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Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster

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ABSTRACT

Understanding buildings as material depots radically changes the way resources need to be managed within the construction industry and the built environment. Similar to warehousing, buildings, cities and regions will have to keep track and anticipate the stocks and flows of materials, needing to document and communicate (at the right moment) which materials in what quantities and qualities become available for re-use or recycling where and at what time in the future. This paper describes the process of documenting materials and products utilized in the construction of the *Urban Mining and Recycling* (UMAR) unit within the *Madaster* platform. UMAR is a fully circular residential unit of Empa NEST created from secondary resources and designed as a material depot for future constructions. Madaster is an online platform, which generates and registers materials passports and calculates a Circularity Indicator for their construction, use, and end-of-life phases. The results of the calculations show that the UMAR unit is 96% circular. Constructed from 95% non-virgin and rapidly renewable materials, the unit has a utility rate of 98% and 92% of its materials are prepared to return into pure-type material cycles at the unit's end of life. In combination, these two case studies provide a unique opportunity to evaluate the capabilities of materials passports and the Madaster Circularity Indicator to document material stocks and flows within a circular built environment, and to assess the potential of circularity indicators as a design tool supporting the transition towards a circular construction industry. The continuous development of tools and systems for material cadastres undoubtedly represents a key prerequisite for the implementation of a paradigm shift towards a functioning circular construction industry.

1. Introduction

The concept of the circular economy (CE) is increasingly gaining attention as a way to overcome the social, economic and environmental problems of the current linear economic system. A consequent closing of loops – e.g. considering waste as a resource – offers not only the possibility to end the loss of valuable finite resources, but also to reduce dependencies on global and volatile resource markets or to provide new job opportunities (European Commission, 2014; Stahel and Reday-Mulvey, 1976; Ellen MacArthur Foundation, 2013; Hebel et al., 2014).

Today's understanding of the CE is informed by several important schools of thought developed within the past 50 years, among others: John T. Lyle's *Regenerative Design*, Walter R. Stahel's *Performance Economy*, or William McDonough and Michael Braungart's *Cradle to Cradle* approach (Lyle, 1994; Stahel, 2010; McDonough and Braungart, 2002). The most renown definition of the CE as an economic system has been framed in 2013 – and revised in 2015 – by the Ellen MacArthur Foundation: „A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles" (Ellen MacArthur Foundation, 2015). Several governments have adopted CE principles into national policy, most prominently China in 2009 and the European Union in 2015 (Standing Committee of the National People's Congress, 2009; European Commission, 2015).

In Europe, the construction industry is the biggest consumer of energy and materials. Calculating the impact for their full life cycle (material extraction, manufacture, transport, construction, use phase and end of life), buildings account for about 50% of all energy use, 40% of all greenhouse gas emissions, 50% of all raw material

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extraction and 30% of all water use (European Commission, 2019). Additionally, the construction sector produced 36% of European solid waste (in weight), which in 2016 (latest currently available statistic) was equivalent to 9.24 billion tonnes (eurostat, 2019). Due to the fact that the rate of consumption is significantly higher than demolition and discard, the European society is building up an economy wide anthropogenic stock at a rate of about 10 tonnes per capita and year, adding to the already existing stock of 400 tonnes per capita (340 tonnes in use as goods, buildings and infrastructure / 60 tonnes in landfills) (Scharff, 2016). The construction industry – due to the nature of buildings and infrastructure – is responsible for a large percentage of this stock. Consequently, the CE increasingly regards the built environment and its stock of components, elements and materials as a valuable reserve for the construction of future cities, and aims to activate this sink (Müller et al., 2017).

While materials and products in anthropogenic CE flows should be re-used or recycled, the strategy of reintroducing resources from the anthropogenic stock into economic processes is called *urban mining* (Cossu and Williams, 2015). The term has been coined after Jane Jacobs' 1969 claim that future "cities will become huge, rich and diverse mines of raw materials" (Jacobs, 1969), and has been discussed widely in recent years. Already today, the anthropogenic stock of several metals and minerals has outgrown their respective naturally occurring reserves (Ruby and Ruby, 2010; Brunner, 2011; Nakamura and Halada, 2015), a significant argument supporting the development of new urban mining technologies and strategies (Gypsum Recycling, 2018; Fraunhofer, 2019; Heisel et al., 2019b) in light of rising raw material prices and volatile markets (Ellen MacArthur Foundation, 2013; Lacy and Rutqvist, 2015). However, while mining processes of the existing stock can advance the transition from linear to circular material use, future buildings within a CE need to be understood already as *material depots* where an effective and direct re-use and recycling of all components is guaranteed by design (Rau and Oberhuber, 2016). Key design and construction parameters in this regard are (1) a consequent design for disassembly, (2) a design for adaptability and (3) the use of high quality, non-toxic and circular components, elements and materials (Geldermans, 2016; Heisel et al., 2019a).

Understanding buildings as material depots radically changes the way resources need to be managed within the construction industry and the built environment. Similar to warehousing, buildings, cities and regions will have to keep track and anticipate the stocks and flows of materials, needing to document and communicate (at the right moment) which materials in what quantities and qualities become available for re-use or recycling where and at what time in the future (von Richthofen et al., 2017). The implications for the design and construction process, the supply and value chains within the construction industry, as well as the data generation and management are significant, and currently the focus of diverse global research initiatives (Debacker and Manshoven, 2016; Acharya et al., 2018; Thelen et al., 2018; Circle Economy, 2019; Ellen MacArthur Foundation, 2019).

A circular built environment consequently requires a detailed data set to understand and enable the closing of material flows. As a result, the concept of the materials passport (MP) (Hansen et al., 2013; Hutton et al., 2016; Luscuere and Mulhall, 2018) has emerged. Over recent years, several product solutions have been developed and either are on the verge of or have just reached the market (Maersk Line, 2012; EPEA and SundaHus, 2017; EPEA, 2019; Madaster, 2018a). In general, materials passports are a digital dataset of a specific building, providing a detailed inventory of all the materials, components and products used in a building, as well as detailed information about quantities, qualities, dimensions, and locations of all materials. In addition to this thorough documentation on the individual building level, standardisation and the central registration of such passports on materials passport platforms (comparable to a land registry) are seen as a prerequisite for a circular management of resources in the built environment (Rau and Oberhuber, 2016).

This paper describes the process and results of documenting a case study building on a materials passport platform, following the steps of data generation and input into the database (section 2), the consequent generation of materials passports and a Circularity Index (section 3). It then offers a discussion of these results (section 4) and their potential for a circular built environment (section 5). The chosen platform for this research project is Madaster, which is set up as an online registry, providing the database, software and tools for private, industrial and governmental users to generate, store and manage individual materials passports and building portfolios (Madaster, 2018a). The chosen case study building is the *Urban Mining and Recycling* (UMAR) unit (Heisel et al., 2019a) designed and constructed by Werner Sobek with Dirk E. Hebel and Felix Heisel at the NEST (Next Evolution of Sustainable Technologies) of Empa Dübendorf (Swiss Federal Laboratories for Material Science and Technology) in Switzerland.

Described as future living and working laboratory, NEST (Empa, 2015) consists of a central backbone building with cantilevering platforms to accommodate exchangeable living and office buildings, so-called units. NEST is a modular research and demonstration platform for advanced and innovative building technologies, which allows novel materials, components and innovative systems to be tested, demonstrated and optimised under real-world conditions. The UMAR unit (Figs. 1–3) was opened in February 2018 as a two-bedroom living and research module for students of institutes Empa and Eawag. Simultaneously, the unit is open for public tours and events, attracting an average of 1000 visitors per month. In this double role of living lab and showcase, UMAR's objective is to proof that it is possible already today to design, detail and construct according to the principles of the CE, while communicating their content, benefits, effects, technical details and aesthetics to clients, industry and stakeholders alike.

The title of the unit refers to the two reserves and their respective modes of acquisition and utilization, which were activated for the construction of the unit – through (1) urban mining of anthropogenic stocks and (2) recycling of anthropogenic flow materials. As described earlier, urban mining refers to the re-activation of materials accumulated in the urban environment, which were not specifically designed for re-use or recycling (thus mining). Recycling comprises all those materials that were designed to remain in technical or biological cycles at maximum value and quality. Following the understanding that "cycles have no beginning and no end," (Stahel, 1997) materials and components from various sources (and thus at various positions in the cycle) have

Fig. 1. UMAR at the Empa NEST © Zooey Braun, Stuttgart.

Fig. 2. Interior view of UMAR © Zooey Braun, Stuttgart.

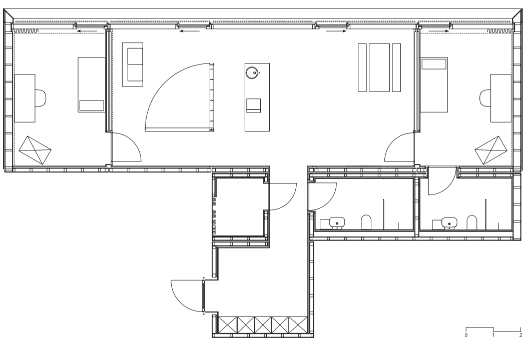

Fig. 3. Floor plan of UMAR © Sobek with Hebel and Heisel.

been used within the UMAR unit — ranging from virgin resources and recycled materials to re-used products (Fig. 4). In order to make informed decisions in the material selection process, a detailed life cycle assessment (LCA) has been prepared for the unit and its components (Kakkos et al., 2019). Constructed from secondary materials, the unit is also designed as a material depot for future constructions. As such, all connections are reversible (e.g. through screws or interlocking connections) in order to guarantee the reintroduction of all materials into their respective pure-type biological or technical metabolisms (McDonough and Braungart, 2002). Consequently, all connections are easy to access and all material properties and specifications documented in preparation of the planned decommissioning of the unit (Fig. 5). This aspect also provided the necessary data for the research at hand.

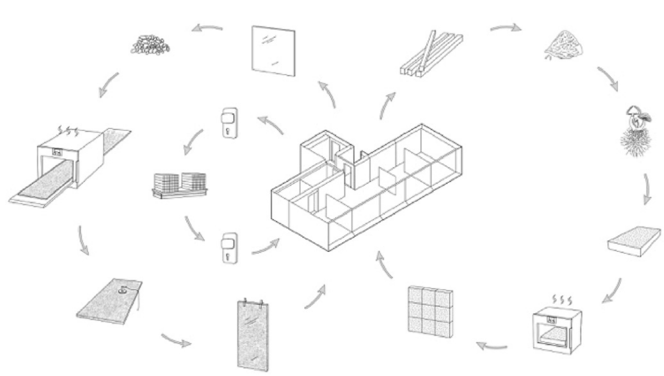

Fig. 4. Scheme of three exemplary closed material cycles within the UMAR unit: On the left side, the technical glass cycle shows the recycling of window glass into MAGNA Glaskeramik to be utilized in the bathrooms; the smaller cycle shows the direct re-use of door levers from a bank building in Brussels. On the right side, the biological metabolism shows the transformation of timber beams into mycelium-bound insulation panels. © Felix Heisel and Laura Mrosla

2. Methodology

Documentation is one of the most important cornerstones of the transition from a linear to a circular economy. On one hand, it allows for the measurement of progress and an evaluation of the transition through indicators. On the other hand, this data is a precondition for the management of stocks and flows in the system, as well as the lowering of barriers in its implementation. Especially within the EU, several research consortiums are currently working on the development of appropriate methodologies and circularity indicators, e.g. the EU's Level(s) or BAMB Buildings as Material Banks (Saidani et al., 2018; European Commission, 2019; Sharp et al., 2018). Materials passports are keeping record of the material composition of a product or building through the documentation of quantities such as weight, volume, dimensions and location of materials within a structure. In order to serve as an effective instrument in measuring the potential of this material stock for future re-use or recycling, additional qualitative information such as the toxicity of components is equally important. A central element represents the assessment of a product's or building's circularity through circularity indicators, by grading a structure's performance in regard to its use of secondary feedstock, as well as its potential to reintroduce these materials back into the economic cycle. In 2015, the Ellen MacArthur Foundation published the Material Circularity Indicators (MCI) (Ellen MacArthur Foundation and Granta Design, 2015), which are based on the restoration of material flows at product and company level following four principles:

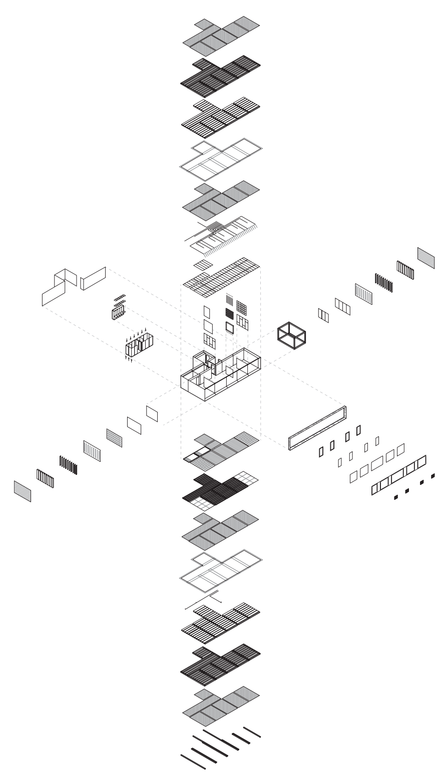

Fig. 5. Axonometric representation of UMAR's design for disassembly into pure-type material layers for re-use, recycling or composting.© Felix Heisel and Sara Schäfer.

- using feedstock from re-used or recycled sources
- re-using components or recycling materials after the use of the product
- keeping products in use longer (e.g. by re-use/redistribution)
- making more intensive use of products (e.g. via service or performance models).

The indicator aims to measure “the extend to which linear flow has been minimised and restorative flow maximised for its component materials, and how long and intensively it is used compared to a similar industry-average product. The MCI is essentially constructed from a combination of three product characteristics: the mass *V* of a virgin raw material used in manufacture, the mass *W* of unrecoverable waste that is attributed to the product, and a utility factor *X* that accounts for the length and intensity of the product’s use” (Ellen MacArthur Foundation and Granta Design, 2015).

Building on and adapting the MCI for the specifics of the construction industry, the Madaster Foundation developed the Circularity Indicator (CI). The CI assesses the level of circularity of each building between 0 and 100 per cent based on the users uploaded information to the platform. A building that has been constructed from virgin materials and is being landfilled after a shorter than average use phase is considered a fully ‘linear’ building with a Madaster CI of 0%. On the other end of the spectrum, a building constructed from re-used and/or rapidly renewable materials that can be disassembled and easily re-used elsewhere at the end of the use time is a fully ‘circular’ building with a score of 100% (Madaster, 2018a). As described in more detail below, the Circularity Indicator assesses a building and its products during three phases of its lifetime: the construction phase (goal: 100% secondary material resources), the use phase (goal: functional life-span > industrial average life-span), and the end of life phase (goal: 100% recoverable content). The accumulation of the resulting three specific indicators – one value per phase – results in an overall CI building score. In a last step, this building score is again adjusted by two correcting factors: the completeness of the data in terms of material input and in terms of element classification and building layer attribution (see Fig. 7). This weighted CI score equals the final Circularity Indicator.

2.1. Calculation method

The calculation of indicators for the three phases is done according to the criteria described in sections 2.1.1-3 (Madaster, 2018b) provides further information as well as an extended documentation.

2.1.1. Construction phase

$CI_{Construction}$ represents the ratio of virgin materials to recycled, re-used or rapidly renewable materials and is calculated according to the formula

$$CI_{Construction} = F_R + F_{RR} + F_U$$

whereby F_R represents the fraction of recycled materials (% of total mass), F_{RR} represents the fraction of rapidly renewable materials (% of total mass), and F_U represents the fraction of reused products and/or components (% of total mass). In order to calculate the building CI in the next steps, $CI_{Construction}$ is further balanced by indicators for the efficiency of the recycling process preceding the construction phase (E_F in %) and the mass of waste generated during the recycling process (W_F in kg).

2.1.2. Use phase

CI_{Use} represents the expected lifespan of utilized products, compared to the average life span of status-quo products in the same application. The formula for the indicator is

$$CI_{Use} = L / L_{av}$$

whereby L represents the potential functional lifespan of a product in years and L_{av} represents the industry average lifespan of the building layer this product is applied in. The actual score is determined by calculating the weighted average of all products from the various system layers.

2.1.3. End of life phase

$CI_{End\ of\ Life}$ represents the ratio between waste materials and re-usable and/or recyclable materials generated when a building is refurbished or demolished. The formula for the End of Life Phase Circularity Indicator is

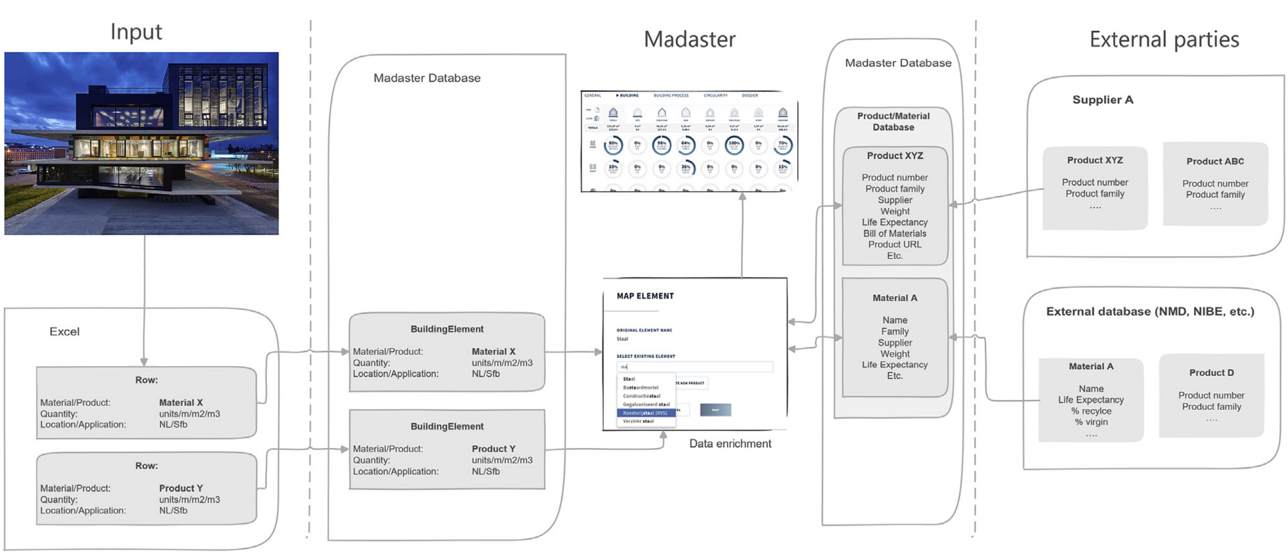

Fig. 6. Scheme of data input, hierarchy, calculation, output and connection to external partners on the Madaster platform. Illustration edited and reprinted with permission of Madaster.

Fig. 7. Screenshot from the Madaster platform, displaying the Circularity Indicator for construction, use and end of life phases, as well as the overall CI Building Score and the weighted Madaster CI score for UMAR.

$$CI_{End\ of\ Life} = C_R * E_C + C_U$$

whereby C_R represents the fraction of materials that can be potentially recycled at the end of its useful life (% of total mass), E_C represents the efficiency of the recycling process in the end of life phase (%), and C_U represents the fraction of components and/or products that can be potentially reused at the end of their useful life (% of the total mass).

In order for components and/or products to be counted towards C_R they must fulfill the following conditions, as re-use and recycling is only possible when materials can be successfully extracted from a building:

- The mountings are easily accessible, and the product can be easily removed without damaging other parts of the building;
- The product can be easily disassembled using standard tools without damaging the object or objects to which the product is attached;
- The attachments and mountings used to install the product are standardized and prefabricated.

These conditions for design for disassembly are currently entered manually into the dataset. An automated assessment of these criteria is part of the future development of the Madaster platform.

2.2. Data input

The paper at hand utilized the Madaster platform and CI for a circulatory evaluation of the UMAR unit. The methodology of this study follows the consecutive steps and methods described before and summarized in Fig. 6: (1) collection and verification of necessary building material data and specifications for materials and products passports; (2) data input into the Madaster platform and creation of corresponding material and product data sheets including a step of manual data enrichment on the Madaster platform; (3) calculation of the Building Circularity Indicator; (4) evaluation of the results in relation to the available date, the principles of the CE as well as the design parameters of the UMAR unit.

During data input, the platform distinguishes between materials and products, in order to generate relevant numbers for the re-use and recycling on product, component or material level (Madaster, 2018a). The specific structure and the required information for a material or product data set are discussed in sections 2.1.1-3 and further illustrated in Tables 3–5.

A detailed information on the location of a product within the building is important in respect of its re-use and recycling potential, as well as its expected functional service time. In this respect, the Madaster platform additionally links the product to the Dutch classification of building elements or NL/SfB (BNA, 2005). These codes are also linked to the building layer model (site, structure, skin, services, space plan and stuff) (Brand, 1994), estimating the replacement or maintenance interval of a specific product within the building. In order to generate the information in Table 1, materials are additionally grouped into material families, namely stone, glass, wood, plastic, organic and metal.

3. Data collection and input in the materials passports platform

In order to enter the UMAR unit into the Madaster platform, in a first step 32 material data sheets were created, which were then connected to 90 products in a second step. Material data sets include elements such as name, specific weight, supplier, lifetime, feedstock sources and quality, end of life scenario and efficiency of recycling process (Tables 3 and 4). Product data sets include elements such as brand, product code, supplier, functional and technical life span, volume, quantity, connection details in respect to ease of disassembly and material separation, as well as a bill of materials and the NL/SfB Code (Table 5). As most products today are made from a variety of materials, the bill of materials often refers to several different material data sheets in changing volumes or percentages. As the Madaster Foundation is based in the Netherlands and the Swiss version of the platform did not yet exist at the time of the data input, product application and location information had to be translated into the Dutch classification of building elements (NL/SfB). The data was collected in Excel and uploaded to the Madaster platform through the provided channels. In a next step, further information (e.g. building for disassembly criteria) were added manually through the administration page on the Madaster platform.

Table 1 summarizes the collected material and product data for the whole UMAR unit, categorized by main material families and

Table 1
Volume and mass of materials used in the UMAR unit categorized according to material families and applications/locations (totals may contain differences due to rounding).

	Totals		Site		Structure		Skin		Services		Space Plan		Stuff	
Totals	151.52	m^3	0.00	m^3	44.26	m^3	84.22	m^3	0.20	m^3	20.82	m^3	2.02	m^3
	48.40	t	0.00	t	25.13	t	9.68	t	0.95	t	11.13	t	1.51	t
Stone	79.69	m^3	0.00	m^3	0.00	m^3	77.79	m^3	0.00	m^3	1.88	m^3	0.00	m^3
	5.02	t	0.00	t	0.00	t	2.96	t	0.00	t	2.07	t	0.00	t
Glass	2.49	m^3	0.00	m^3	0.00	m^3	1.58	m^3	0.00	m^3	0.91	m^3	0.00	m^3
	5.92	t	0.00	t	0.00	t	4.07	t	0.00	t	1.85	t	0.00	t
Wood	55.93	m^3	0.00	m^3	44.00	m^3	4.66	m^3	0.00	m^3	5.32	m^3	1.95	m^3
	29.76	t	0.00	t	23.09	t	2.13	t	0.00	t	3.21	t	1.36	t
Plastic	0.84	m^3	0.00	m^3	0.00	m^3	0.11	m^3	0.04	m^3	0.62	m^3	0.05	m^3
	0.73	t	0.00	t	0.00	t	0.02	t	0.04	t	0.66	t	0.06	t
Organic	11.27	m^3	0.00	m^3	0.00	m^3	0.00	m^3	0.00	m^3	11.26	m^3	0.01	m^3
	0.85	t	0.00	t	0.00	t	0.00	t	0.00	t	0.85	t	0.00	t
Metal	1.32	m^3	0.00	m^3	0.26	m^3	0.08	m^3	0.16	m^3	0.81	m^3	0.01	m^3
	6.06	t	0.00	t	2.04	t	0.54	t	0.91	t	2.49	t	0.08	t

Table 2
Combination of parameters to determine case study product and material combinations.

metabolism	biological	technical	technical
strategy	biodegradation/growth	recycling	re-use
building layer	structure	space plan	stuff
material family	wood	glass	metal
case study	3.1 Structural timber frame	3.2 MAGNA Glaskeramik	3.3 Jules Wabbes door lever

Table 3
Summary of material data sheet on spruce wood utilized in the UMAR unit. Material specific values are sourced from (European Wood Initiative, 2010). Legend: Regular - design values/*(Italic)* - sensitivity analysis.

Material Information		**Feedstock Sources**	
Material Name	Spruce	% Recycled	0
Specific Weight (kg/m^3)	450	% Rapid Renewables	100
Material Family	wood	% Virgin	0
Supplier	Zimmerei Kaufmann	**End of Life Scenario**	
Lifetime (years)	100	% Recycled	*(80)* 100
Description		% Landfill	0
		% Incineration	*(20)* 0
		Efficiency of Recycling Process	
		% Efficiency of Recycling Process Raw Material	100
		% Efficiency of Recycling Process End of Life	100

Table 4
Summary of material data sheet for Magna Glaskeramik utilized in the UMAR unit. Material specific values are sourced from (ift Rosenheim GmbH, 2016). Legend: Regular - design values/*(Italic)* - sensitivity analysis.

Material Information		**Feedstock Sources**	
Material Name	Magna Glaskeramik	% Recycled	100
Specific Weight (kg/m^3)	2,400	% Rapid Renewables	0
Material Family	glass	% Virgin	0
Supplier	Magna Glaskeramik	**End of Life Scenario**	
Lifetime (years)	15	% Recycled	*(80)* 100
Description		% Landfill	*(20)* 0
		% Incineration	0
		Efficiency of Recycling Process	
		% Efficiency of Recycling Process Raw Material	100
		% Efficiency of Recycling Process End of Life	100

building layers. In total, the unit utilizes 151.52 m^3 or 48.40 tonnes of materials. As a modular timber frame structure, the majority of material input (in mass) shows in the category wood, while the utilized stone wool insulation in the exterior walls as a very light but voluminous material distorts the numbers in the category stone (in volume). A list of all materials and products including their respective volume and weight values can be found in the Supplementary Information (Table SI 1).

Considering the size and complexity of this complete building data set we decided against discussing all potential combinations of materials and products within this section. Thus, the following subsections provide information for three specific and exemplary parameter combinations, aiming to cover through their selection all relevant options at least once. Table 2 shows the chosen parameter

Table 5
Summary of product data sheet for Jules Wabbes Door levers utilized in the UMAR unit.

Product Information		**Feedstock Sources**	
Product Name	JW door lever	% Reuse	100
Product Code (EAN/GTIN)	-	**End of Life Scenario**	
Supplier	Rotor DC	% Reuse	100
Functional Lifespan (years)	7		
Technical Lifespan (years)	>50	• The fastenings are accessible and the product can be removed without removing/damaging other parts of the building	Y
Volume / Weight (m3 / kg)	3.02 kg		
Description		• The product can be disassembled with standard (hand) tools without damaging the product or products attached to the product	Y
		• The fastenings and assembly method of the product is standardized and pre-manufactured	Y
		Bill of Materials	
Location (NL/SfB)	32.31	Material A (%)	Bronze (100%)

combinations to illustrate the case study selection; Fig. 4 further illustrates the same case studies and their respective parameters.

3.1. Structural timber frame

The most used material family (in terms of mass) in the UMAR unit is wood, which can be found predominantly in the building layer structure (Table 1). Not all of the 23.09 tonnes of this category are actually utilized as structural timber (as some sub-structure elements count into the same category), but the big majority of this amount builds up the frame structure of the unit's timber modules, as well as their structural floor and ceiling elements. The timber utilized in UMAR is FSC-certified spruce, silver fir and light brown ash. The wood was cut in the forests near Bregenz in Vorarlberg, Austria. Transportation distances were kept to a minimum, since the general contractor and the main carpentry of the project, as well as the sawmill are all located in that same valley. One such material data set is shown in Table 3.

Within the circular economy, the end of life scenario within the biological metabolism should not include incineration, as untreated organic material (e.g. timber) can be returned to the metabolism through bio-degradation without losses, independent of its final use value even after cascading uses. The efficiency of pure biodegradation has a calculation value of 100% (Ellen MacArthur Foundation and Granta Design, 2015). The design and construction of the UMAR unit fulfils the above conditions for a closed biological metabolism. The product data sheets associated with the data set for spruce wood (Table 3) include information that all single elements are out of untreated, solid timber beams in standard dimensions, connected reversibly to provide for a cascading re-use and recycling at maximum value and utility. For a sensitivity analysis (Section 4) we additionally assume a −20% value on circularity in the end of life phase to account for unplanned and unforeseen treatment of materials during disassembly (e.g. incineration of cut offs through status quo waste treatment channels).

3.2. Magna Glaskeramik

The UMAR unit utilizes glass in two different products, as flat glass for the façade windows and as glass ceramic for the bathroom walls and the kitchen counter top. The following data set applies to the second product, a glass panel sold by the brand name Ice Nugget and produced by German company Magna Glaskeramik GmbH. These glass panels are produced from 100% recycling cullet of industry and container glass scrap material, and can be recycled 100% at the end of their service life into new glass products of the same value and utility e.g. new Magna Glaskeramik products or container glass (Magna Glaskeramik, 2019). Due to the fact that Magna Glaskeramik activates secondary recycling glass as the raw material, a new material data sheet – rather than just a new product data sheet – needed to be created for data input (Table 4).

The product data sheet (Ice Nugget) associated with above data set includes the information that all single elements are utilized in standard dimensions and held in place by clamps at the top and bottom. Waterproofing is achieved by dry gasket sealants under pressure. No silicones or other adhesives were allowed in the unit, so that all Magna Glaskermik products (if not directly re-used) can be returned pure-type into the glass cycle without any loss of value. A sensitivity analysis for unplanned and unforeseen treatment of the material during disassembly (e.g. disposal through status quo waste treatment channels) assumes a value of 80% for end of life recycling.

3.3. Jules Wabbes door levers

In 1974, renowned designer Jules Wabbes was awarded the interior re-design of the headquarters of Generale de Banque in Brussels. Aiming to reflect the reliability of the bank, Wabbes chose precious high-quality materials such as granite, bronze or brass. When the new owner of the building requested for its demolition in 2016, one of the city's conditions for the permit was the re-use of all of Jules Wabbes' items. As a result, company Rotor Deconstruction took over the inventory, carefully dismounting and redistributing these objects – eventually leading to the installation of 10 Jules Wabbes door levers in the UMAR unit. As loan items, these levers contractually return to Rotor Deconstruction once their service time in the unit ends, ensuring the continuous re-use of the items in yet another building (Heisel et al., 2019a). The respective product data set is shown in Table 5.

3.4. Calculation of circularity indicator (CI) and results

Based on the above described 122 material and product data sets for the UMAR unit, the Madaster platform calculated the unit's CI according to the software algorithms explained in section 2. The aggregated results are illustrated in Fig. 7, which is a screenshot from the Madaster platform.

The results are displayed according to the three use phases (construction, use, end of life) with their corresponding Circularity Score in per cent. According to the Madaster platform, the UMAR unit has been constructed from 95% non-virgin and rapidly renewable materials, has a utility rate of 98%, and 92% of its materials are prepared to return into pure-type material cycles at end of life, based on the total weight of all materials used in the building. The overall Madaster CI assigns a circularity of 96% to the UMAR unit. To reach an understanding of the importance of correct material handling during the end of life phase, also a sensitivity analysis with a 20% reduction to the recoverable content of all products was calculated. The results still show a high circularity: 87% non-virgin and rapidly renewable materials, a utility rate of 98%, and 86% materials prepared to return into pure-type material cycles. As discussed earlier, the assumptions of this sensitivity analysis aim to anticipate unplanned or unforeseen end of life scenarios within the calculation – and do enforce the importance of a well-planned and controlled disassembly.

4. Assessment and interpretation of results and scope

The Madaster platform concentrates on the stocks and flows of material fractions in a circular construction industry. It consequently draws on definitions and formulas that support and remain within this scope. An example is the definition of recycling efficiency as "the ratio obtained by dividing the mass of output fractions accounting for recycling by the mass of the waste (…) input fraction expressed as a percentage" (European Commission, 2012). Important other indicators of sustainable and circular construction such as the embedded energy of materials and products, the energy consumption of building operation or the water necessary for production and operation during the whole life cycle of a building are for the moment excluded from the indicator (Madaster, 2018b). Another important fact to keep in mind is the applied definition of recycling, which at the moment encompasses all materials that are not incinerated, landfilled or directly re-used. The necessary evaluation in terms of quality of recycling (e.g. backfilling, downcycling or recycling according to the definition of the CE) can and must be done through the recycling efficiency value. Madaster is currently working on predefined material and product data sets that reference most variables from objective third parties (see Fig. 6 – External Parties). We see this as an important step in order to reach comparable and accurate calculation results in accordance with the definitions of the circular economy currently applied.

Acknowledging this scope, the platform can be an important tool to evaluate design decisions and the effective implementation of CE design principles (Heisel et al., 2019a). Specifically, the CI displays the amount of secondary materials used in a design or construction and the potential to reintroduce these materials or products into pure-type cycles at the end of life. For example, the recycling efficiency of Magna Glaskeramik has a value of 100 per cent. However, this value only applies to the amount of material actually returned to the glass cycle through recycling. Landfill as the only available alternative of course does not provide any points towards circularity. However, a multitude of decisions during the design, construction, use and deconstruction phases influence whether the application of a material within a specific product fulfils CE criteria. The provided indicators and calculations can help understand the various implications of a specific decision in regard to the circularity of materials. Further, the utility rate offers an impression on the quality, durability and aesthetics of applied materials and products, all of them being equally important aspects of sustainable construction.

Such calculations can be done after the building has been finished (as in the case of UMAR) to verify assumptions taken during the design and construction phases, but could and should also become a tool in the design phase. In this regard, it would be important to have different options for varying depths of analysis. Beginning with quicker and understandably rougher calculations, the process could gradually become more detailed and accurate as the project progresses from design to permit to construction and eventually to renovation and dismantling. The current integration of a direct import option of (informed) 3D-BIM models (Building Information Modelling) (Honic et al., 2019) into the Madaster database might be one way to achieve such an integration of the tool already in early design stages.

One of the main reasons for the implementation (and use) of platforms such as Madaster in the first place is the need for a detailed documentation of materials within buildings, which offers a new level of knowledge necessary to understand and use the built environment as a material depot in the future. Only if we know which materials in what quality become available when and where, can we begin to match supply and demand of re-use and recycling flows (von Richthofen et al., 2017). Outside of the scope of this research paper, knowledge on material properties, dimensions, locations and their circularity level also allow a financial evaluation of a building's material stock (changing from a material depot to a material bank), which can be an important means to demonstrate the possible value preservation through circular design and its material choices, and can act as a driver for circular construction (Rau and Oberhuber, 2016). Fully circular case studies such as UMAR can thereby serve as valuable examples to develop and evaluate industry benchmarks.

Additionally, continuous material documentation over the use time of a building can provide the necessary information to lower permission and financial barriers for the direct re-use of materials in high-quality and high-performance applications such as e.g. structural steel (Heisel et al., 2019b). In this respect, information saved in the Madaster platform needs to be managed as a dynamic data set, a digital twin of the actual building, which is being updated every time changes are applied to the building or something happens to the building. This not only includes planned renovation projects but also fires, earthquakes or other events that can have an influence on the utility and value of the material stock.

As CO_2 performance will be an increasingly important parameter in the assessment of a global building stock and the industry's activities, the CI score can also be used to assess how material choices affect the building performance in terms of CO_2 emissions. The necessary data sets for the implication in Madaster still have to be developed, but research already demonstrates that circular use of materials has a significant potential to reduce GHG emissions (Ellen MacArthur Foundation and McKinsey, 2013; Wijkman and Skånberg, 2016). As mentioned earlier, such data already exists for the UMAR unit (Kakkos et al., 2019) and could be incorporated directly as soon as the respective functions exist.

5. Conclusions

The transition towards a circular economic model in which products, components, and materials are kept at their highest utility and value at all times (Ellen MacArthur Foundation, 2015) is an important step to overcome the current social, economic and ecological challenges we are facing today and build a resilient, future-proof economy. The construction sector has a central role in this transition, as it is the largest consumer of resources, with the highest emission of green house gases and largest volume of waste generated. This implies a fundamental rethinking of current business models and practices, treating waste as a resource and designing buildings in such a way, that they can serve as a material reserve for the future. However, the built environment today still represents a massive, yet undocumented and unspecified stock of material resources. Materials passports and circularity indicators are thus important means to provide the necessary data for managing material stocks and flows within the system and assess the performance of individual buildings in terms of material consumption and their potential for future re-use. Additional information on CO_2 savings and a financial evaluation of materials through circular design and circular material choices can serve as a driver to preserve value in the system and drive the transition towards a circular economy. Lastly, if done properly and consistently, material documentation can significantly reduce material costs in construction along the whole value chain (Smeets et al., 2019).

The UMAR case study implements these concepts consequently and acts as a demonstrator and living lab. The experiences from the case study can provide an industry benchmark on the high level of circularity that can be achieved already today. It shows the importance of interdisciplinary teamwork in design and construction throughout all involved professions, from the very beginning of the process to the very end. It acts as an important case study in communicating these principles and their benefits to the involved actors. It also reveals the many obstacles on political and administrative levels that still need to be overcome towards a circular construction industry; and it provides a unique set of materials, details and data in the continuing research on upscaling single circular prototypologies (Heisel and Hebel, 2019) and approaches towards a circular built environment or a circular industry.

The Madaster platform provides the means to document and communicate these design decisions, as well as their evaluation and effectiveness through a comparable set of values and indices. It lies in the nature of the experiment that unfortunately so far there is no other circular case study with a comparable level of detail within the Madaster database (data input for a case study in Heilbronn titled Mehr.WERT.Pavillon (Heisel et al., 2019b) is under way, but not yet finalized). Once further case studies will have been entered, a comparative study would be a necessary and interesting next research step to evaluate both data input and calculation methods in respect to the underlying design methodologies of the circular economy.

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Appendix A. Supplementary data

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