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A systems-based sustainability assessment framework to capture active impacts in product life cycle/manufacturing

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Abstract

Impacts associated with various product life-cycle phases can be characterized geographically and classified as embodied or active; embodied impacts are accounted for in the realization of a product, e.g., water used in manufacturing; active impacts occur during use and post-use phases, e.g., microfibers in the living tissues of aquatic life. Active impacts can often be more significant than embodied impacts. Embodied impacts are easy to quantify and regulate through efficiency-based measures; whereas active impacts are difficult to trace and quantify, requiring an effectiveness-based approach. Active impacts have greater bearing on sustainability and require systems-based approach to discern causality of impacts traceable to manufacturing/design. Further, current sustainability assessment (SA) tools inadequately trace geographically distributed nature of product life-cycle phases and associated impacts. This paper discusses a systems-based SA framework for manufacturing to capture and trace active impacts to the corresponding life-cycle phases, currently limited to acute and chronic impacts on societal health. The same methodology could be extended, subsequently, to accommodate economic and environmental impacts (of concern).

Keywords: Active Impacts; Sustainability assessment; Product life cycle; Manufacturing

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1. Introduction

Engineering product life cycle consists of product conception through design, production, sale, customer use and service to finally decommissioning [1]. Each phase of a product life cycle takes place at different geographic locations. Manufacturing consists of a globally dispersed network and requires various materials and energy resources as inputs sourced from different geographies; and produces products, byproducts, solid waste and emissions as outputs. Manufactured products are used and disposed at diverse geographies. Various impacts are associated with each phase as a product progresses in its life cycle. Tracing the network and impacts is a crucial challenge for LCA tools [2].

Nomenclature

AIEA	Activity, Impact, Entity and Attribute
BPA	Bisphenol-A
EU	European Union
GHG	Green House Gas
ILO	International Labour Organisation
LCA	Life Cycle Assessment
LED	Light-emitting Diode
OEM	Original Equipment Manufacturer
PBDE	Polybrominated diphenyl ethers
PFA	Perfluoro alkoxy alkanes
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SA	Sustainability Assessment
USDOC	United States Department of Commerce

Impacts associated with a product during its life cycle can be classified as embodied and active impacts. Embodied impacts are caused during the realization (manufacturing) of a product, while active impacts occur during the use and post-use phases of a product life cycle [3]. Embodied impacts are the impacts and resource-use which have already occurred, e.g., pollutants/emissions due to manufacturing and/or transport, energy and water use. Whereas active impacts are ongoing impacts and resource-use, e.g., microplastics (harmful impact on marine species and habitats [4]) that make their way to the oceans from the washing machines [5], and energy and water used by washing machines. Ideally, it is important to consider both embodied and active impacts for holistic life cycle sustainability assessment. Existing sustainability assessment measures primarily focus on assessing embodied impacts as such impacts are easy to measure and quantify. Assessing active impacts is a challenging task because of the inherent uncertainty involved as (i) data for the use phase of products in not available for any stakeholders, (ii) product's characteristics are different, and (iii) users and circumstances of product use varies [6]. Foregoing discussion calls for few questions, e.g., *What kind of active impacts may occur during a product life cycle? Which dimension of sustainability do active impacts belong to? How to identify, trace, and assess active impacts?* To understand the distinction between embodied and active impacts, a case of aluminium industry setting has been discussed. Challenges in development of framework for assessing active impacts have been identified. A systems-based sustainability assessment framework that facilitates the assessment of active impacts has been proposed. This paper attempts to articulate active impacts that are attributed to manufacturing and design decisions, currently limited to societal health impacts.

2. Background Review

The focus of this section is to study various kinds of impacts occurring during a product life cycle. The distinction has been explained with the help of few examples in following sub-sections.

2.1. Impacts in product life cycle: Embodied vs Active

An impact is a function of location, medium, time, route of exposure, natural process, toxicity, rate of release, and concentration of release etc. [7]. It can be attributed to the product (material), manufacturing process or both. Table 1 illustrates the diversity of impacts occurring during a product life cycle. Embodied impacts occur in industrial environment during manufacturing and include various impacts from environmental, economic and social dimensions, e.g., operator's health and workplace injuries, GHG emissions, energy use, manufacturing costs etc. Active impacts as name suggests, are ongoing and progressive impacts and occur beyond the industry environment, and can be associated with material extraction, service operations and product use, end of life, recycling and disposal, e.g., health risks due to BPA contamination in environment [8], chemicals (PBDEs, phthalates, dioxins, pesticides, and PFAs) in our everyday household products [9], microplastics in air and water [10][11], metal concentrations in environment because of unethical/informal unregulated recycling practices [12]; non-biodegradable plastic fibers, unnatural exposure of the human eye to blue peaks of LED lit appliances (monitors, phones and luminaries). In many cases, active impacts could be more significant and not accounted for in conventional assessments, e.g., for smartphones, use-phase impacts exceed manufacturing impacts in terms of GHG emissions when accounted for in the LCA study [13].

Table 1. Classification of product life cycle impacts, extended from [14]

Embodied Impacts*			Active Impacts			
Within Manufacturing boundaries/during Manufacturing Operations			Beyond Manufacturing Boundaries/Post Manufacturing Operations (Service/Maintenance)		Use Phase	End of Life Phase
Environmental	Economic	Social	Acute	Chronic	Acute and Chronic	
Energy consumption, Water consumption, Raw material usage Natural land use, solid waste generation, gaseous and liquid emissions	Manufacturing Cost, Profit	Employee health and safety	Public health and safety issues due to unintended/ unforeseen material/ toxicity exposures	Cases of cancer due to certain processes and materials use	Exposure to material used in products, Fire/accidents caused due to product failure Reduced "use life" of products, Impacts caused due to behavioral change, Risk due to lack of safety and certification standards	Chemical leaching into groundwater Discarded materials from appliances affecting human health
Efficiency measures			Effectiveness measures			

*Resource-use and associated impacts are detrimental/unintended outcomes associated with manufacturing process of realization of a product.

Embodied impacts are generally efficiency based and can be predominantly attributed to design and manufacturing phase. Active impacts are effectiveness based and can be related to use and post-use phase, e.g., manufacturing process precision might affect product performance and hence manufacturing decisions may have direct effect on product's use-phase impacts [15]; certain health impacts of welding process (increased risk of mortality and cases of lung cancer) can be attributed to manufacturing [16]. Both impacts occur and are characteristic to diverse geographies as the product progresses in its life cycle. The distinction between two categories of impacts discussed here is important because active impacts are difficult to estimate beforehand in general sustainability assessments.

2.2. Sustainability assessment in manufacturing: Efficiency vs Effectiveness

"Sustainable production is the creation of goods and services using processes and systems that are: Non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for workers; communities, and consumers; and socially and creatively rewarding for all working people" [17]. The definition is effectiveness based as it stresses on avoiding impacts than reducing impacts in contrary to widely used US DOC definition which says, "Sustainable manufacturing includes things such as making products using less energy and materials, producing less waste, and using fewer hazardous materials as well as products that have greener attributes such as recyclability or lower energy use"[18]. Existing manufacturing sustainability assessment measures follow commonly applied reductionist approach [19], where impacts per product are minimized throughout the life cycle. Conventional environmental concerns comprise incomplete efficiency-based assessments generally traceable to resource use, process and resulting contamination (substance flow) assessment attributed to the manufacturing of a product. This results in a partial consideration of the actual consequences within a larger interconnected system [20]. Furthermore, effectiveness-based assessments such as exposure to toxicity in the use and disintegration of a product are totally left out, both in their methodologically consideration and their identification, quantification and systemic consequences. Efficiency based measures are actually yielding rebound effects with a net increase in resource and energy consumption, rather than a decrease. Sustainability improvements reported by industries mainly focus on design, supply chain, technology and waste avoidance activities primarily in environmental dimension [21]. Most of the practices aim to comply with regulatory and market pressures, as reactive approaches prevail over proactive ones [22]. The focus of assessment practices on effectiveness along with traditional efficiency based measures is much needed [23]. Assessment of embodied impacts falls in the category of reactive assessment because impact is assessed once it has happened or post-facto. Active impacts require a proactive approach as such impacts are likely to happen in future and difficult to foresee (with confidence) upfront. Sustainability focuses on the viability and health of natural environmental systems to sustain humanity [24]. Active impacts have greater bearing on sustainability as such impacts are effectiveness based. Therefore, assessment of active impacts is important for effectiveness-based product sustainability assessment.

3. Systems-based sustainability assessment framework for capturing active impacts

This section proposes a systems-based sustainability assessment framework to capture and trace active impacts, currently limited to societal health concerns. A systems approach involves understanding the behavior of various interconnected entities comprising the system and their interactions. A case of an industry setting in a progressive city in India is presented to describe the scope of active impacts. The details are discussed in following sub-sections.

3.1. Case study: Aluminium industry

Information presented in this sub-section is based on questionnaire survey and interview conducted at a large-scale OEM aluminium industry. In addition, few assumptions are also made to explain the concept. The industry requires inputs as materials (aluminium alloys), resources (water, air, manpower), and energy. It consists of processes (extrusion), machining equipment (milling, annealing, quality testing), product systems, workers and executives. Developed products (roofing sheets for automobiles, buildings and solar panels, foils, coils) are sold via distributors which are further used at various locations. Semi-finished products are used by other industries as inputs for manufacturing of new products. Scrap is used within the industry and sent to recycling industry and landfill. The production process releases various air emissions, solid particle emissions, waste water to local/surrounding environment. Figure 1 shows a schematic representation of the aluminium industry setting with inputs and outputs. G1, G2, G3… represents different geographic locations (geotag) for raw material sourcing, manufacturing, product use and disposal. Embodied impacts for this industry may include impacts involving energy, water and material use during the manufacturing. Impacts causing due to waste and emissions may be insignificant on a global scale, but causes adverse impacts on human and nature in immediate surroundings [25], e.g., migration of red mud sludge components to underground water [26]. Further, leaching of aluminium (in product's use phase) from beverage cans, cooking utensils causes adverse health impacts [27] and chronic exposure to aluminium is linked with Alzheimer's disease [28]. These are few examples of active impacts. Such impacts hardly surface in existing sustainability assessment measures in manufacturing.

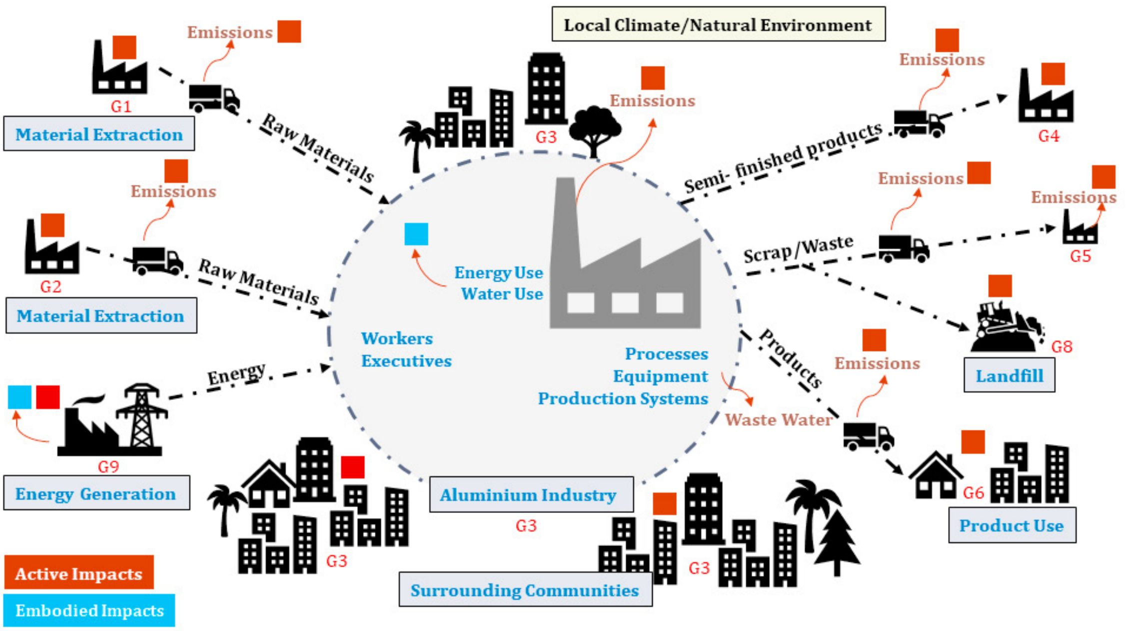

Figure 1. Schematic representation of aluminium industry

3.2. Challenges in development of framework

Assessment of active impacts is a challenging task as compared to embodied impacts because of unavailability of comprehensive phase-wise temporal data, including user behavioral data, characteristic to the corresponding geographies. Major challenge related to the development of a framework to assess active impacts is to address uncertainties involved in product use and end of life, e.g., recyclability, long lifetime of aluminium [25]. User's behavior also plays an important role in deciding the active impact of a product during its use phase. Another challenge is to develop a comprehensive database related indicators for such impacts, e.g., human toxicity models are available for a very small percentage of overall chemicals (3000 out of 90000) registered in EU for REACH directive [29]. The framework requires data from various sources. Appropriately communicating the results (how and to whom) of the impact assessment is another challenge as cases of active impacts involve significant qualitative data. Data on how many such kinds of impacts exist is also important.

3.3. Proposed framework to trace and assess active impacts

The first step towards development of an assessment method for active impacts requires a comprehensive societal health database of such impacts to begin with, and subsequently extended to impacts characteristic to the local environment and economy. The information on occurrences of active impacts can be collected from various data sources locally, e.g., historic data from labour organizations; illness and injury data from health organizations, e.g., local hospitals, feedback/questionnaire survey of consumers, societies and industries. Another possible way is for collecting such information is to follow bottom-up approach, i.e., by identifying possible active impacts associated with materials and manufacturing processes from literature, industry databases, e.g., outputs of welding process (fumes, radiations, heat and waste) are linked to potential health risks, e.g., lung cancer, increased risk of mortality

[16]. AIEA table consists of Activity, Impact, Entity and Attribute, where attributes are the characteristic of entities [30], e.g., "number of cases of cancer among workers" is an *attribute* of an *entity* "worker" with *impact* category "occupational health" under *activity* "manufacturing". The table permits a convergence of inputs from various

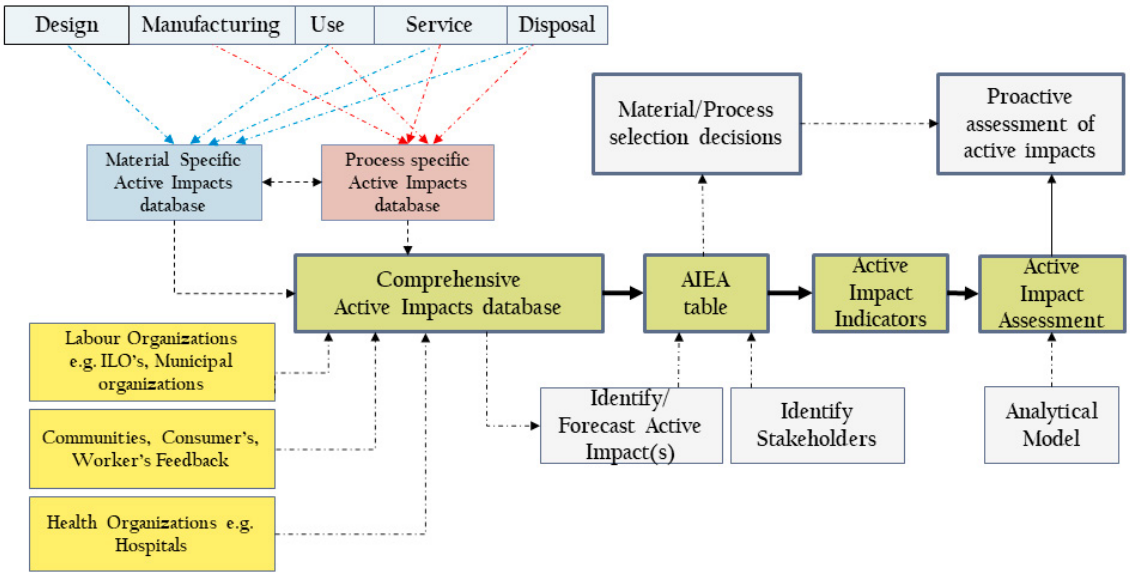

Figure 2. Proposed framework to capture active impacts

stakeholders and participants in developing a systems model, with dexterity to accommodate inputs in various scales viz., variable to system/sector. An important outcome of the exercise is the identification of specific data required to carry the study/assessment forward [30]. Location and case specific sustainability indicators (qualitative and quantitative) for active impacts could be developed based on the comprehensive database and AIEA table (to assess likely impacts with varying probabilities). Linking impact with an activity (process, material selection, use or disposal) could assist in proactive decision making. Framework for capturing active impacts is shown in figure 2. The framework could provide a more revealing insight into the nature of embodied and active impacts traceable to possible interventions in the design/manufacturing phase.

4. Discussion

This paper aims for developing a systems framework to capture and trace active impacts to design/manufacturing decisions. The proposed framework currently does not consider the technical dimension; technical objective is the value offered by the industry to customers through its production technology such as alternatives for executing production process, requirement of new technology [31]. The AIEA table used here has been successfully adopted in eliciting expert feedback from an interdisciplinary group on environmental, social and economic impacts and associated data to characterize sustainability [30]. Following an effectiveness-based assessment approach may bring in some technical challenges. Dealing with such challenges is equally important to design products with sustainability concerns in mind. Further, the implementation of this framework requires an interdisciplinary approach, with knowledge/specialization from other domains. Therefore, dependency on other domains adds to uncertainty. The framework needs to be refined further to include the role of multiple (direct/indirect) stakeholders and the corresponding nature and intensity of likely impacts. The database is an important part of this framework and is required be updated continuously. Future work is to propose sustainability indicators for an industry and evaluating the indicators for the manufacturing industry case.

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