FRAMEWORK FOR ENVIRONMENTAL ASSESSMENT OF USING INDUSTRIAL BY-PRODUCTS AND USED BUILDING MATERIALS

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ABSTRACT

In Sweden, environmental assessments in the process of development permits regarding use of by-products and used building materials in constructions is mainly performed from the narrow perspective of the material itself, i.e. the material level. Certainly, such an assessment does not involve substitution of natural resources or environmental aspects of reuse in a wider sense. We argue that these mainstream environmental assessments should use broader system boundaries. We propose a framework based on four different assessment levels; (i) the material level, (ii) the local environment level where the material should be applied, (iii) the narrow life cycle level including a restricted life-cycle perspective and (iv) the industrial system level where the production processes of the by-product or used building material and its actors are working. Consequently, these levels address different issues. An environmental assessment of reuse in general according to this framework would illuminate various aspects of each level. Moreover, each level involves different evaluation methods to answer addressed questions. For example, leaching tests are suitable at the material level in order to study which and how much substances that could leach from the material. At the local environment level, substance flow analysis can illustrate relevant flows and stocks in the nearby environment. At the narrow life cycle level an abridged life cycle assessment adds non-geographic but life cycle oriented information. Lastly, at the industrial system level, methods as strategic environmental assessment or extensive life cycle assessment could be used. The result of an environmental assessment use of by-products and used building materials using this broad framework would provide a good basis for a discussion about environmental performance involving consequences such as substitution of natural resources, local environmental impact, large scale effects, and global environmental issues such as supply of rare metals and climate change.

INTRODUCTION

Since Sweden is a sparsely populated country, still rich in natural materials for buildings and constructions, the incentive to large scale use of industrial by-products and used building materials respectively, for such purposes has not been very strong, compared to some other European countries. However, the government is attempting to decrease the overall volume of solid waste deposited in landfills. One example of this is the newly introduced landfill tax, which has increased the interest in activities aiming to decrease the amount of solid waste deposited in landfills, for instance, by finding new ways to make use of solid waste and by-
products.

The use of industrial by-products and used building materials is often termed reuse or recycling. One underlying argument for reuse measures in general is to economize the use of natural resources. Nevertheless, not all kinds of reuse can substitute the use of natural resources [1]. This is because any loss in material quality, i.e. degradation, by reuse processes has to be compensated for, by inputs of virgin raw materials and energy in the original processes (ibid). This idea is based on thermodynamics, from which it follows that the material quality is high for refined raw materials and degrades through further production and use. Therefore, to re-attain the high state of material quality, energy has to be added. An implication of this is that the general term reuse should be divided into several categories in order to elucidate the conservation of material quality. Connelly and Koshland (1997) [1] proposes the categories (in material quality degrading order): i) recirculation where the material quality is conserved, ii) upgrading, divided into recycling and partial recycling, which means that energy has to be added to bring the material back to its pre-consumed state and iii) cascading which degrade the material quality and often require some energy.

In contrast to crushing buildings for cascading into other sectors, a prerequisite for recirculation of building materials within the building sector is that the components that will be recirculated are intact after deconstruction or selective demolition. Additionally, upgrading of building materials would also require deconstruction or selective demolition. These reuse process would encourage reuse within the building sector. However, demolition of buildings and constructions generates crushed materials that could be cascaded into other societal sectors as well, for example road and earth constructions. Cascading and thereby degradation of the material quality, seems to entail an outflow perspective, i.e. what, for example, a building demolisher should do with the solid waste. In contrast to this, an inflow perspective on materials use, i.e. what, for instance, a building contractor could use in new constructions, is mainly facilitated by recirculation and upgrading. It may even be a prerequisite.

The material flows mainly focused on in this paper are those connected to the building sector: i) recirculation, upgrading and cascading of building materials and products within the building sector (the inflow perspective from the actor’s point of view), ii) cascading of materials within the building sector (the outflow perspective from the actor’s point of view, i.e. not conserving material quality even if it is possible), iii) cascading of building materials into other sectors, mainly the construction sector (the outflow perspective from the building sector’s point of view), iv) use of industrial by-products from other sectors into the building sector (the inflow perspective from the building sector’s point of view).

There could be potentially positive environmental effects of increased use of industrial by-products and used building materials through development of new product applications. However, it is not very much discussed, if and to what extent, these activities contribute to improved environmental performance. For example, used building materials, such as crushed concrete from the building sector; industrial by-products such as slag from the blast furnace process in steel production (BF-slag) and bottom ash from a municipal solid waste incineration plant, is to replace non-renewable natural resources, which in Sweden are represented by natural gravel and crushed rock. However, because of the risk that the materials could leach toxic substances into the nearby environment, the regional and central authorities in Sweden restrict the use. Consequently, environmental assessments of industrial by-products mainly has focused on measurements of total chemical content and leaching behaviour. However, research methods addressing material characteristics could not evaluate total use of resources and the environmental pressure of the use of by-products in a broader sense [2]. One reason to this is that the system boundaries of such methods are too narrow. Therefore, a development of environmental assessment is required in order to accurately address and assess the use of different materials. The framework for environmental
assessment proposed here would contribute to a better understanding of the overall environmental aspects of using industrial by-products and used building materials. The framework is earlier developed for use of industrial by-products in road and earth constructions (c.f. [2]). In this paper the framework is additionally discussed for the building sector’s use of industrial by-products and used building materials, respectively.

AIM AND METHOD

In this paper, we present a framework for environmental assessment of the use of industrial by-products and used building materials and consequently discuss different approaches for environmental assessment. This will be addressed by applying methods or tools using different system boundaries (c.f. [2]). To illustrate the importance of the system boundaries to the outcome of an environmental assessment we have chosen to study four different assessment levels. These levels are organised in a structure where the system boundaries expand from the most narrow and detailed level to a comprehensive level where overall environmental pressure are the main interest (Figure 1). The first or the narrowest system in this context is the material itself, its properties and its contents of substances, i.e. the material level. Secondly, the system boundaries are expanded and by using a for example substance flow analysis (SFA) or environmental impact assessment (EIA), the material is studied in its spatial context, i.e. the local environment level. Thirdly, a life-cycle perspective is applied that also includes aspects such as transport and the pre-treatment of the studied materials, i.e. the narrow life-cycle level. Finally, the widest systems approach, the industrial system level, adds a cross-sectoral dimension in the assessment. In this context, this means that several industrial sectors, such as the building sector and industry respectively, are addressed in order to include the generation of used building materials and the use of industrial by-products and the avoided raw material extraction. Consequently, these levels address different issues. An environmental assessment of use of by-products according to this framework would illuminate various aspects of each level. Moreover, each level involves different evaluation methods to answer addressed questions. Concerning the first three of these levels, there are examples of studies in the literature, while there is a lack of studies applied in the research field of used of building materials and the use of industrial by-products on the fourth. The result of such an environmental assessment using this broad framework would provide a good basis for a discussion about environmental performance involving consequences such as substitution of natural resources, local environmental impact, large scale effects, and global environmental issues such as supply of rare metals and climate change. Concerning use of industrial by-products for road structures, the potentially different outcomes of the environmental assessment depending on what system boundaries that are applied are earlier discussed in [2]. In this paper, we will additionally address the material flows of the building sector using the framework for environmental assessment.

THE MATERIAL LEVEL

The methods currently used at the material level (Figure 1) mainly address the chemical content and possible leaching (c.f. [3-6]). These studies could contribute to improved knowledge about the content of substances in both industrial by-products and virgin resources that, depending on origin and generation processes respectively, could vary a lot. Leaching behaviour in laboratory could, only to some extent, show the possible long-term effects on the environment. To accurately address this issue, further research and development of field studies is needed. In order to relate the emissions from a specific application to the environment, the state of the environment must also be investigated (see the local environment level). Using chemical analysis of total content and leaching behaviour makes it
possible to address issues concerning emissions from the construction materials. However, it is not possible to evaluate resource aspects in general at this level of study (Figure 1).

In environmental assessment of use of industrial by-products and used building materials there often, and logically, is a comparison to virgin raw materials and conventional construction materials. At the material level this will result in a long list of substances present in the reused material or by-product and the substances’ possibilities to leach from these. The result of such study would be that for some substances, one material is environmentally preferable and for other substances another material is better. Higher priority might be given to some substances depending on toxicological aspects or the environment where the materials should be used [2]. Additionally, which environmental issues that are considered most important are contingent upon values and this also affect the interpretation of the result. Because of this, it is a complex process to determine which materials are suitable from an environmental point of view.

Figure 1: Examples of system boundaries defined by the four levels discussed in this paper, illustrated by different borders. These encircle the specific parts (processes) of the production chain that the studies at a certain level could take into account. In contrast to processes, products are shown in *italics*. The system boundaries for the narrow life-cycle level and the local environment level respectively, should be seen as proposals. The system boundary of the narrow life-cycle level drawn here is an example of the inflow perspective. The material level contributes with knowledge required at all other levels. Based on [2].

**THE LOCAL ENVIRONMENT LEVEL**

The local environment level applied to the building sector entails the indoor environment, which becomes additionally important. Field studies would address pollution of the local environment, by soil samples and ground water tests (c.f. [4, 7, 8]) and also indoor air measurements in buildings. This would possibly respond to if leakage from used materials and by-products actually occurs and in what concentrations the substances are found in the nearby environment. The process of development permits for industrial projects often involve an environmental impact assessment (EIA). These are mainly focused on the local environment perspective often not including upstream and downstream processes like use of natural resources and handling of waste [9]. However, could compared to the borders
proposed in Figure 1, also include other processes and a broader discussions of utilisation of virgin resources. Some authors have suggested that EIA employ a wider perspective to meet present environmental changes [10, 11].

As well, substance flow analysis (SFA) will provide knowledge of the local environment and make it possible to assess industrial by-products and used building materials in the context where they should be used (Figure 1). SFA addresses a spatially defined area to make inventories and analyse a material or a substance in a well-defined system (c.f. [12-14]). The procedure is to make use of the results generated at the material level, results from field studies and also to add data of total amount of materials used. Thus in contrast to other studies, when performing a SFA, the material stocks and flows of a substance are modelled. This procedure connects the anthropogenic use of substances in the technosphere to its occurrence in the environment. The point is to illustrate these relations in the same picture, or flow chart, in order to determine the magnitude of a certain material use and trace the most significant sources of environmental pollution [12-14]. To utilise a SFA gives the opportunity to compare stocks and flows of virgin raw materials to those of reused materials and by-products in a spatial context. In addition, future potential environmental problems could be addressed by applying a long-term perspective to the flow chart.

To study one substance only (as in SFA) is not enough to build a comprehensive view of the complex environment. A set of strategically chosen indicator elements could constitute a basis for the environmental assessment of the use of by-products, used building materials and the state of the environment in which these construction materials are used. To study the total amount of materials in a system (SFA) is one way to assess the amount of resources directly needed for the application of interest. This could be seen as a rough estimation of the utilisation of natural resources. However, SFA could not really address the total amount of resources required to process the construction materials along the material chain. However, this could very well be included in the EIA process that could involve several methods and tools in order to gather information about the studied project (see the narrow life-cycle level).

The general summary of this local environment level will be the same as for the material level; to determine the environmental performance of construction materials from a pollution perspective, i.e. what substances and environmental issues to focus on, thus becomes contingent upon values.

THE NARROW LIFE-CYCLE LEVEL

Similar to the substance flow analysis, the life-cycle perspective in general also takes a system approach (c.f. [15, 16]), however, the system boundaries are expanded to include processes such as extraction and production processes, transport, construction techniques, consumption and disposal (Figure 1), as well as the use of energy in all processes. Even though the system boundaries are a bit different, the inventory of relevant inputs and outputs of a product system is rather similar to the procedure of SFA.

The narrow life-cycle perspective discussed here is restricted in its scope compared to a standardized life-cycle assessment (c.f. [15, 17]). However, the point is the same: to evaluate the environmental impacts associated to inputs and outputs through the life-cycle of an entire construction, one single material or a service. By this means, the environmental performance of different products that fulfill the same purpose, i.e. having the same functional unit, can be compared [15]. Performing a life-cycle inventory, spatial and temporal system boundaries have to be defined as well. Also, since used building materials, solid waste and industrial by-products mainly not are the primary interest of building construction activities and industrial production a relevant question is to what extent the use of resources and environmental pressure should be allocated to these products. At this narrow life-cycle level we argue that
cutting off earlier production processes and avoided waste handling would be sufficiently appropriate. That is, excluding the production processes that earlier generated used building materials and industrial by-products (Figure 1) and consider the studied materials as wastes that otherwise would have been landfilled, however, not crediting the reuse for avoiding landfill (c.f. [18, 19]). This decision certainly affects the outcome of the study since these excluded effects could be the dominating environmental aspects [20]. Furthermore, an extensive life-cycle assessment takes a vast number of environmental aspects into account. Instead, the narrow life-cycle perspective uses strategically selected key parameters. An environmental assessment of the use of industrial by-products and used building materials at the narrow life-cycle level will point out the activities that contribute to the dominating environmental pressure in terms of use of resources and emissions to air, water and soil, during the chosen part of the life-cycle (Figure 1). The method could also point out areas of possible improvements where operative measures would be especially efficient.

Environmental assessment at the narrow life-cycle level, pollution issues and resources aspects could be addressed if the system boundaries and the set of key parameters are chosen to include this. However, the pollution aspects could only be discussed in general because the emissions could take place at geographically disparate places. Resource use in the life-cycle could, for instance, be studied through the amount of primary energy used [21]. The results from studies at the narrow life-cycle level depend on case-specific data and are affected by the construction itself and the processes included, such as pre-treatment of the materials, transportation and the construction. Therefore these studies mainly are case-specific rather than general [18, 19]. Even though a few different parameters are examined, it is not likely that the results will favour one material. A comparison probably emphasises different parts of the life-cycle as dominant for the environmental pressure, depending on the materials studied and the activities included. The final interpretation of environmental assessment at the narrow life-cycle level would therefore be a matter of values based on what environmental pressure is considered most important [2, 19]. However, using this narrow life-cycle level, activities taken place in different sectors are not always fully included and therefore it seems like use of by-products, such as BF-slag and bottom ash, in the building sector substitute for non-renewable natural resources. Moreover, used building materials and industrial by-products could certainly have a market value and therefore should be treated as co-products and the system boundaries should be expanded (c.f. [22]) to the industrial system level.

THE INDUSTRIAL SYSTEM LEVEL

In the broadest system approach for environmental assessment discussed in this article; the industrial system level is addressed. Methodologies that possibly would cope with these issues are extensive LCAs and strategic environmental assessment (SEA). SEA can be seen as a comprehensive process of evaluating environmental pressure of a policy, plan or programme (PPP) and its alternatives [23]. The methods and techniques for carrying out a SEA depend on the case in question and could be anything from simple checklists and matrices to life-cycle analysis and cost-benefit-analysis (c.f. [24-26]). The overall purpose is to find and assess the most important direct and indirect environmental effects early in the decision-making process in order to mitigate environmental impacts of the PPPs. Even though some SEAs and a vast amount of LCAs have been performed, there is a lack of studies applying the wide system boundaries of the industrial system level and consequently addressing the overall environmental pressure of use of industrial by-products and used building materials and also reuse activities in general such as recirculation, upgrading and cascading. Reasons to this could be that finding proper data and modelling the complex situation that should be studied could be difficult and very time consuming. However, the
broad system boundaries of the industrial system level make it possible to address exchange and utilisation of used building materials and use of by-products between industries and sectors by, for example, system expansion (c.f. [22, 27]). System expansion includes the determining and dependent co-products and co-producing processes so that allocation could be avoided [22].

Environmental consequences of cascading of industrial by-products in building materials or cascading of building materials into other sectors could be addressed in a very broad sense at the industrial system level. This means that all actors concerned could be included in a study and for this highest system level the most significant impacts of cumulative effects could be evaluated by using SEA. Also issues such as the industry’s incentives to cascade by-products, reduce inputs of non-renewable natural resources, or reduce outputs, could be studied. Moreover, Bringezu [20] proposes to include the input of materials that are dislocated for economic purposes, which mean the inclusion of, for example, overburden at the mines. This procedure, to consider activities taking place in other societal sectors, including environmental problems that do not occur locally or within the immediate responsibility of the actor, makes it possible to analyse material use from a life-cycle perspective. Consequently, exchange of materials within industrial systems can be studied. Thereby, the industrial system level of environmental assessment could identify some problems linked to cascading. To start with, if, for instance, industrial by-products are to be used by an actor in another societal sector, the responsibility accompanies the material. If long-term effects of the use of by-products are not accurately considered, the manager will be cautious about using these materials. Furthermore, if the system of cascading materials is to be developed without environmental assessment, it may not be environmentally preferable. In that case, the promotion of a cascading system could consolidate existing industrial systems and hold back the development of new technology, because there is no incentive to decrease the emergence of by-products. Moreover, a consolidation may hinder internal measures regarding processes that could change the composition and the amounts of the by-products (c.f. [28, 29]). In turn, this may hamper the development of better reuse systems that really could reduce the material throughput and inflows of natural resources.

We suggest that studies at the industrial system level would contribute a lot to the environmental assessment of the use of by-products and used building materials, in a very broad sense. Information and knowledge from studies at the material level, the local environment level and the narrow life-cycle level could also perform a basis for studies at this level. The idea to use several studies with different approaches and thereby sequentially build up knowledge and generate information is also discussed by Finnveden et. al (2003) [26] that propose a framework of analytical tools for the SEA process.

Both pollution aspects and the use of natural resources could be addressed at this level, as well as the complex industrial context in which these activities take place. However, studies at this level could be very complex and the quest for consensus about allocation principles and system boundaries should continue. The research field of industrial ecology that includes studies of interactions between societal actors and the environment [30] could possibly address and develop these emerging issues.

**DISCUSSION**

All assessment levels presented in this article address different system boundaries (Figure 1), which result in different possible methods or tools. The questions addressed at one level could not always be discussed at other levels because the system boundaries restrict what possibly could be included in a study. Consequently, the outcomes from an assessment at one level could differ from the others. In conclusion, different aspects will be significant for
different methods or tools. Note that the system boundaries of the narrow life-cycle level (Figure 1) are, from the building sector’s point of view, presented from a material inflow perspective. A study based on an outflow perspective could, consequently, include processes such as disposal and refinement. To cover the wide spectrum of environmental impacts, the evaluation techniques should include levels other than the dominant material level. In all studies, when deciding on methodology, perspectives and system boundaries, the principle outcomes of the study will be influenced to a large extent. How to define the system boundaries, that is on which assessment level a study should be performed, is a critical decision and determines what possibly could be investigated. Applying different systems boundaries to the same problem will emphasise different issues and could therefore contribute to a broader basis in the decision-making process. There will probably not be a straightforward answer to the question of an environmental assessment. Nevertheless, using this proposed framework for environmental assessment the knowledge and information could be built up sequentially by applying studies at each level.

For discussing the pollution aspects of reuse, it seems like the material level and the local environment level would be the most appropriate, because the system boundaries are narrow enough to focus on a local scale (Figure 1). On the other hand, studies performed at the narrow life-cycle level and at the industrial system level could additionally include the utilisation of natural resources and thereby address a much broader spectrum of environmental issues (Figure 1; Table 1).

Table 1: An overview of possible environmental aspects, methods and results, for each assessment level in the framework. After [2].

<table>
<thead>
<tr>
<th>Environmental aspects addressed</th>
<th>The material level</th>
<th>The local environment level</th>
<th>The narrow life-cycle level</th>
<th>The industrial system level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental aspects addressed</td>
<td>Total chemical content and leaching behavior</td>
<td>The materials in use and their spatial context</td>
<td>Key environmental aspects during a part of the life-cycle</td>
<td>Overall environmental aspects</td>
</tr>
<tr>
<td>Addressing environmental pollution?</td>
<td>Yes</td>
<td>Yes</td>
<td>Partly</td>
<td>Partly</td>
</tr>
<tr>
<td>Addressing the use of natural resources?</td>
<td>No</td>
<td>Partly</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Example of methods/tools</td>
<td>Chemical analysis</td>
<td>EIA, SFA</td>
<td>LCA, EIA</td>
<td>SEA, LCA</td>
</tr>
<tr>
<td>Results of an environmental assessment</td>
<td>Contingent upon values, dependent on substances studied</td>
<td>Contingent upon values, dependent on substances studied</td>
<td>Contingent upon values, dependent on selected parameters, system boundaries and allocation principles</td>
<td>Contingent upon values, dependent on system boundaries</td>
</tr>
</tbody>
</table>

For example, one of the main reasons stated in favour of use of industrial by-products in road construction in Sweden is that the use of natural gravel impairs the supply of high quality drinking water because that the boulder-ridges where the drinking water is taken out consists of natural gravel. Therefore, there is a conflict between the possible environmental benefits of replacing natural gravel and the pollution of the road environment originating from
the by-products. This conflict has to be addressed by using methods that allow wide system boundaries. Moreover, to at all include the environmental benefits of used building materials and use of industrial by-products in environmental assessments, the broader system boundaries in narrow life-cycle level and the industrial system level must be used.

However, at all levels, environmental assessment is partly a matter of values. As a matter of fact, the results from a study have to be interpreted and valued according to which environmental pressure is considered most important. This will also indicate different measures. Therefore it is essential for decision-making in this field, that we develop the mainstream environmental assessments. Using wider system boundaries would improve the basis for decision-making.

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