.0 setting and the limitations of conventional LCA techniques in addressing the emerging needs of smart supply chains. The capabilities offered by smart enterprises and the requirements of future LCAs as ubiquitous systems have been highlighted.

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