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Appropriate use of Green Manufacturing Frameworks

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Abstract
Multiple frameworks have been developed for sustainable or green manufacturing systems and products, which can be roughly divided into life-cycle assessment methodologies and life-cycle assessment standards. Methodologies include process LCA, input-output LCA, and hybrid LCA; standards include the ISO14044 standard, the US EPA Life-Cycle Engineering Standard, and various emerging greenhouse gas protocols. We discuss in this paper the differences between these frameworks, and define the specific use cases where each framework is best suited. We achieve this by looking at manufacturing systems and processes across spatial and temporal levels of complexity and assess the suitability of existing frameworks at each level. The main questions addressed are: (1) what are appropriate LCA methodologies for different scales of manufacturing? (2) how do existing standards apply across various levels of manufacturing?

Keywords:
Sustainable Manufacturing; Green Manufacturing; Life Cycle Assessment

1 INTRODUCTION

The interest in achieving green manufacturing progress on the path to more sustainable production is growing. This is driven by steadily increasing costs of energy and resources, risks associated with material availability and use, consumer demands, government regulations, and interest in reducing the environmental impacts of production. Past improvements in manufacturing productivity have been achieved by identifying some element of value in an existing process or system that could be better exploited if externalized from the process or system and its value optimized without affecting the core process efficiency. The same is true of sustainable manufacturing which, when its value to manufacturing is determined, will allow manufacturers all across the supply chain to optimize the process with the environmental costs in mind.

Most manufacturing processes are complex, embedded in sophisticated systems of production and, in general, require substantial data to characterize the "state" of the process as a benchmark for improvement. Strategies for improvement range from specific "technological wedges" [1] to inclusion of green analysis with more traditional lean process methodology. And the tools used for the calibrating the process and evaluation of the potential areas of improvement range from traditional life cycle analysis to return of investment strategies based on environmental metrics [2].

The question usually put forward is 'where to begin?' One of the challenges in assessing the environmental sustainability of a manufacturing process (or system) is the need to parse the process or system in a way that makes it appropriate for application of one of these tools for analysis.

This has been a hard problem to solve due to the complexity of manufacturing systems. Sorting out when and how to use various analysis tools makes it easier to begin. This usually involves determining reasonable size elements of the problem ("bite sized chunks", so to speak) based on process or system complexity and the level at which the process resides in the design to manufacturing space.

These decisions on "greening" the process or system need to be taken at all levels of the design of the process including machinery used in production. As an example, new automotive technology driven by the move to hybrid vehicles will substantially affect both the design of the automobile and the processes and systems of manufacture. There will be new manufacturing systems set up to produce these, and other, new products.

When we design and implement these new production systems, a number of questions arise relative to their "greenness" that must be answered. Questions such as:

- How do we find the optimal balance between productivity, cost, quality and sustainability?
- What performance characteristics do you track and how do they relate to each other?
- In your analysis, what metrics, LCA, and decision-making tools can scale over multiple levels?
- What decisions made at one level need to be tracked at other levels?

And, for researchers working in this field, how can we design software, metrics, and reporting methodologies to account for all of these elements? Further, how do we link the detailed process/unit data with systems level approaches? And, finally, how do we develop "across the board" strategies and tools to synthesize the work of everyone's work?

This paper first defines the temporal and spatial levels across which decisions must be made to optimize a system's performance in all areas including environmental impact. Existing frameworks are then reviewed and discussed as to how well they fit into the temporal and spatial levels. This provides practitioners guidelines on how to utilize the frameworks along with insight into where there are holes to be filled through the creation of new or harmonizing frameworks.

2 LEVELS OF COMPLEXITY IN MANUFACTURING

The complexity and sophistication in the organization of manufacturing systems and processes necessitates a keen understanding of the organization for accurate environmental analysis. To assist in this effort, manufacturing can be broken into "levels of study" across two orthogonal frameworks, spanning organizational and temporal levels.

From the perspective of the organization of the system, we can consider manufacturing processes as being composed of four levels, from the level of the individual devices where unit processes take place, through to that of the enterprise, incorporating all the activities in the manufacturing system, including supply chain externalities. These four levels are as follows:

1. **Product Feature:** At this scale, product features are defined using specific process execution steps. Decisions on materials, modularity, and functionality are made that will influence all remaining decisions throughout the supply chain and manufacturing.
2. **Machine/Device:** Defined as an individual device or machine tool in the manufacturing system, which is performing a unit process, this level includes support equipment such as gage systems, device level oil-circulating systems, etc.
3. **Facility/Line/Cell:** Defined as a logical organization of devices in a facility acting in series or parallel to execute a specific activity (such as manufacturing a part or assembly). This also includes any distinct physical entity housing multiple devices, which may or may not be logically organized into lines, cells, etc.
4. **Supply-Chain:** The entire manufacturing enterprise, consisting of all the individual facilities, the infrastructure required to support the facilities, as well as the transportation and supply chain externalities.

An equally compelling orthogonal view of manufacturing can be made through the design to manufacturing life cycle. Here, we start with product or process design, and work our way through the design of the manufacturing process, process optimization, and finally post-process finishing and abatement. These levels are temporal in nature, and characterize a degree of control over total environmental impact. These four levels are as follows:

1. **Product Design**: The earliest in design and manufacturing. At this stage there is the most opportunity to influence environmental impacts and decisions throughout all future stages. At Level 1 critical decisions on part precision, materials, and design for assembly/recycling are made. Here there is scope to design the product as well as its manufacturing process to satisfy specific requirements in all the criteria.
2. **Process Design**: The product design is fixed; however here a manufacturing process to suite this design is created. Flexibility to optimize the system is limited to known tools and processes that work with the specified design. Here there is extensive control over the performance of the process in all the criteria as allowed by the product design.
3. **Process Adjustments**: The basic manufacturing process is fixed but small changes to the process through process parameter selection and optimization is used to control the critical features such as precision, burr formation, and energy or consumable consumption.
4. **Post-Processing**: Post-process finishing and abatement processes are used in controlling the part-precision and the environmental impact; at this level there is no control over the process as it has already been designed.

Figure 1 illustrates the interaction between the four temporal and spatial levels described here. Moving up and to the right in the figure means a loss of decision-making flexibility.

From these hierarchies – which span temporal and organizational levels – we get a sense of the complexity involved in information capture and transfer in manufacturing systems. For effective decision-making, we need to understand both what quality and quantity of information needs to pass between the levels and how decisions early on will percolate through the spatial and temporal levels.

3 EXISTING STRATEGIES AND FRAMEWORKS

Multiple standards exist on how to conceptualize and measure environmental impacts. This section will first review generic Life Cycle Assessment approaches for determining the environmental impacts of a product, process or system. Protocols and standards on how to apply these LCA approaches are then described. Finally, greenhouse gas (GHG) specific frameworks are described. GHG frameworks are chosen as an example here because they are maturing rapidly due to climate change concerns.

3.1 LCA Methodologies

Process LCA

Process LCA is the most popular method, currently, for conducting life-cycle assessment, and is often referred to as the SETAC-EPA method because of the role played by SETAC [3] and EPA in this method's development [4]. The inputs and outputs of multiple stages of a product's life are investigated in turn, and the results are aggregated into single metrics of impact such as eutrophication, toxicity, and greenhouse gas emissions.

Process LCA traditionally encourages the use of complicated process-flow diagrams to visualize the flows of energy and materials into and out of a specified system. Although time-consuming the process LCA methodology can be adept at capturing environmental impacts within a specified boundary of analysis. It does not, however, scale well to a comprehensive system analysis and therefore must be limited in scope to a handful of products or processes [2].

Multiple tools exist on the market to assist researchers in conducting process LCA (such as GaBi, Ecoinvent, and Umberto). These tools contain data from previous researchers on the environmental impact of materials and processes that are then strung together by the user to form a system. While these databases are generally seen as reliable and are widely used, it is often difficult or impossible to assess the quality or boundary of analysis chosen by previous researchers and conclusions should be made carefully.

Input-Output LCA

Input-Output (IO) LCA utilizes economic input-output tables [5] and industry-level environmental data to construct a database of environmental impacts per dollar sold by an industry. The boundary problem of process LCA is solved in this method because the economic input-output table captures the interrelations of all economic sectors [6]; however, aggregated industrial categories limit the specificity of the results [7].

Hybrid LCA

For a comprehensive analysis, it is not recommended to use either Process or IO LCA independently. While process LCA can provide a detailed analysis of specific process flows, IO LCA is able to quickly capture the interrelations between all sectors of the economy [8, 9, 10]. The scope of process LCA is limited by time and data; whereas the specificity of IO LCA is limited by the granularity of the IO table. There have been numerous excellent accounts on how to combine process LCA and Hybrid LCA [11 ,12, 13, 14, 15, 16, 17]. As a simplification, however, Hybrid LCA can be thought of in one of two ways: either process data is augmented with IO data to provide a comprehensive analysis (bottom-up), or IO data is modified by process data to provide specificity (top-down).

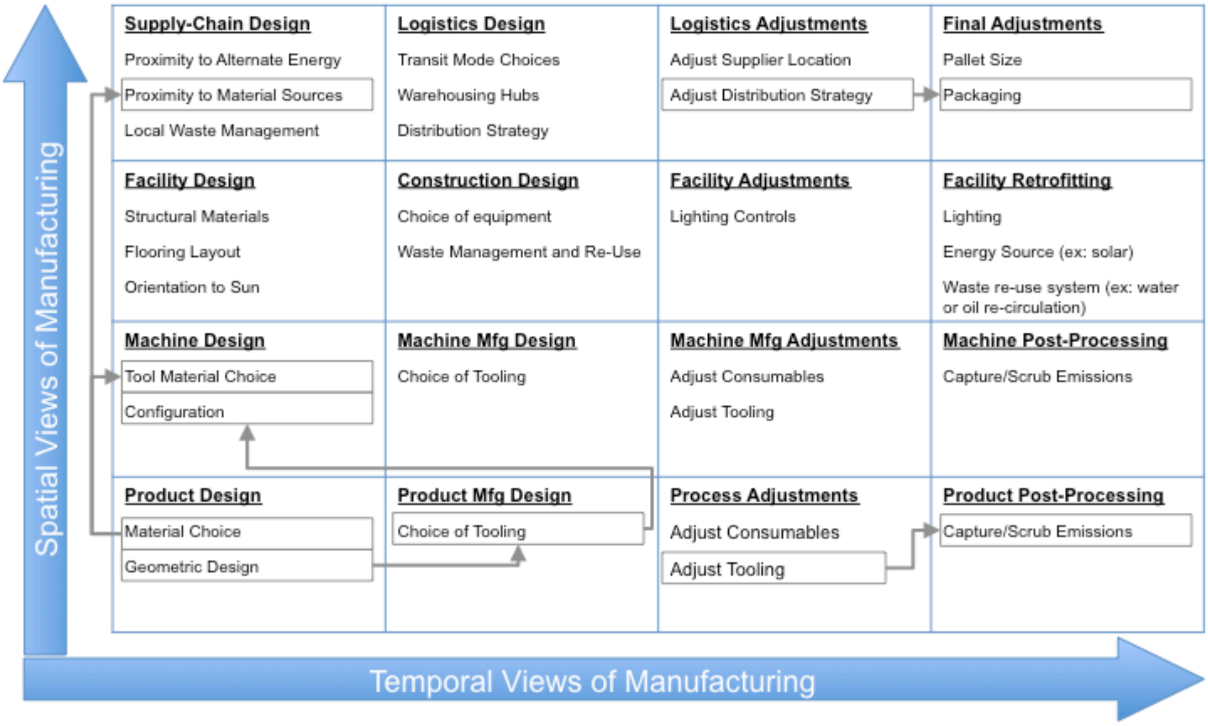

Figure 1: An Integrated view of Manufacturing Design Levels and the decisions they contain. Arrows represent the flow of information from one decision to another.

3.2LCA Frameworks and Standards

ISO 14040 and ISO 14044 :2006

ISO 14040 [18] and ISO 14044 [19] are two of the most widely referenced standards on how to do a life-cycle assessment. The ISO standard assumes a process based LCA approach and is organized into four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation.

The first, and arguably most important component of any environmental assessment is to determine the goal of the study. With agreement on the ultimate purpose of the work being completed, questions such as "how much detail is required to meet the needs of the intended application and audience" can be more readily addressed. This then allows questions on data quality requirements to be answered.

With the goal in mind, the scope (or system boundary) of the study can be assessed. For example, given the goal of comparing the lifetime GHG of a particular consumer product, studying the emissions due to transporting the product from the store to the customer is not critical, if it is the same for all the products being considered. In fact, for comparative studies, only the areas found to be different between the two items being compared need to be measured.

Another critical part of the "scope" step of ISO14044 is determining exactly what functional unit will be used. This can be very important for comparisons of machine tools, where the environmental impacts for each part produced could give very different comparisons than the environmental impacts per minute of machine use.

Because this is a process LCA approach, an inherent step included in the scope definition is a cut-off criterion; whereby any material or energy flows of a small enough value are deemed not necessary to include in the assessment. These decisions are often made based on the mass, energy, or assumed environmental impact of the ignored flow. ISO14044 explicitly states, "The deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study." Of course, it is impossible to know if something will significantly alter the results if they haven't been measured – which argues for the hybrid approach discussed earlier. While written as a process LCA standard, the hybrid approach is further supported by language in ISO14044, as it states, "in practice, all data may include a mixture of measured, calculated or estimated data."

With the goal and scope determined, it is then time to do the majority of the work required for an LCA: the inventory analysis. This step involves executing the LCA plan that was determined in the goal and scope definition using the LCA methodology of choice and adhering to the set boundaries and data quality requirements. Where necessary, sensitivity analysis may be used at this stage to refine the system boundary, allocation principles, and the inventory procedures.

Next, the LCA practitioner has a large set of emissions and consumption values from the inventory assessment that can be aggregated into more meaningful values through an impact assessment. Using chosen impact categories and characterization models, various emissions that are all classified as having the same impact can be aggregated into an “equivalent” set of emissions. A well-known example of this is seen with greenhouse gas emissions; where emissions such as methane and nitrous oxide are classified in terms of their “global warming potential” relative to carbon dioxide and then combined into a single “CO2-equivalent emissions” value.

Finally, the interpretation stage utilizes the LCA practitioner’s judgment to summarize the results, analysis limitations, and quality of the assessment for further iteration, research, decision-making, and reporting.

US EPA : Life Cycle Engineering Guidelines : 2001

Rather than operating as a only a guideline for life-cycle assessment in general, the US EPA LCE guidelines are specifically for translating LCA data into engineering requirements, or “understanding performance, cost, and environmental implications and translating them into engineering requirements, goals, and specifications” [20].

The US EPA LCE process is similar to ISO14040:

1. Establish requirements and goals
2. Life Cycle Inventory: determine and document flows of material and energy. In particular, the EPA guidelines suggest that any flows or processes linked to specific requirements and goals are documented.
3. Link technology and options to requirements and goals and document if the technology exceeds, meets, or fails-to-meet the requirements.
4. Identify and implement key technologies for implementation to meet desired goals more efficiently (such as source reduction, source recoverable materials, efficient equipment, etc).
5. Iterate steps 2 through 4.

To streamline the process, the EPA suggests that available and existing “…information sources should be scanned with the purpose of capturing desirable and non-desirable technology types within each life cycle stage.“ This phrase points towards a hybrid approach where IO data could be utilized as a ``screening'' method to assess where new technologies to eliminate inefficiencies and pollutants would be most beneficial.

In talking about how life-cycle engineering should be implemented, the EPA organizes information spatially (facility, local, regional, and global) and temporally (material production, manufacturing and construction, use/support/maintenance, decommissioning, and recovery/disposal).

The EPA guidelines also outline specific engineering choices that might be made to influence environmental impact. These include material selection/changes, equipment selection/changes, improved purchasing choices, improved operating practices, disposition practices, and improved logistics. Notice that the EPA guidelines are for manufacturing improvements and inherently assume the product cannot be re-designed, as product re-design would also be an effective way to reduce manufacturing environmental impacts.

NIST SLIM

The National Institute of Standards and Technology has an ongoing set of projects titled, “Sustainable and Lifecycle Information-based Manufacturing” [*21*]. Because the work is ongoing, no conclusive recommendations have been made; however it is mentioned here because the program’s three main goals are very much in line with this paper: (1) determine standards requirements for sustainable manufacturing (2) develop models of product and process information (3) establish testing methodologies for information models and standards.

3.3 GHG Specific Frameworks and Standards

CO2PE

The CO2PE standard is an emerging standard on energy and GHG measurement of manufacturing processes. The goal is to combine process LCA knowledge with manufacturing knowledge to build a database of manufacturing processes and their energy and emissions characteristics [22].

PAS 2050

Publicly Available Standard 2050 [23] is a standard for the GHG LCA of products and services. Following from the ISO LCA standards, PAS 2050 outlines specific requirements for how to handle situations such as land-use change and use-phase emissions. The standard encourages a comprehensive life-cycle approach using screening methods to evaluate what emissions are important and then focusing analysis on the critical components of the lifecycle. This is in-line with a hybrid LCA approach, although the standard is written from a process LCA perspective.

Corporate Reporting and Inventory Standards

Corporate GHG standards have so far been limited to include only direct emissions from corporate facilities and vehicles and emissions from electricity. Standards can be classified into inventory standards and reporting standards, where the former outlines methodology and the latter outlines both methodology and reporting requirements. The Climate Registry [24] and EPA Climate Leaders [25] are good examples of reporting standards, while the WRI/WBCSD GHG Corporate Standard [26] and ISO 14064-1 [27] are well-known inventory standards.

There are many similarities between the standards:

1. Data for a “base year” must be reported as a means of comparison over time. If data calculation methodologies or boundaries change over time, the base year must be updated to reflect these changes so that it can always be used for direct comparison.
2. All emissions except direct, electricity, and purchased steam are voluntary.
3. The organizational boundaries of the assessment can be defined either by operation, financial control, or equity share.
4. eGrid electricity emissions data is suggested for regions of the U.S. where more specific data is not available. The WRI GHG Protocol also provides country specific electricity emissions factors.
5. Performance metrics such as GHG/$ are optional
6. Biomass emissions must be reported separately from other direct emissions.

Despite these similarities, there are important differences between the standards:

1. Location of Emissions: The Climate Registry only requires direct and electricity emissions that occur within the United States, Mexico, or Canada to be reported. Similarly, the EPA Climate Leaders protocol is limited to U.S. emissions. The WRI GHG Protocol and ISO 14064-1 suggest that all relevant global emissions to be included.
2. Data breakdown: The Climate Registry additionally requires that each facility be reported separately.

3. Verification: The use of a third party Verifier is specifically required for reporting into The Climate Registry. It is suggested for the other protocols but not specifically required.
4. Emissions Factors: EPA Climate Leaders and The Climate Registry utilize the same emission factors for combustion. The WRI/WBCSD GHG Protocol's emissions factors are slightly different.
5. Accuracy Tiers: The Climate Registry specifies tiers of data accuracy depending on data availability and requires that the tier be reported for each emissions source.

Compared with the comprehensive supply-chain view provided by LCA methods and product standards these corporate standards are highly limited in their scope. No emissions from the upstream supply chain, use-phase, or end-of-life are included in the inventory or reports.

Note, however, that the World Resources Institute is currently producing new standards for corporate Scope 3 accounting (both upstream and downstream) and product-level GHG assessments [28, 29]. These standards complete the data gap in the current corporate standards, which only address direct and indirect emissions.

Also note that many of these resources rely extensively on reference material provided by the IPCC guidelines [30].

4 HOW DO EXISTING STANDARDS AND LCA APPLY ACROSS THE DIFFERENT SCALES OF MANUFACTURING?

The paper up until this point has provided information on existing LCA standards and methodologies that could be applicable across various scales of manufacturing for decision making. Three LCA methodologies were presented in section 3: process, input-output, and hybrid. Essentially, input-output alone is not sufficient to make design decisions at any level and track progress; therefore only process and hybrid methodologies are considered here.

There has been a focus on the process LCA approach by both existing standards and consequently by people attempting to implement these methods across the supply-chain. This ill-conceived focus on process LCA has made the efforts overwhelming and strategically impossible given the large amount of data collection required for a purely process LCA approach.

Furthermore, the focus on quantifying facility level emissions has made extrapolation down to the machine-tool level or up to the supply chain level difficult.

Given the strengths and limitations of each methodology, Figure 2 suggests when each methodology is appropriate for each temporal and spatial level of manufacturing. The key differences to understand are that process LCA is most appropriate for detailed analysis of specific stages of an assessment or well-defined pieces of the manufacturing lifecycle. Hybrid assessment is best for two purposes: (1) ensuring a complete analysis across the boundaries of the analysis and (2) providing a screening to determine where process LCA is most effective

5 SUMMARY AND RECOMMENDATIONS

This paper attempts to answer a number of critical questions relative to the application of analytical tools for enabling green manufacturing. Manufacturing systems and processes were observed across spatial and temporal levels of complexity and an assessment of the suitability of existing frameworks were made at each level. The main questions addressed were: (1) what are appropriate LCA methodologies for different scales of manufacturing? and, (2) how do existing standards apply across various levels of manufacturing? It is apparent that depending on the goal and scope of the assessment there is an appropriate tool available; however all tools do not apply at all levels. Top-down hybrid LCA methodologies are effective at capturing full supply chain and enterprise level emissions; however process LCA approaches are most effective for tradeoffs at the factory or machine tool level of analysis. Most standards have focused on process LCA or limited enterprise LCA (just direct and electricity emissions). However, we are hopeful that this hole in existing standards will be filled by the emerging WRI standards on Scope 3 and product analysis [17, 18].

Future work is needed to harmonize existing standards across the levels and in the development of guidance for practitioners on when to utilize the various available and emerging methods, standards, and protocols. Additionally, work is needed to better understand what tools and data standards are needed to share data between the various manufacturing levels to enable better decision making at all levels.

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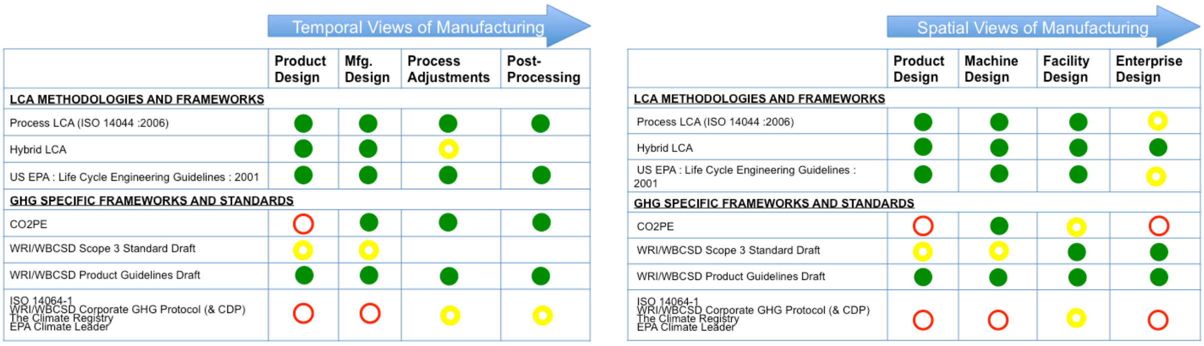

Temporal Views of Manufacturing

	Product Design	Mfg. Design	Process Adjustments	Post-Processing
LCA METHODOLOGIES AND FRAMEWORKS				
Process LCA (ISO 14044 :2006)	●	●	●	●
Hybrid LCA	●	●	◐	
US EPA : Life Cycle Engineering Guidelines : 2001	●	●	●	●
GHG SPECIFIC FRAMEWORKS AND STANDARDS				
CO2PE	○	●	●	●
WRI/WBCSD Scope 3 Standard Draft	◐	◐		
WRI/WBCSD Product Guidelines Draft	●	●	●	●
ISO 14064-1 WRI/WBCSD Corporate GHG Protocol (& CDP) The Climate Registry EPA Climate Leader	○	○	◐	◐

Spatial Views of Manufacturing

	Product Design	Machine Design	Facility Design	Enterprise Design
LCA METHODOLOGIES AND FRAMEWORKS				
Process LCA (ISO 14044 :2006)	●	●	●	◐
Hybrid LCA	●	●	●	●
US EPA : Life Cycle Engineering Guidelines : 2001	●	●	●	◐
GHG SPECIFIC FRAMEWORKS AND STANDARDS				
CO2PE	○	●	◐	○
WRI/WBCSD Scope 3 Standard Draft	◐	◐	●	●
WRI/WBCSD Product Guidelines Draft	●	●	●	●
ISO 14064-1 WRI/WBCSD Corporate GHG Protocol (& CDP) The Climate Registry EPA Climate Leader	○	○	◐	○

Figure 2: How LCA and GHG methodologies apply at various spatial and temporal levels. Green (solid dot) indicates that the methodology applies well, yellow (half filled dot) indicates moderate applicability, and red (open circle) indicates poor applicability.

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