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A Methodology Concept for Territorial Metabolism – Life Cycle Assessment: Challenges and Opportunities in Scaling from Urban to Territorial Assessment

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Abstract

To allow for the assessment of regional-scale geographically non-contiguous production system derived environmental impacts, a combined method of Territorial Metabolism – Life Cycle Assessment (TM-LCA) is proposed. By creating a two-pronged framework for the development of background system modelling, the TM-LCA method allows for process-based environmental impact modeling at a regional scale utilizing the concept of a production territory for the assessment of changes to durable production systems, such as energy infrastructure and agricultural systems. The TM-LCA framework creates the opportunity for direct assessment of environmental impacts, incorporation of system dynamics, and the use of multi-criteria decision analysis, which might be difficult or impossible to implement in other regional scale environmental impact assessment frameworks.

Keywords: Urban Metabolism; Environmental Assessment; Regional Scale; Territorial Metabolism

1. Introduction

As the desire for more sustainable cities and regions increases, so too does the need for adequate and appropriate methods and frameworks for quantification of the environmental performance of such systems. The need for this type of sustainability quantification has led to the development of urban metabolism (UM) models (see Figure 1) and environmentally extended input-output models (EEIO), which can be of great utility, but are often somewhat lacking in terms of transparency and can often only quantify a limited number of environmental impact indicators [1]. Furthermore, studies based on EEIO models are not well suited for modeling prospective temporally dynamic systems. This is because any system dynamism would have to be incorporated into a characterization factor, in EEIO called the 'direct intensity vector' [2], that links an economic value with an environmental impact indicator. Normally, these factors are empirically derived from market data (i.e. trade statistics), which makes prospective assessment challenging, if not entirely precluded, as it would necessitate the mixing of both empirical and modelled data [2]. Due to the assumption of sector homogeneity, EEIO frameworks can also obfuscate the root cause of environmental impacts [2], making scenario generation difficult. While these limitations are present, UM or EEIO are often some of the only presently available methods for environmental assessment of large complex systems, such as systemic (regional scale multi producer or complex single producer) production, where a full process based LCA that encompasses the entire regional system would be impractical.

Nomenclature	
EEIO	Environmentally Extended Input Output
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MCDA	Multi-Criteria Decision Analysis
TM	Territorial Metabolism
UM	Urban Metabolism

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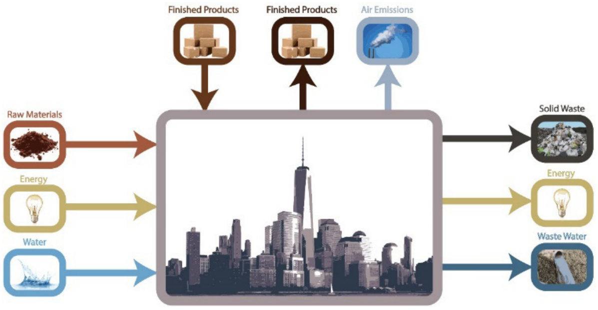

Figure 1: Conceptual visualization of a standard urban metabolism flow analysis

Table 1: Methods of large-scale environmental impact assessment. UM descriptions.

Method	Generalized characteristics
EEIO	Economically based system accounting utilizing a direct intensity vector to transform from economic flow to environmental impact. Can lack transparency and ability to define hotspots for improvement. Difficult to develop prospective temporal dynamics due to uncertainties introduced by mixing empirically measured and modeled estimates in the direct intensity vectors in dynamic EEIO. Due to the assumption of sector-homogeneity in EEIO, it is often not possible to assess a single producer.[2]
UM-Gen. 1	Based on material flow analysis. Can conflate material flow with environmental impact. Lacks incorporation of upstream and downstream processes.[1]
UM-Gen. 2	Based on UM with the inclusion of emergy assessment. Assumes all energy types are equal, missing variation in environmental impact from varying energy sources. Does not account for environmental impacts from other sources. [1]
UM-Gen. 3 (UM-LCA)**	Based on UM and incorporating LCA. Allows for greater transparency in determination of environmental impacts from given flows. UM Generation 3 is intended for assessment of systems at the scale of a city or urban area. Because of this, it lacks specific direction for expansion to larger scale assessment. [1]
TM-LCA***	Incorporates LCA in a UM-based method similar to a UM-G3 [1], but incorporates a framework allowing for the aggregation of multiple non-contiguous areas, which, when aggregated, are defined as a ‘territory’.

In approaching a method for the quantitative assessment of the impacts of new system development (e.g. energy production or waste treatment) at a regional level, the methods developed in UM studies could offer utility in a more complex environmental impact assessment method. Recent study has shown that UM studies coupled with life cycle assessment (LCA), UM-LCA, can be effective as a tool for benchmarking the environmental performance of cities across a broader range of environmental impacts than previously possible with traditional UM studies [1], [3]. The increased range of potential impact quantification is particularly notable, as it is well documented that single indicator based environmental impact assessments, such as assessments based on greenhouse gas emissions, are often not representative of the entire environmental burden induced by a product/service or system [4], [5]. Additionally, by incorporating a process-based model, system dynamics could be introduced, allowing for prospective impact assessment for durable systems [6]. Furthermore, the incorporation of multi-criteria decision analysis (MCDA) in the impact assessment phase of the LCA would allow for better representation of environmental impacts [4].

In order to allow for the aforementioned incorporation of a process and life cycle based assessment system at a regional scale, a framework for implementation must be developed. By incorporating methodological elements from existing model types (as described in Table 1), such as UM or EEIO, an underlying methodological background can be developed. This forms a foundational model, to which a framework for implementation of territorial scale environmental assessment can be attached. Typically in an UM, material flows into and out of a geographically well-defined contiguous area are accounted for (Figure 1). The UM flow assessment approach can be effectively developed to an environmental impact indicator based assessment using the UM-G3 [1] method. However, when applied to a larger region, such an assessment can become too resource demanding (in terms of time, data, etc.). In order to manage this issue, we propose a new coupled-method of territorial metabolism-life cycle assessment (TM-LCA).

2. Methodology

In order to scale from urban metabolism to territorial metabolism, a framework for determining what elements should be included in the assessment should be made. In a traditional urban metabolism analysis, the flow of all materials into and out of a well-defined urban area are accounted for (Figure 1), but this might become either impractical or lack sufficient detail to be of use if applied at the larger scale of a region. In order to reduce the complexity of the system, while maintaining pertinent details, a scaling concept is applied to define the territory (Figure 2).

There have been a number of varying definitions of territory in relation to LCA [7], [8]. Typically, the territory refers to a “geographic space managed by local stakeholders [that] is characterized by a regional identity” [7]. For the purposes of this work, however a slight differentiation is made from this generalized definition to allow for more utility in the assessment. Rather than utilize the geo-political delineation of a territory (such as shown in the national and regional outlines in Figure 2), the territorial scale, or 'production territory', for the purposes of this work will be defined as the aggregated individual producers and the land within their geographic delineations contained in a defined region. Process data corresponding to the processes occurring among the aggregated producers (the territory) within the region and their interface with the surrounding background are modeled, while unchanging (non-related) background processes are ignored. This allows for the pinpointing of impact 'hotspots' while reducing the overall workload from what would be present if non-related processes were to also be included. The result of this division of modeled and un-modeled processes is an environmental impact assessment of a production territory. The approach only partially covering the territorial activities can hence not be used for an absolute assessment, such as a typical UM or EEIO would for the region, but is ideal for use in assessing the environmental implications associated with implementation of e.g. new production scenarios, new supply chain constellations or waste treatment technologies.

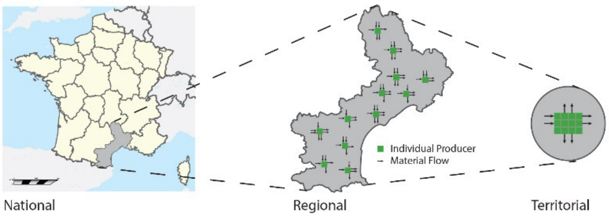

Figure 2: Scaling concept from national to regional allowing a process based aggregation of individual producers, shown in theoretical form for the Languedoc-Roussillon region in France.

2.1. Development from TM to TM-LCA

In order to integrate environmental impacts into the TM model, a conversion from material/service flow to impacts must be made. In EEIO and UM, there are differing methods allowing for quantifying the induced and avoided environmental impact (described in Table 1). To best-allow for the generation of scenarios for e.g. implementation of new technologies or production technologies, a process based LCA method is applied to the material and service flows across the boundary from the territory to the surrounding region. This can be accomplished by the incorporation of a standard database such as ecoinvent [9] for background processes in combination with user developed processes for scenario development. The development of these processes should as much as practically possible follow the ISO 14040 series standards [10]. It is likely, however, that the inclusion of e.g. system dynamics or MCDA will preclude some elements of the ISO standards. For example, in a dynamically developed product system where system expansion makes the product system excessively complex to assess, making allocation the only possible method. Or, if MCDA is used, then it is likely that explicit weighing would be included in published comparative results. In such a case, where ISO standards have been exceeded or compromised, it should be noted precisely.

2.2. Material Flow Data Development

In an ideal situation, primary life cycle inventory (LCI) data for all producers in a production territory would be available for use in the aggregated territorial process-based model. However, this is often not the case even when all producers in a production territory are owned by the entity wishing to complete a TM-LCA. In order to handle this shortcoming and increase the representativeness of the inventory used for the territorial model, a two-pronged approach is applied for modeling the territorial production processes where complete coverage by primary LCI data is not achievable. First, national or regional material flow data is applied and scaled to the territory. Processes are assigned to the material flows to create a material flow analysis based model. Then, if possible, a representative mix of individual producers are analyzed and modeled. The inventory data collected from individual producers is then scaled up to the level of the territory. This procedure provides indicator specific environmental impact ranges (Figure 3) that better reflect the actual environmental performance potential of the territory than if either (i.e. top up or bottom down) method were applied on its own.

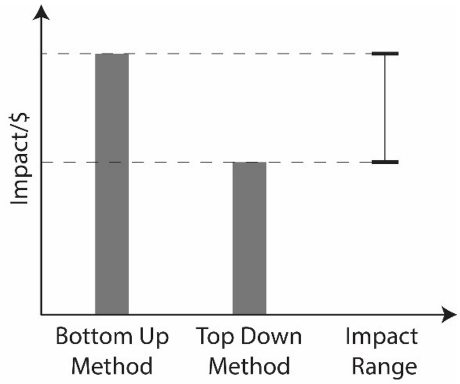

Figure 3: Bottom up and top down operational impact range visualization. Shown for economically normalized flow analysis.

To ensure completeness of the material flow analysis, ideally all material flows should be incorporated. This is, however, often not practically possible. Following the logic of ISO 14040 recommendations allowing for the omission of flows with less than 1% impact contribution [10], and in order to reduce data demands without compromising the resultant outcome, flows comprising 1% or less of the total mass-flow, or economic flow, depending on flow development method, could be omitted. This should not amount to more than 5% of the total flows. In addition, care should be taken to ensure that flows likely to produce a significantly stronger impact response per unit emitted are sufficiently assessed in a sensitivity analysis to ensure that their omission will not affect the results should they be included in the cutoff.

3. Discussion

For situations where a complex regional scale production system is to be assessed, such as in agricultural production, the TM-LCA method is well suited to provide detailed scenario analysis, in particular in the assessment of systems where multiple producers or a complex single producer cannot be adequately assessed using a standard LCA method. The environmental impact assessment inherent in the method can be extended to include non-environmental indicators, making it an ideal method for both regulatory bodies and commercial enterprise. This is made possible because the TM-LCA method is process-based, rather than e.g. homogeneous-sector economic flow characterization based as in EEIO, which creates the opportunity for further development of the model. This could include the incorporation of temporal system dynamics in the LCI, which might increase the validity of such a model [6]. Expansions could also include the incorporation of alternative methods of damage assessment such as MCDA, which could further increase the validity of the results if e.g. carbon-tied and non-carbon-tied alternative scenarios are being tested [4]. By using MCDA, there is also the opportunity to incorporate non-environmental factors into such a model, such as life cycle costing or ease of implementation metrics.

3.1. Potential challenges,

While the TM-LCA method offers great utility, there are also a number of challenges. One of the primary challenges in implementing a TM-LCA is data availability for the foreground processes and the representativeness of background processes used from existing databases. Care should be taken to check if a background processes are a dominant contributors to the results. If such a case occurs, the significant background process should be properly vetted to ensure that it is adequately representative; else, primary data should be procured. Furthermore, the completeness of the model must be ensured. In particular, if a flow cutoff is used to simplify the model, it should be demonstrated that this would not have a material effect on the results.

3.2. Potential Limitations, and Drawbacks

Apart from the challenges that face the TM-LCA method, a number of limitations and drawbacks should also be taken into account. One of the most apparent limitations is that this method, in most cases, will not provide an assessment of the entire region. As such, it cannot be used in lieu of UM assessment or EEIO. So, if such information is desired of an assessment a method such as UM-G3 [1] would be better suited. Also, the method is data driven and hence as LCI data becomes more and more diverse and hence case representative, the higher the quality of the conclusions that might be drawn from a regional assessment. As such, the results should be seen in an appropriate light with regard to data quality. Furthermore, the TM-LCA method requires more data collection than a standard process LCA for a typical single-producer's product, as such it will likely take more time and potentially incur more costs. Because of this, the potentially added value in relation to a product LCA should be considered in the decision to implement a TM-LCA.

3.3. Implications for production management and regional governance

The inclusion of process based life cycle assessment methods in the TM-LCA method allows for a number of assessment tools and perspectives that would otherwise be difficult to implement/represent with traditional UM or EEIO methods. For instance, because environmental impacts are directly measured in a process-based analysis, environmental hotspots in production can be identified, giving both governing agencies and producers valuable information. The process based impact assessment also allows for system dynamics to be incorporated, which is an important element in accurately assessing durable system implementations [6]. Furthermore, the inclusion of MCDA could also improve the ability to compare environmental impacts of certain types of scenarios [4] and allow for non-environmental impact assessment such as life cycle cost or ease of implementation. The potential for inclusion of these elements, as well as the target geographic scale, make the TM-LCA method ideal for informing regional governance bodies, trade associations, and large scale commercial producers.

4. Conclusions

The TM-LCA method is of great utility when applied for the comparison of regional scale sector or large-scale single producer implementation of alternative production methods and technologies as well as other system-scale change alternatives such as the implementation of alternative waste management technologies. By setting a consistent method for such assessments, the variability inherent in the implementation of ad-hoc solutions is avoided, which will become more imperative as the use of LCA in increasingly complex and varied types and scales of systems continues to broaden.

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