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Management system for building materials as a basis for closed loop material flow analysis considering material efficiency and climate change mitigation

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Abstract. Resource management is becoming increasingly important in the construction sector. In order to support the recycling of materials, it is necessary to determine the quantities in the building stock and those caused by construction activities. At present, a large number of different actors use different categories for construction materials and the raw materials they consist of as well as for waste categories, depending on their field of activity. This results in imprecisions that make it difficult to consistently track and influence mass flows and hinder targeted resource management. This is the starting point of this paper as it discusses possibilities to establish a consistent allocation of materials to context-typical groups following the approach of continuous material flow analysis. On the input-side, aspects of mineral planning and on the output-side aspects of waste and secondary raw material management are being considered and references to grey emissions are established along the entire process chain. In this way, cross-departmental planning relating to recycling management and climate protection will be supported. With regard to the object of consideration and the level of action, a distinction is made between two different spatial scale levels: on the one hand, the individual building level, where the material inventory approach is used to provide detailed information on the building's material composition, and on the other hand the regional level, for which more aggregated information on building material groups is provided in the form of material cadastres. Current results of a research project in Germany are presented.

1. Introduction

1.1. Context

The construction sector is the main cause of anthropogenic material flows [1], which affect the use of natural resources and the climate [2]. The sustainable management of these flows must be guided by the principles of conserving natural resources and minimising undesirable effects on the global and local environment resulting from the production, use, recycling and end of life processes of building materials. Starting points are (1) the slowing down and closing of material cycles and (2) the development of suitable management structures from raw material extraction to urban mining. Two levels are being considered: (a) individual buildings and (b) regional building stocks. Active resource management at these levels is currently still hindered by (1) a large number of actors involved and a lack of incentives to create and maintain standardised material information/documentation, (2) interrupted information flows, and (3) a lack of a system of categories/identifiers and (waste) code numbers that allow a continuous tracking of material flows. This paper therefore presents a corresponding classification of categories/identifiers for resources, materials and waste categories, which were developed in a project founded by the German Federal Environment Agency [3]. A contribution is made to "determining, assessing and influencing resource utilization and environmental pollution caused by buildings and their supporting infrastructures" in accordance with the Graz Declaration for Climate Protection in the Built Environment [4]. The aim is to create the conditions for a transformation towards low-carbon and climate-friendly construction - see conference topic 4 "Urban metabolism and circularity" of WSBE20 and SDG 12 "Responsible consumption and production" [5]. There are also references to the indicators of SDG 11 and SDG 13.

1.2. Information needs of relevant actors and decision-makers

The selection of materials and the influencing of regional material flows is a design, planning and management task. This presupposes that the respective decision-makers have suitable information at their disposal and are able to assess the effects of their decisions. At the level of individual buildings, the interest of designers, building owners, value analysts and banks in information on the material composition and subsequent separability is growing in connection with sustainability assessments (assessment of environmental performance and carbon footprint, environmental and health compatibility, de-constructability, recycling potential, risks to the environment and health). This is part of the tasks of the life cycle analysis accompanying the design process as well as the object documentation (building file).

On the building stock level, there are three main areas for which material-related information on the building stock and its dynamic development are of interest: (1) the regional planning responsible for securing the supply of mineral building materials (requires the handling of raw material categories), (2) the waste management responsible for the recycling of outflows (requires the handling of waste categories and pollutant-related risk assessments with regard to recyclability), and (3) comprehensive municipal planning units with responsibility for sustainability topics like climate protection programmes (requires the handling of material-related, climate-relevant emissions) [5].

This clearly shows that there is a growing need for a suitable basis for the continuous capturing, evaluation and targeted influencing of material flows.

2. Methodology

The underlying methodology follows the principle of continuous material flow analysis, in accordance with [7]. Material flows induced by the production, use, recycling and end of life processes of construction materials and products are analysed and quantified in successive process steps. This includes a transition from one category (natural resources / raw materials / building materials / construction and demolition waste / secondary materials) to the next. Starting point are typical building materials, the analysis of which is extended to the up- and downstream processes. With regard to the composition of the construction materials, typical recipes are taken into account. From this, types of raw materials are determined, the relevant information basis for national sustainability reporting [8] as well as national and regional mineral planning [9][10]. The correlation between building materials and the outflow-related categories is ensured by classifying building materials according to the system of European waste codes [11]. These are discussed and, if necessary, modified with regard to their suitability for providing necessary information to support the recycling industry in the management of construction and demolition materials for the production of secondary raw materials. The provision and processing of materials is carried out using energy and is accompanied by chemical processes (e.g. calcination of cement). In the process, Greenhouse gases (GHG) are released. Information on the "objectified energy input" and "objectified greenhouse gas emissions" is recorded and taken into account in addition to the resource-related data using LCA.

3. Results - Concept for an information management with regard to material flows

The information management system required for the conservation of resources - see also figure 1 - serves (A) to secure a supply of primary and secondary raw materials, (B) to facilitate a material accounting system at the regional level using the material cadastre (I) and at the level of individual buildings using the material inventories (II); and (C) to support recycling and waste management. In addition to the flow of materials from the point of extraction from to their final return to the environment, emissions arising during the life cycle of the materials are also recorded (6).

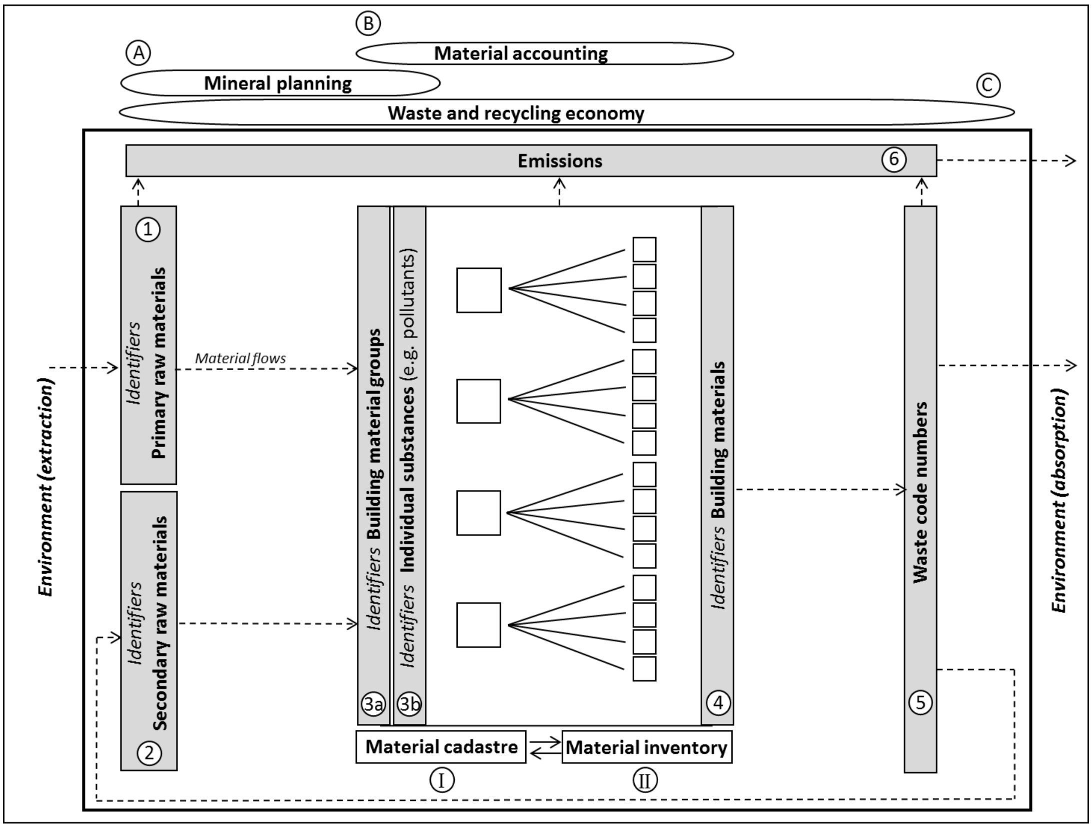

Figure 1. Concept for the application and adaptation of material categories for material cadastres (regional level) and material inventories (building level)

The information management required to control material flows has so far been hindered by the lack of a consistent system of “identifiers” for resource categories, types of materials and sorts of waste. The proposed solution is based on a system of "identifiers" for resources or respectively raw material groups (1), which serve to describe the extraction of raw materials from the environment. They can be traced back as well as transferred to the "identifiers" of material groups (3a), which are required for the creation and use of regional material cadastres (I). For building-specific material inventories, more differentiated "identifiers" are used for building materials/construction products (4), to which the name of product and manufacturer can also be assigned. Identifiers of individual substances (3b) are used to represent impurities and pollutants. These can also be used to describe risks associated with elution, gas release and hazardous substances. The waste categories themselves are identified by means of an adapted system of waste code numbers, from which recycling or disposal paths can be derived.

4. Discussion

The presented concept aims at providing information for the management of materials and material flows for relevant actors at different stages of the value chain (see introduction section). This results in requirements for the differentiation of categories for the description of raw materials, building materials, construction and demolition (C&D) waste and secondary materials. Alternative approaches, as they are considered in other literature regarding the topic, are included in the discussion below.

4.1. Natural resources / Raw materials

National reports on resource use are usually based on the EU-wide harmonised method of economy-wide material flow analysis (ewMFA) [13][14]. The extraction of raw materials from nature and the import of goods, changes in the stock of goods within society and the release of waste and emissions into nature or exports are taken into account [12]. In principle, "materials in goods" and "raw materials" are put into correlation here. However, this is not always done consistently in reporting. For example, natural raw materials (e.g. iron ore) are included under raw materials in the same way as processed materials (iron and steel) [13]. The degree of differentiation of this method is also limited, e.g. only correlations with the construction sector as a whole can be established, but not individual sub-sectors such as the construction of residential or non-residential buildings or infrastructure. This also means that further differentiation according to sub-markets and sectors and the associated building typologies, which in some cases differ significantly in terms of the materials used - e.g. single-family and multi-family houses or factory and workshop buildings, retail and storage buildings, agricultural service buildings, etc. - is not possible. This method is also limited in terms of spatial differentiation. A further weakness of this method is that only flows can be depicted, but not stocks [15].

Another approach to be considered is the MIPS method. MIPS indicates – among other aspects - the quantity of abiotic and biotic resources used for a specific product or service [16]. According to this, MIPS is not a pure accounting approach but claims to provide an ecological evaluation of products. For this purpose, all materials, which are moved during the manufacture of the product, are taken into account when calculating the material intensity, regardless of whether they are included in the product. MIPS is "substance non-specific". Only rough resource categories, e.g. abiotic and biotic, are used. It is not possible to differentiate between resource categories as used in mineral planning (e.g. gravel, sand, crushed natural stone).

The concept presented in this paper is consistently oriented towards management tasks. Information regarding the demand for raw materials and their use primarily addresses actors in mineral planning. The approach follows the principle of bottom-up MFA. This enables the differentiated mapping of building materials contained in building stocks or individual buildings. A further disaggregation of the materials, using recipes or bills of material, allows a further differentiation of raw materials, which meets the requirements of mineral planning. For example, quantities of concrete can be used to determine the need for gravel and sand, and windows can be used to determine the need for wood and glass.

However, the quantities determined in this way remain incomplete, as the recipes do not take into account losses that can occur in production processes. One solution is to use additions based on average wastage and breakage losses or average transport and assembly losses.

4.2. Building materials / construction products

The literature on MFA with reference to the built environment offers very different classifications for building materials (an overview is provided by [16]). Material designators follow different approaches. They describe, among other things, functions (e.g. insulation material), essential characteristics (heavy versus light), production processes (blast furnace cement), the installation location (e.g. between rafters / roof insulation), or raw materials and building materials respectively (e.g. PVC pipe, aluminium frame). As a rule, references are made to a few main material groups, but in further differentiation it remains inconsistent. References to other categories such as secondary materials (e.g. recycled concrete) remain the exception.

The categories proposed here for the labelling of construction products (definition according to [23]) aim to ensure the most appropriate allocation possible concerning the raw materials used and the material categories as apply after their having been used as construction materials, such as C&D waste categories and secondary materials. This results in the minimum differentiation requirement of the building material categories for the material description of building types. So far, this approach has been implemented with regard to the structural works of buildings. In principle, it can also be applied to building services systems, and although the knowledge base for this is much weaker, reference can be made to individual works [24][25].

At the level of individual buildings, further information is added, in particular with regard to the content of additives. This information can be taken from detailed material data sheets published by manufacturers of building materials (an example for such a data sheet can be found under **Fehler! Verweisquelle konnte nicht gefunden werden.**). In order to establish a relation to this information, detailed manufacturer names and product designations are therefore additionally recorded and communicated in material inventories for individual buildings. Alternatively, pollutant contents and risks for building types can be derived from information on construction methods and construction periods or from corresponding representative building types (archetypes).

4.3. Waste and secondary materials

The number of MFA studies supporting C&D waste management is substantial. However, references to C&D waste categories are usually not explicitly made [18][19]. The approach presented here, though, makes this allocation and extends the categories to be able to establish correlations with categories that waste managers use. In practice, the assignment of building material outflows induced by demolition activities to C&D categories is not clearly defined. The waste manager is left with a certain margin of discretion. These remaining uncertainties are countered with clear assignments by experts integrated in the research project with many years of experience in practice-oriented research on waste management. As described above in the section "methodology", a further development and differentiation of the C&D waste codes is proposed, which will enable a better assessment of the recycling potential of the waste fractions. – for example, the subdivision of the category "masonry waste" into bricks, sand-lime bricks, aerated concrete blocks, concrete blocks, adobes and bricks filled with insulation.

Construction and demolition waste is not the same as secondary materials. The latter arise as a product of waste treatment processes. In the present concept, these processes and the resulting secondary materials are taken into account.

The conceptual transition between C&D Waste and secondary resources has not yet been resolved satisfactorily. Secondary resources are still considered waste until they are used in new products. The main reason for this lies in waste legislation, which provides the framework for this. Under German waste law, the waste status of a material ends when it has undergone a recycling process. In addition, there must be a purpose for the material and a corresponding market – i.e., a potential demand. The material must have the appropriate technical properties. Its use must not lead to harmful effects on humans or the environment [26]. The "value" of a substance is thus very closely linked to its intended use, which also results in quality requirements. To date, no regulations exist which clearly describe these references so that they meet the requirements of waste law to the extent that the waste characteristic is no longer applicable. The example of recycling aggregates illustrates this clearly. Certification systems with corresponding CE markings have been developed and standards defined for different areas of application such as use in concrete (DIN EN 12620) or asphalt (DIN EN 13043). Nevertheless, RC aggregates remain in the waste regime and remain waste until they are incorporated into the new building product (concrete or asphalt). Only in individual cases was it possible to define deviating regulations. This is illustrated by the example of plaster. On the initiative of the plaster industry, it has been possible to define criteria that define the end of the waste status of RC plaster before it is used in the production of new plaster building materials. However, this required close coordination between the building materials industry, the recycling industry and the regulatory authorities in relation to a clearly defined application. For the system of material designators, this means that references between waste categories and secondary raw material categories must be established as the basis for a description of the references between material, intended use and resulting technical requirements. In this context, experience and orientation values as published in studies that describe the corresponding processes in general terms can be used [7][20]. In order to derive the end-of-waste criteria from this, the coordination between the industries and authorities involved is additionally required as described above for the example of plaster.

4.4. Emissions
Environmental impacts due to climate-relevant emissions can be taken into account by correlating the material categories with processes from LCA databases. The bottom-up MFA method used here can be interpreted as a life cycle inventory analysis (LCI) according to ISO 14040, ISO 14044 [21][22][27] . This is followed by the life cycle impact analysis (LCIA), which quantifies the related environmental impacts. This makes it possible to combine the goal of resource conservation with the goal of climate protection [28].

The clarification or specification of terms and categories for determining the type and quantity of materials used is currently being driven forward by the increased use of Building Information Modeling (BIM). BIM virtually forces the use of unambiguous terms/identifiers. In this context, international standardisation work has begun to make environmentally relevant information on building materials / building products "BIM-able" [31] It can be assumed that BIM can support resource management in the life cycle of buildings in the future.

5. Conclusions
The paper shows how the idea of continuous material flow analysis could be used to categorise materials in order to meet the sometimes interdisciplinary information requirements of groups of actors such as planners, waste management companies, etc. The combination of nuanced building-related information and information regarding the regional building stock allows an active and continuous resource management. In particular, material requirements (input) and accumulation of materials (output) can be described on the level of raw materials, building materials and waste categories, and regional material stocks can be recorded and analysed in their dynamics.
In addition to a standardisation of the systematics of identifiers for resources and materials, a further development of the waste categories of the regulation via the European Waste Catalogue is recommended. Here, a stronger focus should be placed on possible recycling options for the materials.

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