Development of a Raw Material Model for Urban Systems – A Contribution to Support Material Flow Analysis and Resource Management

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Summary

The major aim of this project is to analyse the raw material flows over the whole life cycle of urban areas. The basis for this inventory sets the identification of what types of materials and how much are contained in different building types and selected infrastructure of the German building stock. Furthermore a developed life cycle model can give an indication at what times raw materials are required (e.g. insulation for retrofit measures), and when raw materials become available again, for recycling or disposal, after the end of life of individual components of the analysed area.

Keywords: Resource efficiency, material flow analysis, urban mining, raw material use, construction materials

1. Introduction

According to estimates of the German Federal Ministry for the Environment, the German building stock contains around 10.5 billion tonnes of mineral building materials, around 220 million tonnes of timber products and around 100 million tonnes of metals. Due to continuous building activities, especially renovation and retrofit measures, it is estimated that this raw material stock will grow by a further 20% until 2050 [1]. The building sector is one of the most resource intensive economic sectors in Germany. The German National Strategy for Sustainable Development sets targets of doubling the raw material productivity until 2020 based on 1994 levels [2]. The developed raw material flow model for the building industry that is described within this paper can aid in reaching these proposed targets.

2. Model Development

The major aim of this project is to analyse the construction related material flows over the whole life cycle of urban areas. The basis for this inventory sets the identification of what types of materials and how much are contained in different residential building types of the German building stock and selected infrastructure such as roads. Furthermore a developed life cycle model can give an indication at what times raw materials are required (e.g. insulation for retrofit, or new construction), and when raw materials and potential pollutants become available again, for recycling or disposal, after the end of life of individual components of the analysed area.

The developed raw material cadastre can then be integrated into geographic information systems (GIS), such as the CityGML standard as an additional layer and be linked to energy information for example (e.g. heating demand), to analyse the influence of raw material flows on the energy consumption of individual buildings and the analysed area as a whole. As the individual material flows (life cycle inventory) will be identified, it will also be possible to link this information to life cycle assessment (LCA) data to identify the environmental impacts (e.g. CO_2 emissions) the continuous changes of urban systems and the anthropogenic stock may have.

This integrated approach is not only examining the life cycle of material flows of urban systems over time, but it also tries to link and provide an interface to existing systems and calculation methods, to move towards rating the overall resource efficiency over time. As stated in VDI 4800, a conclusive rating of the overall resource efficiency of systems can only be achieved if the use of all natural resources is being quantified and then placed into relation with each other [3].

3. References

[1] Internationaler Ressourceneffizienzatlas (2011), http://www.ressourceneffizienzatlas.de/beispiele/strategien/detail/article/urban-mining-staedte-als-rohstoffquelle.html (Accessed on 20.03.2015)

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[3] VDI Richtlinie 4800 (2014), Ressourceneffizienz - Methodische Grundlagen, Prinzipien und Strategien

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The continuous spatial-temporal model will be able to capture how urban spaces change over time, from a raw material perspective. The 3D/4D model will be feed with actual data, where 3D indicates the spatial dimension, such as building geometries obtained from 3D city models (e.g. CityGML standard) and the fourth dimension (4D) represents the temporal dimension.

The object orientated modelling language, Universal Modelling Language (UML) was chosen to link the relevant attributes and influence factors which represent the complex structure of urban systems. This object orientated approach is a transdisciplinary approach and allows room for future expansion to provide a link to other models, beyond the system boundaries of this project. These links are very important as many different factors from different disciplines need to be considered to accurately model the dynamics of changing complex systems, in this case urban spaces.

3. Methodology

A combination of bottom-up- and top-down-assessment is used to identify the material flows.
The bottom-up-method aggregates the composition of individual buildings and infrastructure, such as roads. Existing information on the material composition of building categories (typologies), grouped by building age and type will be used to feed the model. This includes existing datasets, such as the catalogue of the “Institut für Ökologische Raumentwicklung (IÖR)” or “Institut für Wohnen und Umwelt (IWU)” typologies. Data for the primary energy consumption of different building types and standard building components for example can also be abstracted from these sources. Historical data, life-cycle-assessment data of individual buildings, demolition data and case studies will also be used.

The top-down-method will make use of national statistics, such as production figures for the selected raw materials.

3.1 Bottom Up Approach

For the bottom-up approach GIS has shown to be an ideal tool, as unlimited building information, not only on material consumption can be added to 3D city models. Building geometry and the geometry of individual components (e.g. wall areas, window area, roof area and type and other information) will be taken from existing 3D/4D city models, depending on the available level of detail (LOD). For many parts of Germany a comprehensive LOD 2 model is available, which has an accuracy of about 1 meter and shows a buildings individual roof type. LOD 3 models have a higher accuracy, and can show individual openings of facades (e.g. windows and doors). LOD 4, also referred to as walkable architectural models can provide information such as a building's interior.

Developments in GIS and Building Information Modelling (BIM) methods have made it possible to construct higher level of detail (LOD) models, such as full architectural models. With the aid of 3D surveying techniques, which create so called point-clouds, these higher level of detail models can be constructed. This process is however very time consuming and expensive, especially when looking at the scale of a city or cluster. For these reasons LOD 2 models will be used as input data for the model.

Together with the building age and type, combined with material composition data extrapolations on the construction stock can be made. An example of the results of one case study is shown in Table 1, where detailed information on materials in a multi-family building in Munich constructed in 1962 has been collected.

Table 1: Material consumption of a multi-family dwelling constructed in 1962

			Material Intensity	
Material	Total Weight (t)	Total Weight (%)	(t/m² BGF)	(t/m³ BRI)
Bitumen	4,3	0,07	0,0008	0,0003
Insulation	22,0	0,34	0,0039	0,0015
Ferrous metals	148,6	2,32	0,0266	0,0101
Glass	5,6	0,09	0,0010	0,0004
Timber	54,6	0,85	0,0098	0,0037
Plastics	3,0	0,05	0,0005	0,0002
Copper	1,1	0,02	0,0002	0,0001
Mineral	6156,9	96,26	1,1023	0,4167
Sum	6396,2	100,00	1,1451	0,4329

By calculating the material intensities (e.g. t/m² or t/m³) of the relevant material groups, extrapolations based on the floor area and the buildings volume can be made. When taking an estimated buildings service life of 80 years. It becomes apparent that in 2042 around 6400 tonnes of material will be available for the circular economy just from the single building mentioned in this example.

The majority, namely 96% of the buildings mass, is of mineral composition, such as concrete, tiles, bricks, and mortar. The second largest portion consists of around 140 tonnes of ferrous metals, which mainly come from reinforcement bars, radiators, and pipes. Not all of the ferrous metals can be recovered at the end, due to natural corrosion processes, which have and still are giving of fractions of the metals to the environment.

A relative small proportion of copper based materials are mainly found in electric wiring. The mass of copper for the electric wiring has been calculated from electrician bills, as part of the buildings refurbishment in the last decade. Around 0.2 kg/m² floor area of copper has been additionally incorporated into the building. This amount, minus the losses through corrosion and weathering processes, will become available after the buildings demolition. This amounts to over 1 t of copper that is currently in stored in the anthropogenic stock, which exceeds the natural concentration of copper in the earth's crust.

Timber based materials, mainly from the roof structure account for nearly 55 tonnes in this particular case. However, as the roof was constructed in the 1980ies, timber treatment has been used, especially for the structural elements, which nowadays is regarded as potentially harmful to humans and the environment.

With the current stand of standard 3D city models it is not possible to look inside a building, to identify the volume of inside walls or wall thicknesses for example. Wall thicknesses need to be taken from building typologies or estimated. The proportion of inside walls can be estimated, when taking standard values for the construction area. The Baukosteninformationszentrum (BKI) provides conversion factors for building areas and volumes, which are based on their extensive database. An example would be that the gross floor area translates to around 16-22% of construction area for single family dwellings. For multi-family dwellings this ratio translates to around 13 -16% [4]. These values have been checked within the case studies and coincide with data from the BKI.

3.2 Top Down Approach

The top down approach makes use of national statistics, such as production and demolition figures, just to name a few. A material flow analysis of mineral construction materials for the year 2012 has shown, that by balancing the in- and outputs of the system, the building stock has increased by 425 million tonnes of mineral material during that specific year. The total input of mineral materials for the same year was around 485 million tonnes. Around 60 million tonnes leave the system boundaries, which has been set as the German construction industry. Figure 1 shows the mineral flows within the German construction industry for 2012. The data for this particular case was taken from the Bundesverband Baustoffe – Steine und Erden e.V. [5].

The majority of recycled material content has been reused in the infrastructure sector, mainly road construction and earth works. Unfortunately statistics do not always differentiate between building construction and civil engineering activities. It is also questionable if using demolition waste for filling voids in road or landfill construction can be regarded as recycling. However, by using demolition waste for these applications, the primary material use can be reduced, without the requirement of a high energy input. However, one goal of the circular economy is to promote cascade use of materials and prevent a too high ratio of down-cycling.

3.3 Life Cycle Assessment

Once the material flows (life cycle inventory) are identified and the top-down and bottom-up analysis have been compared the next step is to conduct a life cycle assessment (LCA). The basis for life cycle assessment data will be the Ökobau.dat, a freely available German life cycle database, which contains data on most building materials used in the German construction industry [6]. With the aid of this datasets it will be possible to calculate indicators such as CO_2 emissions and embodied energy, which is the energy that is required to provide the materials. Also resource related indicators, such as the ADPelements (APDe), which purely rates the raw material consumption based on a reference material, can also be identified. The LCA will be based on international standards (ISO 14040 and ISO 14044) and will be in line with the criterias of the German building rating systems DGNB (German Sustainable Building Council) and BNB (Bewertungssystem Nachhaltiges Bauen).

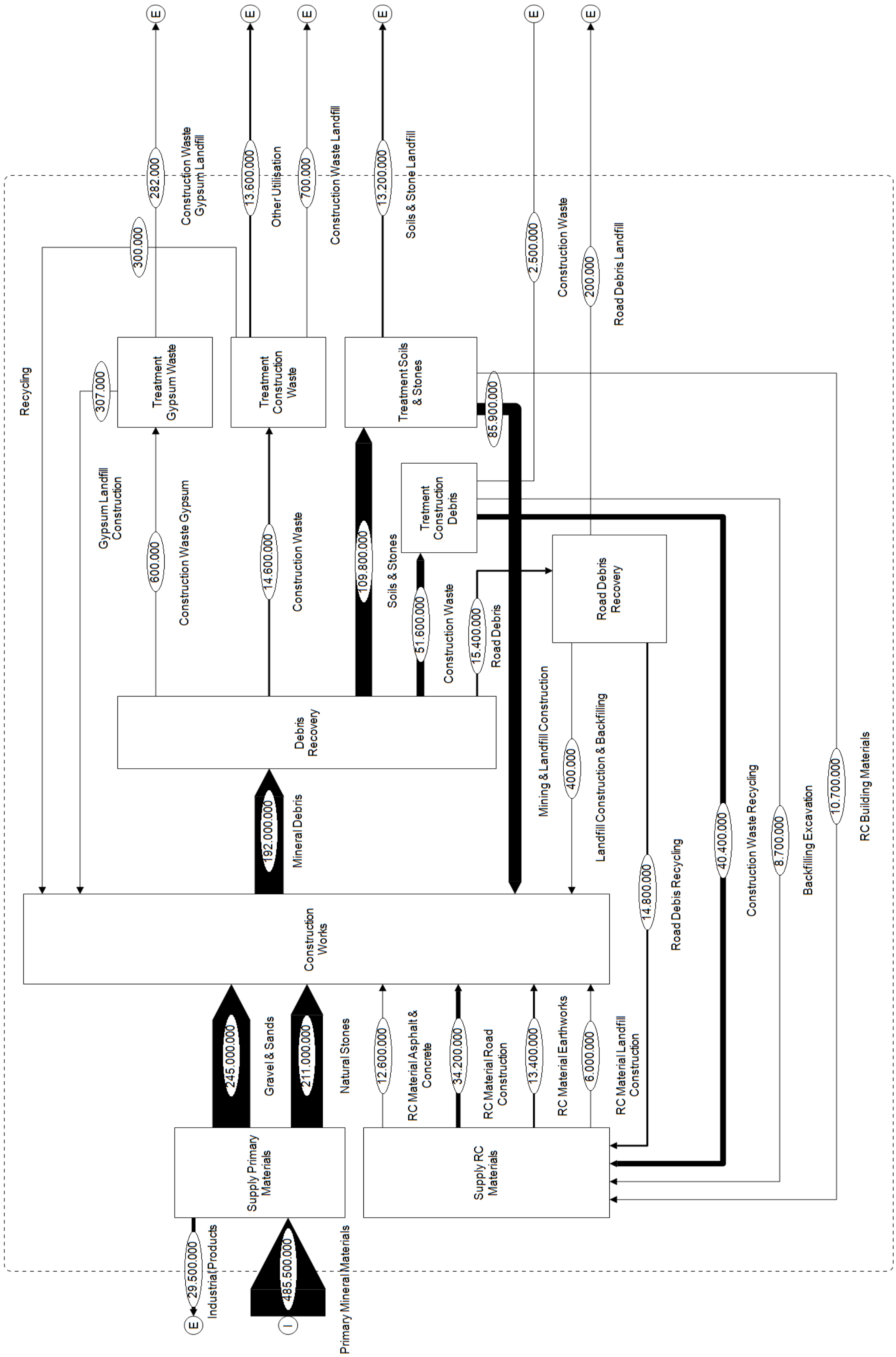

Fig. 1 Mineral material flows within the German construction sector for 2012 in tonnes/year (t/a) (Data from [5])

3.4 Potential Pollutants

A closer examination of potential pollutants that may be contained within the materials and demolition debris (e.g. asbestos, PCB) and the quality and purity of materials is also a very important factor for the integral model. These factors, among others, determine the future recycling options a material may have.

Especially buildings that have been constructed in the 1960s and 70s, that are now ready for retrofitting or demolition contain a variety of potentially harmful and hazardous substances that need to be properly recycled or landfilled. From experience, it will not be possible to calculate actual expected masses and concentrations of pollutants, as these need to be assessed on an individual building scale. Nevertheless, assumptions can be made on the probabilities that these substances arise based on the buildings age and area of application (e.g. building component). Buildings constructed after a certain date, after the use of materials containing potential pollutants have been prohibited, are likely not to contain these substances. Whereas buildings constructed before a ban on use has been pronounced may contain pollutants. Pollutants could have not just been introduced when the building was constructed, but also through renovation- and retrofit measures. An overview of selected pollutants found in buildings is shown in Table 2.

Table 2: Selected pollutants: Timespan of application in Germany

Pollutant	Examples of Application	Application		Prohibiting manufacture	Ban on use
		Since	Until		
Asbestos	Facade, cement additive, flooring, insulation	1920		1993	1993
Synthetic mineral fibres	Insulated building parts (e.g. walls, roof)	1900	1996	2000	2000
Pentachlorophenol (PCP)	Timber treatment			1989	1989
Polychlorinated biphenyl (PCB)	Seals, paints, plastics	1929		1989	1989
Polycyclic aromatic hydrocarbons (PAK)	Glue, tar products (e.g. roofing, asphalt)	1850		1970	
Lindane	Timber treatment	1950s		1984	2006

3.5 Separability

The separability of individual building components is also directly related to the quality of individual materials. As the connection between the individual layers of building components play a vital role in the way the material can be recycled or disposed of. The ability of a building component to be dismantled in an efficient way in the end of life phase sets the path for future recycling options and raw material flows. One way to address this issue in a way that is feasible for this model is to examine standard construction techniques and building components of the relevant age groups.

4. Application Potentials

Rising commodity prices, scarcity of raw materials, and the dependency on material exports are the main drivers for the development of this model. The developed model aims at analysing the material flows of the construction industry in Germany as well as the environmental effects that are caused by these flows. Upon completion the information can be used for the formulation of political goals and their verification. By identifying potential vulnerabilities, measures for system optimisation can be identified. The collection and evaluation of material flows provides a base for this analysis.

Demolition- and commodity companies, as well as recycling- and circular economy industries can gain an overview of potential future mass flows of construction related materials and pollutants (e.g. asbestos). Through the prediction of future demolition wastes, assessments of potential recycling flows and the quality of recycling material can be derived, as well as an assessment of the future need for additional locations for raw material mines, landfills and recycling systems. This information can also aid in the development of new recycling methods, if economically viable quantities of a particular substance or material are identified.

In Austria for example, material flow analysis has successfully been used in the development of the national environmental plan.

On the scale of the property owner, an assessment can be made on the exploration potential of their asset, which can be translated into economic benefits or burdens. Economic burdens can occur if potentially hazardous substances need to treated or deposited on landfills.

5. Further Discussion

It is important to trace resources, in this case building materials and its raw material components not only in a spatial dimension, but also over time. As an indication can be derived at what times materials and potential pollutants from buildings become available for further use, such as a substitute for primary raw materials, further treatment or disposal on landfill sites. In a further step, the gained information from this model can also be used to identify the radial distance where it is still feasible to use secondary raw materials as opposed to primary material resources within the individual material fractions.

In our built environment most elements represented by the periodic table can be found in element or in compound form. However, only a small fraction of material flows for individual substances have been identified on a national or international scale, let alone on a regional scale. Knowing these flows is however fundamental to create a model, which is looking at multiple flows of different materials. Steel alone, depending on the type consists of more than 20 individual elements, some of which may not be recovered through recycling.

6. Acknowledgements

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