# THE OTHER "HALF OF THE CITY" – ANALYSIS OF NON-RESIDENTIAL BUILDING STOCK AND ITS MATERIALS

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## Abstract

The building sector consumes large quantities of resources and generates high levels of C&D waste. From the perspective of Urban Mining, the building stock is seen as a repository of secondary resources. To better manage this repository, we require knowledge of its quantity and dynamics. While a wide range of data is available on residential buildings, little is known about non-residential buildings. Taking the example of Germany, a method is presented to quantify the material stock of non-residential buildings using a Bottom-up approach. The Bottom-up approach includes three parts: First, material composition indicators (MCI) with respect to various building types; second, the country's total floor space, and finally, the total material stock. The paper presented here focusses on the calculation method to obtain building type specific MCIs. The main results are MCIs for each building type as well as the material mass in total. In Germany the total material mass of non-residential buildings is approximately 6.8 billion tons, accounting for 44% of the entire building stock. These results indicate the significance of the embedded natural resources. Thus, a greater focus on the non-residential building stock would improve the efficient use of resources.

## 1. Introduction

One of the greatest challenges of our time is to preserve our natural resources and ensure that we consume these as efficiently as possible. The building stock plays a crucial role in this respect as it is one of the most significant energy consumers (e.g. D&R, 2012; Economidou *et al.*, 2011), represents a vast amount of societal wealth, constitutes one of the largest anthropogenic repositories of raw materials (e.g. Kovacic, 2007) and generates high levels of construction and demolition (C&D) waste. Current discussions on the building stock generally focus on energy consumption (e.g. Rickaby & Gorgolewski, 2000), with considerations of resource efficiency taking a back seat. The concept of Urban Mining can help to shift this focus by viewing buildings as raw material repositories whose intelligent management has tremendous potential for conserving our reserves of raw materials (Kleemann *et al.*, 2014; Brunner, 2011; Lichtensteiger, 2006). Urban Mining aims to bring the materials released by buildings back into circulation. This requires information on the stock and its dynamics (e.g. Kohler & Hassler, 2002; Kohler & Yang, 2007).

A great deal of research has already been undertaken on the material stock and flows of residential buildings (RB) (e.g. Gruhler *et al.*, 2002; Kohler & Hassler, 2002, Bergsdal *et al.*, 2007; Kohler & Yang, 2007; Deilmann, *et al.*, 2009; Hu *et al.*, 2010). By contrast, little is known about non-residential buildings (NRB), although they account for approximately half of the total building stock (in terms of floor space) in many European countries (Kohler *et al.*, 2009; see section 2). Reflecting the range of functions they provide, non-RBs are heterogeneous in terms of types of construction, rendering their systematic description more difficult.

This background provides the motivation for the research presented in this article. A method is described to quantify the material stock of the national NRB stock, illustrated here by analysing the situation in Germany. The biggest hurdle to be overcome in any such attempt is the lack of empirical data. For example, in Germany there are no official statistics serving to quantify the NRB stock such as floor space in m². The same is true for material types and amounts. To resolve this problem, a method was developed to indirectly quantify the material stock of NRBs. This can be broken down into three steps: First, material composition indicators are calculated in t/m² floor space with respect to various NRB types. The building typology used for this reflects the different forms of use of NRBs (e.g. office blocks, agricultural buildings, factories, hospitals, etc.) as specified by official statistics. Second, the total floor space of NRBs is estimated and broken down according to the defined building types. Third, the total material stock is determined by combining the results of the previous two steps. In the following, this method is described in detail. Then results are discussed concerning their plausibility and validity, the significance for Urban Mining considering resource efficiency aspects and the method's applicability to analysing materials in the NRB stocks at European and indeed global level. The paper ends with some conclusions regarding the use of findings to support strategic planning issues, the need for additional knowledge on the NRB stock as well as ways in which the presented research and methods can help to move the discussion forward. However, the paper first gives an overview of the current state of research into the stock of NRBs and its material composition.

## 2. Literature Review

### 2.1 Classifying and quantifying the NRB stock

In contrast to the RB stock, the NRB stock encompasses a wide variety of uses and construction types. One possible approach to describing the heterogeneous NRB stock is to construct a typology of buildings (de Haan *et al.*, 2001). The literature provides a number of different examples of this, which differ according to the objectives pursued with respect to reference area, structural types and system boundaries, e.g. Rußig (1999): three groups of buildings; Gierga & Erhorn (1993): 21 heated non-residential type buildings; Brown *et al.* (2000); Steadman, Bruhns & Gakovic (2000): construction-based types for England/Wales with focus on the building envelope, Deilmann *et al.* (2013) eight main heated NRB categories. Because such typologies and forms of classification have been developed for a range of purposes, they do not provide for easy comparison of data and findings. In most cases, such typologies were devised to investigate questions of energy efficiency or to provide a classification by forms of use. Material-specific typologies in the strict sense are currently unavailable.

While national statistical agencies provide information on the RB stock, there is a general lack of data on the stock of NRBs (e.g. Rußig, 1999). Only a small number of studies have attempted to fill this gap by providing estimates of building stocks, for example in Austria, Switzerland, Germany, France, United Kingdom, Italy, Spain and New Zealand. In most cases, these studies have focused on a particular building sector such as heated NRBs or social infrastructure rather than the entire stock.

A few studies have investigated Germany's entire NRB stock. Kohler *et al.* (1999) estimated the floor space in Germany's entire building stock in 1991 at 2,713 million m². Fleckenstein *et al.* (1989) extrapolate from workplace-specific area data taken from sample studies by considering the number of employed persons and estimated the floor space of Germany's NRB stock of 1,534 million m² in 1989. Using data on the gross stock of fixed assets from national accounts[1], Gruhler & Böhm (2011) have quantified Germany's NRB stock for the year 2000 as 2.4 million buildings with a gross volume of 12,777 million m³ and total floor space of 2,146 million m². In addition to various statistics, geodata are also used to estimate parts the stock (e.g. Bischoff & Kohler, 2003; Deilmann *et al.*, 2013). Behnisch & Ultsch (2009) provide an estimate of 38 million buildings for the total number of RBs and NRBs in Germany. In summary, we can say that, owing to the lack of hard data, it is necessary to make estimates of the existing stock of NRBs.

### 2.2 Material composition indicators

Current estimates of the material stock in existing buildings are either derived from macroeconomic statistics (top down) or extrapolated from building-specific data (bottom up). Top-down approaches (e.g. Müller, 2006; Fishman *et al.*, 2014) provide almost no classification by type of materials and are unable to distinguish between different forms of building stock such as RBs and NRBs. By contrast, Bottom-up approaches supply much more detailed information on the constitution of the building stock. The basic principle of the Bottom-up approach is to define indicators that describe characteristic material compositions of typical buildings (material composition indicators – MCIs[2]) as well as indicators to estimate the physical size of the building stock in terms of some particular measure (e.g. floor space). The total amount of the material stock can then be calculated by multiplying the MCIs with the sum total of the respective stock (e.g. Schiller, 2007; Gruhler & Deilmann, 2015).

In the field of industrial ecology, a number of studies have already been undertaken in different countries on the material stock of buildings. Tanikawa *et al.* (2015) provided a good overview of research over the past decade. Despite these diverse approaches to investigating the nature of the building stock and its dynamics (Kohler & Hassler, 2002), the material composition of the stock is still unclear (Kohler & Yang, 2007). This is especially true for the NRB stock (Kleemann *et al.*, 2014).

The researchers use a number of different terms to describe the composition of the material stock. The authors believe that the term "material composition" best fits the context of the current paper. Up to now most studies in the literature, have only investigated the residential stock (e.g. Bergsdal *et al.*, 2007). However, there is a lack of research on MCIs for the analysis of NRBs. Some studies have distinguished between residential and NRBs without further classification of NRB types (e.g. Hong *et al.*, 2014). Other studies have only considered individual materials of particular economic interest such as copper or steel, or have focused on the vast bulk of mineral materials.

Differentiated MCIs for various NRB types are available e.g. for Germany, Austria, France and Japan. However, the Austrian and French studies (Kleemann *et al.*, 2014 and Michel *et al.*, 2012) are limited to city scale. Research on the material composition at national level has only been undertaken in Japan and Germany (Tanikawa *et al.*, 2015; Gruhler & Deilmann, 2015). The Japanese statistical office provides MCI data for different types of construction. As such official statistics are still lacking in Germany, MCIs must be

[1] Germany's national accounts (*Volkswirtschaftliche Gesamtrechnung*, VGR) (Destatis, 2012) are included in the federal statistical yearbooks (*Statistische Jahrbücher des Bundes*) (e.g. Destatis, 2011b).

[2] The authors define MCI as a specific weight of the materials in kg/m².

derived from other sources of data. Thus, Fleckenstein *et al.* (1989) adopt two general raw-material coefficients to analyse non-residential stock, dividing the NRBs only into two groups. They provide coefficients in form of summed non-metallic mineral material quantities without further differentiation. Based on studies of the building stock of a small town, Bischoff & Kohler (2003) provide information on typical materials of building elements, but without any attempt at quantification.

In summary, currently there is a lack of detailed knowledge of the material composition of building stocks in many countries. One central aim of this paper is to provide a method to create such information in the form of detailed indicators to describe the material composition of NRB types taking the German building stock as an example.

## 3. Estimating the floor space

As previously mentioned, the Bottom-up approach is generally suited to calculating materials in the building stock, classified by at least two main categories of use, i.e. residential and non-residential use. Two specifications are required for this Bottom-up approach:

1. a practical measure of the total stock (e.g. m² floor space) and
2. indicators for characteristic material compositions (MCI).

Clearly, the data quantifying the total stock must correlate in some way with the reference quantities captured by the MCIs. In the following subsections, we discuss the applicability of different reference quantities before providing details of the calculation of MCIs for NRBs.

As previously mentioned, in Germany, official data is only available on the stock of RBs. No statistical data exists on the stock of NRBs. Therefore, the authors generated data by a newly developed model using as base data the gross fixed assets of structures as indicated in the national accounts system of Germany and other sources (Schiller *et al.*, 2015). For 2010, their estimate of the total floor space of NRBs in Germany was approximately 3 billion m².

## 4. Material composition indicators for NRBs

The research presented in this paper adopts a three-stage concept to calculate material composition indicators (MCIs) for NRBs (Figure 1).

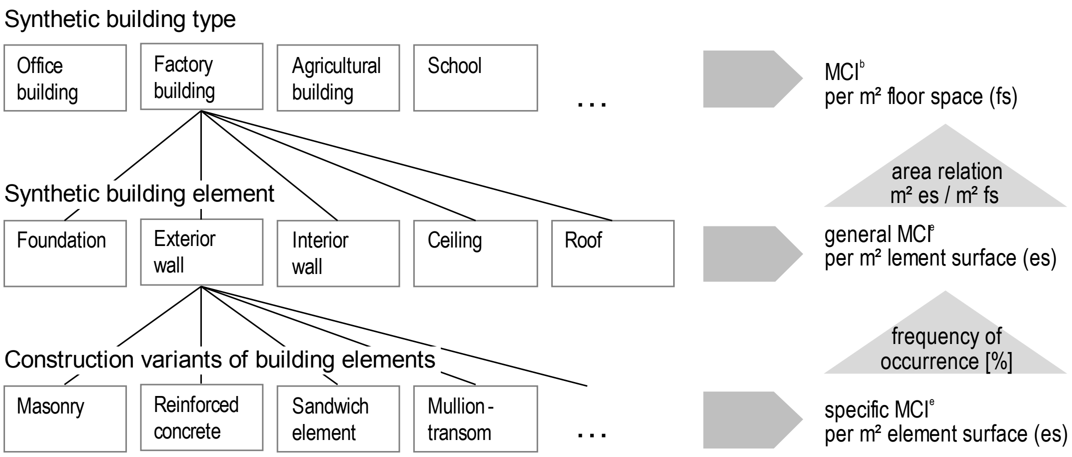


*Figure 1 Modular concept for describing material composition indicators (MCIs)*

The input data is an object database of newly constructed NRBs, compiled and published by the Building Cost Information Centre of the German Chamber of Architects (BKI, 2010, 2012). All BKI data is based on information provided by the planners of these new objects. The BKI database includes about 1,000 NRBs, classified into 38 categories. A date sheet is provided for each object construction plans, general information such as the year of construction, location and type of use, as well as data on areas and volumes, building element descriptions and costs. Eight of these 38 categories (representing 252 objects) were analysed in order to calculate MCIs. The selection was based on a rough estimate of the quantitative relevance (floor space) of the BKI building categories given by Deilmann *et al.* (2013) from an analysis of geodata from four of Germany's federal states. Michel *et al.* (2012) use a similar approach to select the most relevant building to represent the vast bulk of material in Orléans, France. The analysed objects were built in the period 1976 to 2010. The data was supplemented by existing case study findings. Based on these data and density parameters, the first stage involves the determination of MCIs for structural variants of building elements (e.g., exterior wall designed as mullion-transom construction – see **Error! Reference source not found.**).

*Table 1 Composition of the synthetic building element "exterior wall of factory building"*

| construction | frequency of occurrence [%] |
|---|---|
| brickwork, plaster and thermal insulation | 3 |
| brickwork, metal cladding, facing masonry | 12 |
| steel/reinforced concrete construction + brickwork + metal cladding | 35 |
| steel/reinforced concrete construction + sandwich elements / steel sheet cassettes | 35 |
| mullion-transom construction + insulation glazing | 10 |
| glass band / insulation glazing | 5 |
| total | 100 |

The second stage gives a description of general MCIs for building elements by considering the frequency of occurrence of the structural variants within a building element of a specific building type (e.g. exterior wall of a factory building – see Eq. (1)) (Gruhler and Deilmann, 2015). This results in general MCIs for synthetic building elements. A synthetic building element (e.g. exterior wall) represents the average composition of the existing building elements (e.g. concrete wall, brick wall etc.) in a defined building type (e.g. factory building).

$$\text{general } MCI^{e} = \sum_{i}^{n} \alpha_i \times \text{specific } MCI_i^{e} \tag{1}$$

with $\text{general } MCI^{e}$ ... MCI of synthetic building element [kg/m² es]
$i$ ......................... index of construction type
$n$ ........................ number of construction types
$\alpha_i$ ....................... frequency of occurrence [-]
$\text{specific } MCI_i^{e}$ .. MCI of specific building element of construction type $i$ [kg/m² es]

The third stage is to calculate the MCIs for an entire object. This is achieved by considering the ratio of the area of the structural element (m² element surface) to complete building area (m² floor space). The total material indicator of a synthetic building type is the sum of the individual MCIs (correlated to floor space) of each building element (Eq. (2)).

$$MCI^{b} = \sum_{j}^{m} \text{general } MCI_j^{e} \times \frac{es_j}{fs} \tag{2}$$

with $MCI^{b}$ ................ MCI of synthetic building [kg/m² fs]
$j$ ........................ index of synthetic building element
$m$ ....................... number of synthetic building elements
$\text{general } MCI_j^{e}$ ... MCI of synthetic building element $j$ [kg/m² es]
$es_j$ ..................... element surface of synthetic building element [m² es]
$fs$ ...................... floor space of synthetic building [m² fs]

**Error! Reference source not found.** is an example of a datasheet summarizing the general MCIs of the synthetic building element "exterior wall of factory building" in relation to element surface (m² es) and to the floor space of the entire building (m² fs). According to the database, the mean element surface is 1,764 m² and the mean floor space of factory buildings is 2,535 m² (a ratio of 0.696).

In order to use the MCIs for Bottom-up calculation analyses of material compositions of the stock, it is necessary to describe the interface between BKI building types and building types specified by official statistics. Germany's official statistics on buildings classifies the non-residential stock into seven main types. Figure 2 gives the resulting MCI values for these building types.

There is considerable variation in these values for the different building types (up to a factor of three). Building types that tend to require hall-like constructions, for example agricultural buildings, are marked by considerably lower MCIs than buildings with massive interior walls and ceilings, such as office buildings. The extent of circulation areas within the buildings, such as staircases and corridors, is a further influence. These are not considered to be part of the floor space. Hence, buildings with high ratios of circulation areas such as schools or sports facilities show remarkably high MCIs in relation to floor space. Figure 4 also shows significant differences in the material composition of the MCIs. Thus, the MCI of agricultural buildings consists to 67% of concrete (cf. Ortlepp & Schiller, 2014); for trade and storage buildings, the proportion is 25%.

*Table 2 General MCI of the synthetic building element "exterior wall of factory building" referred to element surface and to floor space*

| material | general MCI [kg/m² es] | [kg/m² fs] |
|---|---|---|
| lime mortar, lime-cement mortar | 93 | 4.39 |
| standard concrete B25 | 567 | 66.07 |
| clinkers | 13 | 1.06 |
| vertically perforated bricks | 101 | 11.69 |
| sand-lime bricks | 72 | 8.35 |
| aerated concrete blocks | 194 | 22.54 |
| fibre cement boards | 1 | 0.09 |
| timber boards | 3 | 0.41 |
| timber scantlings | 11 | 1.43 |
| polystyrene rigid foam | 6 | 0.88 |
| mineral wool | 59 | 8.84 |
| PVC film | 2 | 0.08 |
| Glass | 47 | 2.57 |
| Steel | 86 | 13.11 |
| aluminium | 13 | 1.07 |
| total | 1,269 | 143 |

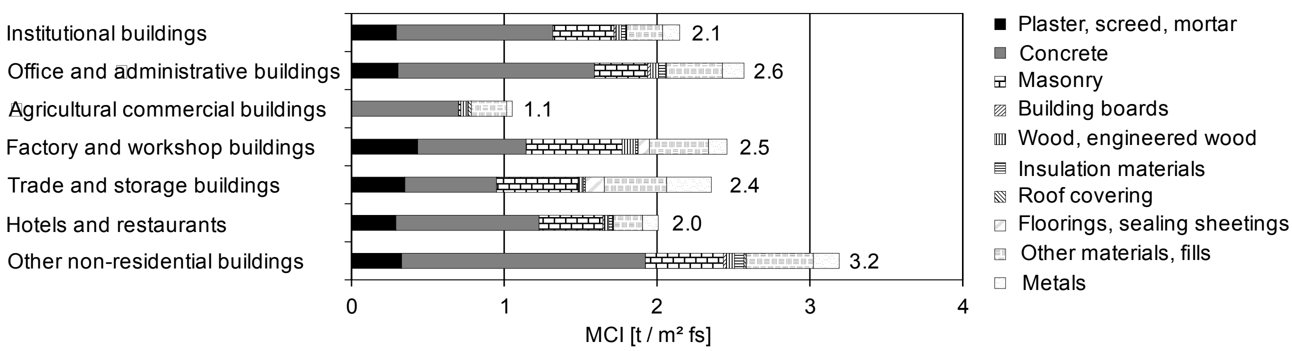


*Figure 2 Material compositions of NRBs by usage types of the official building statistics*

## 5. Total material mass in Germany's NRB stock

By combining MCIs with figures on floor space, it is possible to calculate the total material stock in NRBs classified in various ways:

- By material group and building type (Eq. (3)) – the mass *M* of a building material group *i* of a building type *j* is determined by multiplying the total floor space *FS*(*j*) of the building type *j* with the respective specific material coefficient *MCI*(*i,j*).

$$M_{i,j}\left(NRB\right)=FS\left(NRB_{synth,i}\right)\times MCI_i\left(NRB_{synth,j}\right) \tag{3}$$

with $M$ .......absolute mass [million t]
$i$ ..........index of building material group
$j$ .........index of synthetic NRB type ($NRB_{synth}$)
$FS$ ......floor space [million m²]
$MCI$ ...material composition indicator [t/ m² fs]

- By material group (Eq. (4)):

$$M_i\left(NRB\right)=\sum_{j=1}^{7}M_{i,j}\left(NRB\right) \tag{4}$$

- By building type (Eq. (5)):

$$M_j\left(NRB\right)=\sum_{i=1}^{10}M_{i,j}\left(NRB\right) \tag{5}$$

Mineral materials clearly make up a much larger proportion of the material stock than organic and metallic building materials. The dominant mineral material is concrete (Figure 3). Analyses of RBs (e.g. Schiller *et al.*, 2015) show similar orders of magnitude for the material distribution. The most striking difference is concerning the proportion of metals (primarily constructional and reinforcing steel), which are much higher for NRBs than for RBs (8% of mass as opposed to 1% – 4%). This can be explained by the existence of steel-frame NRBs (in Germany there is no tradition of steel-frame RBs).

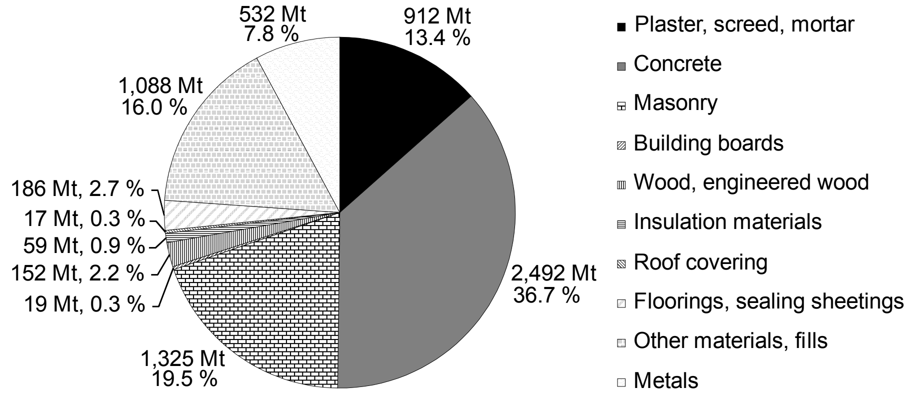


*Figure 3 Material composition of the German NRB stock (own calculation)*

The allocation of total material mass to building type (Figure 4) resembles the distribution of floor space. An exception must be made in the case of agricultural buildings: While agricultural buildings provide 15% of total floor space, they contain only 6% of the stock of building materials. This type therefore ranks fifth in the relative stock of material mass, behind office buildings and the other buildings (schools, etc.).

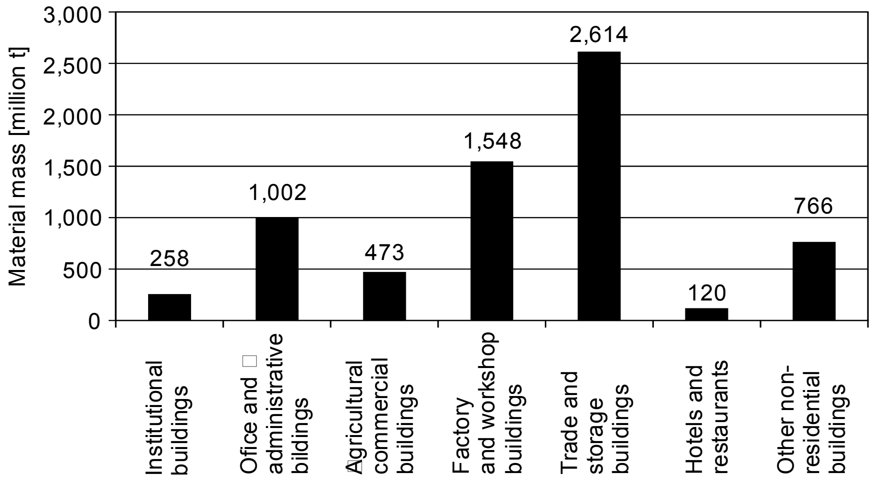


*Figure 4 Material stock in existing German NRBs by building types*

The total material mass of the NRB stock can be derived as the sum of the masses of the individual materials calculated by Eq. (4), or as the sum of the masses of the individual building types calculated by Eq. (5). Both calculations yield the same result of approximately 6.8 billion tons of total building material in Germany's NRB stock. By comparison, according to Schiller *et al.* (2015) the material stock in German RBs is in the range 8.4 to 9.3 billion tons. The material bound in Germany's NRB stock thus comprises approximately 42% – 45% of the total stock of material contained in German buildings.

## 6. Discussion

### 6.1 Material composition indicators

The heterogeneity of NRBs represents an enormous challenge to any attempt to quantify material stocks and flows using material composition indicators. The various uses of these buildings determine their physical structures, which can range from small buildings such as workshops to the facilities of large industrial companies, from lightweight storage facilities to massive buildings with complex fittings. This suggests that indictors must be sufficiently differentiated in order to limit errors in the estimation of material stocks and flows. The analyses presented here confirm this requirement. There are marked differences in the total specific masses of building types as well as their material composition. Regarding the building stock as a potential stock of secondary resources, the presented MCIs are suitable to describe this heterogeneity. In the context of urban mining, a finer differentiation between material categories should enable the development of more recycling options (e.g. Schiller *et al.* 2015). Thus, it is not sufficient to merely distinguish between basic material groups such as minerals, plastics, metals, wood and others.

It is rather difficult to ensure that calculated MCIs are both valid and representative. Solid base data is required for this as well as sufficient transparency in underlying methods of calculating MCIs. A review of the literature shows that these requirements are rarely met in full. Some of the few studies that have used MCIs to analyze material flows of NRBs provide little documentation on the underlying method. The presented work attempts a more precise formulation of the adopted approach to calculating MCIs than other studies (e.g. Wang *et al.*, 2004; Yang & Kohler, 2008; Hong *et al.*, 2014). If information is available, case studies and analysis of sets of individual buildings are presented as a confirmation (e.g. Michel *et al.*, 2012; Kleemann *et al.*, 2014). Comprehensive databases are generally lacking. One exception is the case of Japan, were material figures are available in the form of official statistics (Tanikawa *et al.*, 2015). Thus a basic challenge is to improve the empirical database for MCIs, a step to which this paper can be considered a contribution. However, the adopted database can be further refined by statistical analysis to improve the validity of MCIs. Data availability varies from country to country. It has been pointed out that official statistical data is available in Japan to permit the determination of MCIs (Tanikawa *et al.*, 2015). Any review of such data should consider whether all building elements are taken into account or (as is the case in Germany) only the load-bearing structure is considered (Destatis, 2011a). In the latter case, additional assumptions must be made in the calculation of MCIs, clearly at the expense of validity. Similar efforts to improve base data should be undertaken in other countries. In the United Kingdom, for example, one possibility would be to use available data from quantity surveys to qualify MCIs for NRBs. Currently there are only very few studies which could supply data to evaluate the presented method of determining MCIs.

Currently there are no benchmarks suitable to validate the MCIs presented in this paper. The most serious barriers to validation are the various definitions of building types, reference features and regional requirements on specific constructions designs (e.g. to meet earthquake resistance guidelines). Therefore, validation can only be undertaken for specific building types by considering variations in regional construction types and other design requirements. In the data on Japan's building stock used by Tanikawa *et al.* (2015), for example, the definitions of building types overlap with those adopted in this paper. Another notable fact is that Japanese buildings are generally heavier due to the stronger load-bearing structure, presumably to ensure sufficient resistance to seismic activity. Regarding agricultural buildings, the definition of building type in the Japanese study closely matches that adopted here; indeed, both typologies use the same reference feature (m² floor space). This permits a comparison of MCI for agricultural buildings. The data used by Tanikawa *et al.* (2015) classifies agricultural buildings according to various types of construction, so that the MCI ranges from 1.0 t/m² for wooden frame constructions to 3.9 t/m² for reinforced concrete constructions. The MCI for agricultural buildings determined here is 1.1 t/m². Considering that wooden frames are the dominant form of construction in Germany for agricultural buildings, and that the country's building code stipulates lower strength requirements (reflecting the lower earthquake risk), these figures for wooden frame constructions as well their relationship to other forms of construction seem plausible. However, this indication of the validity of the approach does not remove the need for more detailed evaluation and research.

### 6.2 Estimating the total material mass of Germany's NRBs

In the presented bottom-up approach, the estimation of total material mass is based on the derived MCIs and floor space as input data. Since both of these variables suffer from uncertainties, the final value for total material mass must be viewed as tentative.

Schiller *et al.* (2015) have attempted to quantify the disparity between the results of bottom-up and top-down approaches. Since top-down approaches provide data solely on annual flows, such comparison is only possible for flows rather than stock. Comparing the results of the top-down and bottom-up methods for groups of materials and goods, we see that the material flows obtained from top-down methods are generally higher than those obtained from bottom-up methods, although divergences can exist in both directions. For example, in the case of steel the top-down value is lower than the value determined by the bottom-up method. Hence, it is not always the case that the top-down values form an upper boundary; the determining factor is the specific data at hand. Future research should look at appropriate forms of data qualification (e.g. determination of the spread of values).

### 6.4 Relevance to Urban Mining and resource efficiency

Proponents of Urban Mining argue that capital and consumer goods contain valuable materials that should be recovered. Here the focus is mostly on rare earths and precious metals. However, while such materials make up a considerable proportion of the mass of consumer and production goods, they are only a small proportion of building materials (Schiller *et al.* 2015). Buildings also contain economically interesting raw materials such as metals. As shown here in the case of Germany's stock of buildings, these materials are present in considerably higher proportions in NRBs than in RBs. In practice, recycling paths are already well organized due to the financial savings that can be made by reusing such valuable materials. While the options for the recovery, recycling and reuse of mineral building materials (regulated by the EU Waste Framework Directive) are considerably more limited, these should certainly be exhausted, in line with policy goals (e.g. BMUB, 2012). In such cases environmental arguments hold sway rather than questions of economic efficiency. Every effort should be made to use secondary materials in order to minimize the exploitation of the natural environment while satisfying the demand for natural resources (BMUB, 2012). In Germany more than 90% of the documented mineral construction waste is already recovered, a large proportion of this in surface mining sites as part of recultivation measures. In some cases these measures may conflict with soil and water protection legislation if pollutants leach out from recycled waste used for recultivation or for construction. Both at the national level and at the level of the federal states, stricter limits are being discussed and already partly implemented to limit the use of construction waste as a recultivation material. The impact will be to place the future resource recovery of such mass waste on an uncertain footing. More generally, it is clear that greater knowledge is required of the quantity and quality of materials within the built environment in order to accurately calculate output flows and thus to support resource recovery and waste management strategies at both the national and regional levels (e.g. Hiete *et al.*, 2011).

The method discussed in this paper can help quantify the physical capital of our building stock viewed as a resource. Efficient use of this stock cannot be limited to waste flows and the potential of recovering secondary materials. In the hierarchy of waste management, care and maintenance of the stock must be the primary goal before any consideration of the reuse, recovery and recycling of materials. All strategies of material conservation should not only aim to consume as little material as possible (to be measured by minimum MCI values) but also to ensure the longevity of buildings. This means, for instance, encouraging a wide diversity of use to extend the lifespan of buildings and revising building codes to require stronger structures in order to accommodate new load-bearing requirements or environmental impacts. Of course, such considerations may appear to contradict efficiency objectives. For example, agricultural buildings in Japan have a substantially higher material intensity (larger MCI) than such buildings in Germany due to the more stringent requirements for earthquake resistance. In this way, the longevity of the building stock is extended in Japan, confirming the argument that an overly narrow focus on resource efficiency concerning input materials can in the end lead to higher consumption of materials. This can be described as a misinterpretation of resource efficiency (e.g. Hassler & Kohler, 2014). To sum up, quantification of the building stock is a prerequisite for any resource-oriented discussion of stock development.

### 6.3 Transferability of the proposed method

Differences in the definition of MCIs are generally related to underlying variations in the selected building typologies. In general, building types are defined along types of use, each of which can include various types of construction. There are indications that MCIs can be more easily transferred when based on construction types rather than types of use, as load-bearing structures generally obey international norms, at least in developed countries (e.g. "Eurocodes" for Europe, American (ACI) or British Standards (BS)). Differences in the actual construction may sometimes reflect an individual country's guidelines on building physics, such as ratings for energy consumption. Other considerations, such as earthquake protection, can also affect the type of construction selected to meet the required use. In order to improve transferability of MCI in the global context, further research should attempt to define MCIs for construction types that resist MCI analysis based on type of use.

It is only possible to conjecture on the potential for the transferability of methods for stock estimation. This will largely depend on the availability of required data. However, as non-residential stocks and their changes are currently rarely documented in official statistics, methods to estimate the size of this stock are indispensable.

## 7. Conclusions

NRBs account for 44% of the total building stock in Germany. Clearly, a similarly level of attention must be paid to this stock as is currently paid to RBs concerning the issue of resource efficiency. In this paper, we describe a first attempt to quantify Germany's stock of NRBs by estimating its total size and the material masses contained within.

One general problem in studying the NRB stock is a lack of comprehensive data. For this reason, the paper takes an indirect approach, using financial data and records of the intensity of building activity to make estimates of national floor space. Another difficulty to be overcome is specifying the material composition of the NRB stock in view of its heterogeneity and the patchy availability of data. The database employed in the case at hand suffers from such gaps, undermining the general validity of final stock estimates. However, the authors are unaware of any other publication that has pursued this specific strand of research. Hence, the paper's value added is in the determination of material composition indicators to supplement existing lists of material composition indicators in the literature. Nevertheless, future research is required to improve the reliability of empirical findings and to provide results that are more detailed.

The presented research forms a basis for discussion and further work in the analysis of material stocks. Findings can be used to improve the strategic planning of governmental authorities or to revise the business plans of companies in the construction and waste management sector.

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