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Towards More Holistic Environmental Impact Assessment: Hybridisation of Life Cycle Assessment and Quantitative Risk Assessment

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Abstract

Global and local environmental impacts of products or services can sometimes be in conflict with one another. Therefore, the importance of considering both impacts in environmental management must be recognised. Life cycle assessment (LCA) is useful in evaluating global impacts while quantitative risk assessment (QRA) is effective in local impact assessments. The benefits of combining LCA and QRA in this regard have been recognised. Advantages and disadvantages of different hybridisation approaches were critically examined in this paper. There seems to be no single best approach and a method needs to be carefully selected depending on the type of application.

Keywords: Life cycle assessment; Quantitative risk assessment; Life cycle risk assessment; Environmental impact assessment; Environmental decision making; Environmental management; Multicriteria decision analysis.

1. Introduction

Global and local environmental impacts are often found to be in conflict with one another and the potential problem shifting has been shown in studies of diverse industrial processes [1-4]. Kikuchi and Hirao [1] demonstrated the trade-off relationship between global impacts (global warming potential) and local impacts (occupational and neighbour's health risks) by studying potential human health impacts due to metal degreasing processes. Similarly, O'Connor et al. [3] identified potential trade-offs among different types of impacts including eutrophication, freshwater aquatic ecotoxicity, greenhouse gas (GHG) emissions and water extraction, by studying various configurations of paper and pulp effluent treatment technologies. For instance, they found that eutrophication potential may be reduced, but that would require energy intensive technologies such as reverse osmosis, which may cause higher GHG emissions. Liang et al. [2] also indicated the potential problem-shifting between global and local impacts in biodiesel production depending on the choice of feedstocks used. In their study, it appeared, for example, that algae based biodiesel would cause more global warming potential while waste cooking oil-based biodiesel was more human and eco- toxicity intensive.

As such, it is essential to consider global and local impacts simultaneously for a total environmental management to genuinely reduce impacts rather than just shifting problems. Life cycle assessment (LCA) offers a broad perspective and is effective for global impact evaluation. It determines the potential environmental impacts throughout a product or service's life cycle for a defined functional unit, which is a quantified function provided by a product system [5]. LCA is most commonly used in product development and marketing in corporations, though it has also been proven to be useful in decision-making and priority settings in various applications [6].

Quantitative risk assessment (QRA) is used to evaluate potential risks of specific substances under specific conditions by taking local details into consideration [7]. Consequently it is able to assess the risks more accurately. QRA is often applied to determine whether risks associated with substances or activities are acceptable by referring to benchmark

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acceptable levels. Authorities may apply QRA for risk management to reduce possible risk by, for example, introducing new regulations [6].

Due to their different strengths, LCA and QRA have been thought to complement each other [6, 8, 9]. Consideration of all kinds of emissions and many types of environmental impacts is one of the strengths of LCA [10]. This broader perspective of LCA enhances the ability to evaluate impacts more comprehensively and helps to detect problem shifting which could be of concern when only limited emissions or/and impacts are considered, which often is the case of QRA [11-13].

The focus of QRA is often remarkably narrow compared to LCA. This enables QRA to use more realistic models which improve accuracy. It is capable of distinguishing site- and time-dependent conditions such as distribution routes of substances, exposure pathways and event frequency and duration [14, 15]. LCA generally applies much more simplified models with global or regional average data. Within LCA, emissions are spatially and temporally aggregated referring the functional unit [11, 16]. Because of this aggregation, the temporal and spatial information will be lost [17]. It is based on assumptions that the emissions can be aggregated into a single effect and exposures occur simultaneously [13], although, in reality, the degree of impacts may greatly vary depending on the locations and emission rates. This simplification may lead to incorrect decision making. Implementing a more detailed approach such as QRA may enhance the precision of LCA.

To take advantage of the complementary strength of LCA and QRA, the benefits of combined use of the two approaches has been recognised. This would achieve more comprehensive environmental management and several different types of integration methods have been proposed. In this paper, previously proposed hybridisation approaches are critically analysed and their advantages and disadvantages are discussed.

2. Method

To identify previously proposed approaches for LCA and QRA integration methods, relevant literature was searched through online databases, Scopus and Web of Science. Keywords with Boolean operators [("life*cycle assessment" OR LCA) AND ("quantitative risk assessment" OR QRA)] were used as the initial survey of literature. Then subsequent database searches were performed with more specific terminologies including "risk*based life*cycle assessment", "life*cycle risk assessment", "life*cycle based risk assessment", "life*cycle aware risk assessment", "life cycle risk management", "risk assessment in life*cycle perspective", "risk assessment complemented life*cycle assessment", "multi*criteria decision analysis" and their acronyms. Other literature, technical guidelines, and published books which were mentioned in the identified literature were also reviewed. The integration approaches found through literature search were fit into four main categories and the benefits and limitations of each category were critically analysed.

3. Results and discussion

A number of studies attempting to combine LCA and QRA were identified. Various types of approaches have been examined, but they seem to fit in one of four main categories, which are; 1) conducting LCA and QRA separately and comparing their results using formal or informal multicriteria decision analysis (MCDA), 2) using LCA as a screening tool and then performing QRA for the predominant impacts, 3) applying the life-cycle concept in QRA, and 4) integrating QRA into LCA. The advantages and disadvantages of each approach are summarised in Table 1 and the details are discussed in the following sections.

Table 1: Advantages and disadvantages of each hybridisation approach

LCA and QRA separately	Advantages	• Provides comprehensive view • MCDA can include other criteria, e.g. social and economic aspects
	Disadvantages	• May be costly and time consuming • Decision making may be complex when LCA and QRA results disagree • Weighting may be subjective
LCA as screening	Advantages	• Efficient in finding primary contributors • Reduce workload and cost
	Disadvantages	• Primary contributors may not be obvious • Chosen LCA method may not be appropriate
Life-cycle QRA	Advantages	• Local details are considered • Detects problem shifting between processes/stages of product's life cycle • Helps prioritisation for risk reduction
	Disadvantages	• Only relevant for non-global impacts • Feasible only when limited number of contributors need to be assessed
QRA into LCA	Advantages	• Spatially differentiated assessment can be achieved
	Disadvantages	• Feasible only when limited number of processes are involved in the life cycle

3.1. LCA and QRA separately and comparing the results

With this approach, LCA and QRA are conducted individually and their results are compared. This approach has been demonstrated with various case studies [1, 8, 9, 18-20].

Although LCA assesses the impacts more comprehensively, there still are types of impacts that are disregarded from many of current LCA methods such as occupational health, indoor-air pollution, noise and accidents. QRA can be conducted in addition to LCA to fulfil the need to assess missing impact categories. Recent attempts to include pathogen risk in LCA are an example of this [21, 22].

Kikuchi and Hirao [1] used this approach for their study of metal degreasing processes. LCA for human health impacts due to global warming and human toxicity and QRA for impacts upon occupational health and on the health of neighbours were performed separately. The results of LCA and QRA were found to disagree with each other in the preferred scenarios, which would complicate the decision making. Since metrics used in LCA and QRA in their study were different, it was not feasible to aggregate the results to obtain overall impacts for a comparison. Kikuchi and Hirao (2008) stated that the final decisions needed to be made by decision makers by applying weighting to reflect value judgments, leaving the MCDA stage of the process in the hands of their readers.

Linkov and Seager [12] suggested an approach to using MCDA for the analysis of results. The main strength of MCDA is that criteria other than environmental impacts such as cost and social acceptance can also be incorporated [12], however, MCDA has its own limitations including the use of subjective weighting [23]. The final outcome would depend on the value decisions of stakeholders. For example, manufacturers might prioritise the cost while end users may consider health risks more important. Nevertheless, it has been recognised that a combination of LCA, QRA and MCDA may be useful as MCDA would complement LCA and RA. Since MCDA is capable of dealing with uncertain information [12, 18], this approach many be beneficial especially for emerging technology such as nanomaterials where conventional risk assessment approach face challenges due to a paucity of data and more comprehensive approaches to predict the impacts of an entire life cycle are in high demand [18, 24].

While conducting full LCA and QRA completely separately will provide more exhaustive view, it may be costly and time consuming, which could be a drawback for practitioners.

3.2. LCA as screening and QRA for predominant impacts

The broad perspective that LCA offers is essential for total environmental impact assessments. However, the uncertainty of LCA results due to lack of local detail may be critical in some cases. Although collecting local specific data for all the processes involved in a product life cycle may not be practical, it is recommended that local data is used at least for primary contributors for impact categories operating at regional scales, such as potential toxicity [25]. Using LCA as a screening tool will assists in the identification of primary contributors for which more detailed analysis by QRA can be conducted [20]. It is particularly beneficial when large number of substances and potential exposure pathways are involved. Several case studies using this approach have been found in the literature [20, 26-28].

Carpenter et al. [26], for example, have demonstrated this approach in a study of road construction materials. An LCA was conducted solely first by using Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) [29]. Cancerous human toxicity potential due to groundwater contamination was identified as the most significant impact. Risk assessments with a site specific risk assessment tool, Hydrus2D [30], for the substances associated with cancer effects were then conducted for a closer examination of the risks. Risks predicted in QRA were found to be significantly lower than those of LCA as well as below relevant guideline levels. The reason for the difference between LCA and QRA results was that PaLATE assumed all the substances would reach and contaminate groundwater, while considerable reduction in aqueous concentration of substances over time and with depth was accounted for by Hydrus2D. If only LCA results were considered, an effort to reduce the leachate to groundwater may have been unnecessarily prioritised. This study showed the importance of using QRA to examine actual impacts rather than relying on potential impacts estimated with LCA. It also demonstrated how use of LCA as a screening tool may be advantageous in finding substances requiring a closer evaluation. Conducting QRA only for potentially significant contributors obviously reduces workload and cost.

This approach works well when only a limited number of primary contributors are identified. In other words, it may not be effective for cases where the degrees of contributions of many of substances are similarly high. Also, as applying QRA is only meaningful for substances causing local impacts, it is useful for limited impacts such as toxicity.

Furthermore, depending on the LCA method, screening results may be different. Mattila et al. [31] evaluated three different LCA methods, IMPACT 2002+ [32, 33], ReCiPe 2008 [34] and USEtox [35], as screening tools and found that priority substances identified with each method were inconsistent. They suggest that LCA methods need to be carefully selected as parameters used in each model may be different.

Finally, missing impact categories in LCA may cause a problem. Occupational health impacts, for instance, are often found to be significant [36, 37], however, they may slip through screening as they are not considered in mainstream LCA methods. Because of the limitations of LCA such as these missing impact categories as well as disregarded spatial and temporal details, using LCA solely as screening tool may lead to incorrect or inappropriate prioritisation. Lim et al. [20] and Demou et al. [27] used QRA as screening in addition to LCA to determine primary toxic chemicals. In both studies, many of the primary chemicals identified in LCA and QRA did not match.

3.3. Life-cycle QRA

As discussed earlier, one of the disadvantages of QRA is its narrow focus. For greater comprehensiveness, ‘life-cycle aware’ risk assessment, often referred as life cycle risk assessment (LCRA), has been suggested [37-42]. With this approach, the boundary of risk assessment is expanded to include whole life cycle of a product.

Shih et al. [37], as an example, applied LCRA in the study of bottom ash reuse for road pavement. Risks associated with a few specific substances were evaluated for each process throughout the entire life cycle. Since this approach takes local conditions into account, more accurate assessment can be obtained. LCRA enables one to evaluate occupational health as well as health of nearby residents as demonstrated by Shih et al. [37]. It assists in the identification of which processes or stages in the life cycle should be prioritised in impact reduction to efficiently achieve improved environmental performance.

With this approach, problem shifting between processes or stages can be detected. However, problem shifting between sources or between local and global impacts may be overlooked as only limited substances and impact categories are included. Also, unless prominent contributors are readily known, this approach cannot be applied. In that case, use of LCA as a screening tool may be considered.

3.4. QRA into LCA

Implementing QRA components such as exposure and dose-response assessment into LCA is another integration method and several different approaches have been proposed. The inclusion of toxicological risk assessment into LCA is the most common approach [43]. It has been done in many of the existing LCA methods including IMPACT 2002+ and ReCiPe 2008. It may be the most accessible approach from LCA practitioner's point of view as QRA is readily embedded in LCA software packages. The QRA models this is based on, such as USEtox, are on the other hand necessarily simpler than the exposure pathway models of mainstream QRA. The results are therefore not as accurate as a conventional QRA approach since spatial and temporal information are disregarded and regional or country level average parameters are generally used in the risk calculations. Moreover, regional/country specific data are available only for limited regions such as Europe and North America. For processes carried out in the rest of the world, global averages or averages for other regions need to be used, which leads to additional inaccuracy.

To improve the accuracy, more region specific information is required. The significance of spatial differentiations in LCA has been realized [44, 45]. Krewitt et al. [46] demonstrated its importance by showing how the damage factors in each country of Europe may differ when country specific data was used. Sonnemann et al. [47] proposed a site-dependent LCA method for industrial process chain. In this approach, life cycle is divided into processes and regional or local damage functions are applied in each process. Spatially separated and more site specific risk assessment can be achieved. While it is theoretically possible to apply site specific information for each process in the entire life cycle, it may not be practical for products with huge number of processes occurring different parts of the world such as automobiles and electronic devices. It is more applicable when only a few processes are involved such as waste treatment technologies; landfill and incineration. The amount of data required and their availability may restrict the practicality of this approach.

For more complex product systems, site-dependent impact factors developed by several authors [46, 48, 49] may be useful. Geographical locations of emissions are the only additional data required to apply these factors [49]. Bellekom et al. [50] examine three different LCA cases to determine the level of improvement in accuracy when applying site-dependent factors as opposed to site-generic ones. In their study, while the overall conclusions were not influenced, relative contributions of processes were found to be affected. This suggests that site-dependent approach is meaningful especially in prioritizing processes to effectively reduce environmental impacts.

4. Conclusion

As public interest in local issues such as air and water pollution and concerns about global issues such as climate change have been growing, better quality communication with end users regarding to the environmental performance of products is becoming indispensable. At the same time, limitations of commonly used environmental management tools such as LCA and QRA, when conducted independently, have become increasingly recognised and more holistic environmental management by integrating LCA and QRA is appearing beneficial.

Each of four main categories of hybridisation approaches identified in this study has distinctive advantages and disadvantages. There seems to be no single best approach for all applications and the methods need to be selected depending on the aim of the study, type of application, availability of data, as well as other constraints of projects such as time and cost to maximise the benefits of the combined use of LCA and QRA.

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