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Prototypology for a circular building industry: the potential of re-used and recycled building materials

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Abstract. The growing scarcity of resources calls for a paradigm shift from linear material consumption to circular economy – especially in the construction industry. This shift involves a complete rethinking of design principles, materials, construction technics and technologies, as well as the introduction of new business models evolving from these reconfigurations within the field. This paper will show on-going research on these themes with a focus on direct material re-use and recycling through the discussion of a prototypology – the recently concluded Mehr.WERT.Pavillon (MWP) at the BUGA 2019 in Heilbronn. The research specifically addresses a reversible, mono-material structure that is made from re-used structural steel and recycled glass. The concept of cycles therefor is significant: Utilized materials are not consumed and disposed of; instead, they are borrowed from their material cycle for a certain period of time and later returned there at equal value and utility. Sourced from recycled materials, the prototypology is a built example of urban mining; designed for disassembly at the end of its service time, it also represents a material bank for future projects – while proofing the claim, that it is possible already today to build within a circular system.

1. Introduction: towards a closed-loop building industry

A transition from the currently still dominantly linear economic system towards the Circular Economy (CE) is widely accepted as essential for the implementation of global commitments taken by the European Union (EU) and its Member States, notably the U.N. 2030 Agenda for Sustainable Development and the G7 Alliance on Resource Efficiency [1]. The most-widely accepted characterization of the concept 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” [2]. On December 2nd, 2015, the EU adopted the Circular Economy Action Plan [3] aiming to develop and implement a regulatory framework for the shift towards the CE in its single markets, as well as send clear signals and provide concrete actions to be carried out before 2020. The plan addresses four phases (production, consumption, waste management and closing of loops) in several priority areas of high impact – one of them being Construction and Demolition. Within the union, the building sector represents one of the biggest consumers of raw materials and one of the biggest producers of waste and emissions: construction and use of buildings account for about half of all extracted materials and energy consumption as well as about a third of water consumption and waste production [4]. Article 11.2 of the Waste Framework Directive (WFD) stipulates that “Member States shall take the necessary measures designed to achieve that by 2020, the preparing for re-use, recycling and other material recovery (...) of non-hazardous construction and



demolition waste excluding naturally occurring material (...) shall be increased to a minimum of 70 % by weight” [5].

This EU-wide mandatory target however includes (in the majority) down-cycling and backfilling operations using waste to substitute other materials – procedures that do not fulfil the requirements of the above-mentioned characterization of a CE, where materials or components circulate at their highest utility and value. Consequently, increased efforts have to be spent on direct and high-value re-use and recycling processes in the building industry in order to realize a true shift from linear to circular economy. The article at hand describes an exemplary case study building – a prototypology for the circular building industry (section 2) – and its re-use and recycling (section 3) related steps and decisions in regard to design, construction, structure and permit process for two selected material categories (section 4). A discussion on future work (section 5) and conclusions (section 6) are provided in the end.

2. Prototypology: *Mehr.WERT.Pavillon* at BUGA 2019

Joined from the terms *prototype* and *typology*, the prototypology represents a full-scale building, that is experiment and proof in itself to effectively and holistically discover connected aspects and unknowns of a specific question. Yet, at the same time, it is part of bigger, and systematic test series of different such types with similar characteristics, yet varying parameters [6].

The 2019 German Federal Garden Show (BUGA) in Heilbronn is both garden and city exhibition. The newly built city quarter *Neckarboden* is intended to be a test bed for new urban development scenarios concentrating on highest living standards and qualities for a socially diverse population group within a densely populated central urban setting [7]. Economic and ecologic aspects are foregrounded. Within this context, it was found necessary and relevant to implement a new thinking about resource application, leaving the present linear take-make-throw mentality behind [8].

Situated on a central lot of the BUGA terrain, the *Mehr.WERT.Garten* (translation: *Added.VALUE.Garden*) and its pavilion address the question how we can perform a paradigm shift in the way we use our resources towards a CE of closed and pure material cycles. The *Mehr.WERT.Pavillon* (MWP) is the shell, as well as main element of this exhibition on local and global resource use, alternative materials as well as their applications in circular design and construction. On the one hand, the pavilion makes use of the existing urban mine: all materials used in the project have already undergone at least one life cycle, either in the same or in a different physiognomy. On the other hand, it acts as a material depot, which will become available and productive again for future constructions at the end of the exhibition: Materials utilized in the construction of MWP are specified and employed in a way that allows their complete re-introduction into pure and type-sorted material cycles for re-use, recycling or bio-degradation after the decommissioning and deconstruction of the building. The pavilion’s objective is to proof that it is possible already today to design, detail and construct according to the principles of the CE [9].



Figure 1. View of The Mehr.WERT.Pavillon



Figure 2. View of the façade from the inside

The pavilion's building materials are separated into four groups: (1) the load-bearing structure is largely made from re-used steel originating from a disused coal-fired power plant in north-western Germany. It consists of four inclined supports that fan out like tree branches and are connected to each other by a rigid steel frame structure. (2) The façades and roof are clad in panels manufactured from recycled bottles glass and industrial glass waste. (3) The furniture is built from recycled HDPE plastic waste, while the chairs are 3D printed from plastic household waste. (4) The floor of the pavilion as well as the landscape design of the garden forms an assemblage of various re-used and recycled materials and products made from mineral construction and demolition waste (Figures 1-2).

MWP serves as a laboratory and test run for future construction projects as well as building processes. The aim is to discuss important issues of construction and the associated use of resources with decision-makers from politics, construction planning and implementation and to develop new innovative concepts, applications and methods from these, both in practice and in teaching. Therefore, it is all the more important to note that the concept of MWP originated in a student design studio by the Professorship of Sustainable Construction at the Karlsruhe Institute of Technology [10].

3. Re-use and recycling in construction

The WFD defines waste quite broadly as 'any substance or object which the holder discards or intends or is required to discard' [5], whereby this action can be both intentional or unintentional / involuntary / accidental and neither commercial value nor storage location of the substance or object have an influence on the waste status. Article 4 of WFD introduced a legally binding 5-step hierarchy of waste management operations, which member states must apply in the following order: (1) prevention, (2) preparing for re-use, (3) recycling, (4) other recovery, and (5) disposal [5]. Technically, *prevention* is not a waste management operation, as both quantitative as well as qualitative waste prevention concern substances or objects before they become waste. Obligations under waste management legislation consequently do not apply. This important distinction also applies to *re-use*, defined as 'any operation by which products or components that are not waste are used again for the same purpose for which they were conceived'.

Steps 2-5 together comprise *waste treatment*. Steps 2-4 are defined as *recovery*, where 'the principal result of a recovery operation is waste serving a useful purpose by replacing other materials'. In contrast, step 5 is negatively defined as their opposite: *disposal* includes all operations that are not recovery. Recovery is divided into three sub-categories: preparing for re-use, recycling, and other recovery. *Preparing for re-use* includes all 'checking, cleaning or repairing recovery operations, by which waste, products or components of products (...) can be re-used without any other pre-processing'. *Recycling* on the other hand is defined as 'any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes'. This includes any physical, chemical or biological treatment creating material, which no longer is considered as waste – as long as it closes the economic material circle. Consequently, operations that reprocess materials for fuels or backfilling activities are excluded from recycling and represent *other recovery* – as long as the primary purpose of the treatment still is the substitution of other materials rather than the elimination of waste [11].

Within the EU, construction and demolition waste (CDW) is the single biggest waste stream (by weight): In 2014, CDW accounted for 33.5% of EU waste or 871 million tonnes [12]. This total mass consists of several different material groups such as concrete, bricks, gypsum, wood, glass, metals, plastic, solvents and excavated soil - many of which have a (high) re-use or recycling potential [13]. In fact, most EU countries already today report a recovery rate of CDW above the mandatory 70% target, which applies to the above described steps 2-4 of the waste hierarchy, including material recovery however (contrary to the WFD definition) excluding energy recovery.

Unfortunately, the reported data is still based on varying waste and reporting definitions in separate Member States, which makes comparison and interpretation difficult. It is however very clear that the reported recovery rates always include a high percentage of operations that do not fulfil the criteria of closed material cycles in the CE, where materials, components and products should be kept at their

highest utility and value at all times. In terms of the waste hierarchy, only step 2 at the moment satisfies these criteria, while step 3 would need to exclude any downcycling processes, which in a CE understanding belong to the category of other recovery. Steps 4 and 5 both represent economical, ecological and socio-cultural losses and are to be prevented, remaining within above described hierarchy of steps. A possible definition for recycling within the CE could be: any recovery operation by which waste materials are reprocessed into products, materials or substances *of equal or better purity in fractions* whether for the original or other purposes. Within waste treatment, preparing for re-use remains the favourable operation as it conserves embodied energy, water and knowledge while reducing the need for re-processing and associated emissions.

In all cases it is essential that a material, component or product achieves the end-of-waste (EoW) status after undergoing a recovery operation and thus falls outside the scope of waste legislation before beginning its next life cycle application. In regard to the aspired paradigm shift towards the CE, ideally however materials, components or products never fall into the scope of waste legislation in the first place. Various CE-concepts such as *Design for Disassembly* [9], *Product as Service* [14] or *Extended Producer Liability* [15] aim to prevent the intention, the need or the interest in discarding substances or objects by ensuring their utility and value of a closed-loop application at all times.

Annex I of EU Construction Product Regulation (CPR) summarizes a list of basic requirements for construction works, whereby paragraph 7 addresses issues of sustainable resource use. ‘The construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following: (a) re-use and recyclability of the construction works, their materials and parts after demolition; (b) durability of the construction works; and (c) use of environmentally compatible raw and secondary materials in the construction works’ [16]. Written in 2011, this document lays down important principles of the CE for construction as described above – unfortunately by now not a single Member State has transformed Annex I into national law, keeping CPR at the status of a non-binding recommendation.

3.1. German legislation on re-use and recycling

The case study MWP is located in Heilbronn, Germany. Additionally to EU regulations, it is thus necessary to consider German waste and construction legislation when re-using and recycling materials or products within this specific setting. The German definition of waste can be found in the 2012 Waste Management Act (Kreislaufwirtschaftsgesetz), which transposes WFD into national law. However, there are no national legislative instruments governing the requirements for the recycling of mineral waste or for the use of recycled building materials or spare building materials so far, as these are within the competence of federal state legislation [17].

Because of these legal differences, the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) started working on an overarching national legal framework for ground water, substitute building materials, landfill and soil protection, the so called Mantelverordnung already in 2006. So far, unfortunately no approved version exists, but a 2017 version by the Federal Cabinet includes a new Substitute Building Materials Ordinance (Ersatzbaustoffverordnung), which aims to provide legal certainty with uniform national requirements that apply when discharging substances into groundwater, when constructing engineering structures with the use of mineral substitute building materials, and when backfilling with soil material [18].

One key element of the ordinance is its EoW definition (after extensive testing and documentation) of recovered wastes as a product with specific classes and specifications, e.g. RC-1 for recycling materials or BM-0 for soil materials, allowing their direct application in high value applications [19]. At the current state, application of recycling materials continues to be based on case-by-case approval, where materials certified and approved by an accredited laboratory in one state might not be applicable in the other 15 federal states. Section 4.2 explains the procedure based on a product from recycling glass for application in Baden-Württemberg.

In regard to re-use, legislation makes no distinction between use phases. Re-used products or materials need to be able to comply with the standards of DIN or EN norms in respect to e.g.

structural, fire, health or other specification. The problem here is that most of the times no producer or owner will certify these as the manufacturer of virgin products or materials does. Also, missing documentation on origin as well as treatment during use phases makes this step additionally difficult. As a result, often extensive testing is necessary to specify material or product properties before re-using them. Section 4.1 explains this procedure based on structural steel for Baden-Württemberg.

4. Structural application of re-used and recycled materials on the example of MWP

In general, materials used in construction are subject to numerous national standards and regulations. When used in load bearing elements, however, the demands are particularly high. The approval of a material for a structural application requires strict quality assurance during its production. In addition, it also requires a comprehensive investigation of its mechanical and physical properties as well as the knowledge of its behaviour in different load situations and climatic conditions. In Germany, structural applications must comply either with national building standards or a general technical approval (Allgemeine bauaufsichtliche Zulassung), which corresponds to a European technical approval for construction type and construction product. If there are no such corresponding approvals for the material, an exception can be obtained for the type of construction and construction product in the form of a so-called *approval in individual cases* (Zustimmung im Einzelfall - ZiE). This ZiE is approved by the building authority of the respective federal state. However, its validity is limited only to the specific construction project for which it was requested.

4.1. Re-used structural steel

Due to economic incentives, the recycling of steel scrap has been well established for a long time “without any need for stimulation or subsidy. The recycling rate is 88%” [20]. The direct re-use of structural steel, on the other hand, is currently practiced only to a minor extent with a re-use rate of 11%. In addition to a careful dismantling from the building stock here the knowledge of the material quality (classification) and the previous use is required. It must be determined what imperfections and damage to the disassembled element exist after its use. Furthermore, the nature and frequency of the previous stress situations may be relevant. The re-use of steel elements still has a high development potential, “the biggest challenge here is quality control” [20].

As mentioned, the steel structure of the MWP largely consists of steel tubes that were dismantled from a disused power plant. In addition to an exact visual inspection to determine any possible damage of the elements, the steel was examined for various properties. Tests on tensile strength, elasticity, notched impact strength (Table 1) and chemical composition (Table 2) made it possible to draw the necessary conclusions regarding the material quality. The steel quality proofed to be equal to that of standard structural steel (S235JR or S235J2), which allowed the direct re-use of the elements in a new structure.

Table 1. Test results of notched bar impact tests according to DIN EN ISO 148-1.

	length [mm]	width [mm]	thickness [mm]	consumed impact energy [J]
Dimensions of each specimen	55.0	10.0	5.0	
Average of all samples				67.7

Table 2. Test results of the chemical analysis.

	C	Mn	P	S	Cu
Requirements S235					
DIN EN 10025-2	≤ 0.17	≤ 1.40	≤ 0.035	≤ 0.035	≤ 0.55
Maximum of all samples	0.16	0.70	0.006	0.014	0.20

4.2. Recycled glass products

The use of glass in structural applications in Germany is governed by national standards (DIN 18008 Glass in Building). However, the standards only apply to the use of certain approved glass products. The panes from recycled glass used for the MWP are not covered by such product approval. Although technical approvals exist for certain building applications in facades, these differ from the type of use in the MWP. For this reason, applying for a ZiE for the use of recycled glass products in the MWP was essential. The application was based on the specifications of the existing glass standard and the stress analysis was carried out following the standard's design philosophy respectively. The ultimate stresses determined by standardized tests carried out by independent, accredited test laboratories provided the basic data for design stresses. In accordance with the glass standard, an additional mechanical safety measure was applied below the linearly mounted glass panes of the pavilion's roof through a close-meshed steel net. In addition, the manufacturer was obliged to issue a declaration of conformity for the quality control of the production by means of standardized mechanical tests.

5. Conclusions

MWP proves the feasibility of re-used and recycled materials in structural applications within a full-scale prototypology. However, as described above, the process of planning and building according to CE principles currently still shows many administrative, financial, legislative and physiological hurdles which need to be reduced quickly in order to allow a paradigm shift. Common hurdles to recycling and re-using CDW in the EU are the lack of confidence in the quality of recycled materials, missing documentation on material composition and history, a mismatch of supply and demand (both qualitative and quantitative), insufficient time allocation for audits and deconstruction works, a lack of facilities and expertise and the often low value of high quantity products. There is also uncertainty about the potential health risk for workers both deconstructing and using recycled materials. This lack of confidence reduces and restricts the demand for recycled materials, which inhibits the development of waste management and recycling infrastructures in the EU [21]. Analysing these hurdles, many of the mentioned restriction can be addressed through increased and better documentation and declaration/ certification measures.

5.1. Material documentation

The built environment represents a massive stock of material resources, which is in most cases unfortunately undocumented and unspecified. Even though much research is currently undertaken towards the development of material passports or cadastres [22], the status quo of building construction still continues undocumented. In order to prevent the costly and timely steps of section 4 and allow a circular use of materials and products, it is essential that we begin detailed libraries of materials, their specifications, dimensions, locations, connections, durability, and treatment over the time of use, regarding all buildings as material depots for future constructions [9]. Material documentation is equally essential for both recycling and re-use, whereby in the first case a focus is placed on the exact chemical composition of the material and toxicity, while the second case requires a focus on a detailed history of the materials' or products' life. Both cases require detailed information on the necessary steps in disassembly to return to pure-type material cycles. Additionally, material documentation can significantly reduce building costs if done properly and consistently [23].

5.2. Product declarations

The level of building products offers an additional chance for increased documentation through extended product declarations. Especially on EU level, much research efforts are invested into the development of harmonized Environmental Product Declaration (EPD) or Product Environmental Footprint (PEF) which not only include the above mentioned data points but additionally a description and Life Cycle Analysis (LCA) calculation of the products' recycling potential (module D) [24]. Such information can help steer decision makers and designers in their material and product selection towards elements, which are designed for re-use and recycling in closed material loops, as long as they are also applied according to CE design and construction principles. Integrating such information into Building Information Modelling (BIM) could offer a possible tool for the communication and documentation of material and product specifications, in connection to their location and disassembly guidelines.

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References

- [1] United Nations General Assembly. The 2030 Agenda for Sustainable Development. New York City, USA: United Nations; 2015. A/RES/70/1.
G7 Germany. Leaders' Declaration G7 Summit. Schloss Elmau, Germany; 2015.
- [2] Ellen MacArthur Foundation. Towards the Circular Economy: Business Rationale for an Accelerated Transition. London, UK: Ellen MacArthur Foundation; 2015.
- [3] European Commission. Closing the loop - An EU action plan for the Circular Economy. Brussels, Belgium: European Commission; 2015. COM(2015) 614.
- [4] European Commission. Roadmap to a Resource Efficient Europe. Brussels, Belgium: European Commission; 2011. COM(2011) 571.
European Commission. A lead market initiative for Europe. Brussels, Belgium: European Commission; 2007. COM(2007) 860.
European Commission. Addressing the challenge of water scarcity and droughts in the European Union. Brussels, Belgium: European Commission; 2007. COM(2007) 414.
bio Intelligence Service. Service Contract on Management of Construction and Demolition Waste - SR1. Paris, France: European Commission (DG ENV); 2011.
- [5] European Parliament and the Council. On waste and repealing certain Directives. Brussels, Belgium: European Parliament and the Council; 2008. (2008/98/EC).
- [6] Heisel F, Hebel DE. Prototypical Research: Pioneering Construction Materials. In: Cairns S, Tunas D, editors. FCL: Indicia 02. Singapore: Lars Müller Publishers; 2019. p. 200–7.
- [7] Bundesgartenschau Heilbronn 2019. Die Stadtausstellung in Kürze. (accessed 28.02.2019). https://www.buga2019.de/de/stadtausstellung/stadtausstellung_in_kuerze.php
- [8] Hebel DE, Wisniewska MH, Heisel F. Building from Waste, Recovered Materials in Architecture and Construction. Berlin, Germany; 2014.
- [9] Heisel F, Hebel DE, Sobek W. Resource-respectful construction – the case of the Urban

- Mining and Recycling unit (UMAR). In: SBE19 Brussels - BAMB-CIRCPATH “Buildings as Material Banks - A Pathway For A Circular Future.” 5-7 February 2019, Brussels, Belgium: IOP Conference Series: Earth and Environmental Science; 2019. 012043 (225).
- [10] Sustainable Construction. Building from Waste – a Pavilion for the Federal Garden Show. Design Studio in the Master Programme, Faculty of Architecture, Karlsruhe Institute of Technology. 2017.
- [11] European Commission. Guidance on the interpretation of key provisions of Directive 2008/98/EC on waste. Brussels, Belgium; 2012.
- [12] European Commission. Measuring progress towards circular economy in the European Union – Key indicators for a monitoring framework. Strasbourg, France: European Commission; 2018. SWD(2018) 17.
- [13] Deloitte. Study on Resource Efficient Use of Mixed Wastes, Improving management of construction and demolition waste. 2017. Final Report. Prepared for the European Commission, DG ENV.
- [14] Stahel WR. The Performance Economy. 2nd ed. 2010. London: Palgrave Macmillan; 2010.
- [15] Stahel WR. Circular Economy for Beginner. Geneva, CH: Product-Life Institute; 2018.
- [16] European Parliament and the Council. Laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. Brussels, Belgium: European Parliament and the Council; 2011. Regulation (EU) No 305/2011
- [17] Deloitte. Construction and Demolition Waste management in Germany. 2015. (Resource Efficient Use of Mixed Wastes). V2
- [18] BMUB. German Resource Efficiency Programme II. Berlin, Germany: Bundesministerium für Umwelt, Naturschutz, Bauen und nukleare Sicherheit; 2016.
- [19] Bundeskabinett. Verordnung zur Einführung einer Ersatzbaustoffverordnung, zur Neufassung der Bundes-Bodenschutz- und Altlastenverordnung und zur Änderung der Deponieverordnung und der Gewerbeabfallverordnung. Berlin: Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit BMU; 2017.
- Kreislaufwirtschaft Bau. Mineralische Bauabfälle Monitoring 2016. Berlin, Germany: Bundesverband Baustoffe - Steine und Erden e.V.; 2018. Report No.: 11.
- [20] Zinke T, Ummenhofer T, Hauke B, Siebers, R. Nachhaltigkeit und Normung. In: 2016 Stahlbaukalender. Berlin, Germany: Ernst&Sohn; 2016. p. 411-454.
- [21] European Commission. Guidelines for the waste audits before demolition and renovation works of buildings. Brussels, Belgium: European Commission; 2018. (EU Construction and Demolition Waste Management).
- Hobbs G, Adams K. Reuse of building products and materials – barriers and opportunities. In International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste, Delft University of Technology, Delft, The Netherlands; 2017. p. 109–13.
- [22] Building as Material Banks. 2018 (accessed 29 September 2018) <https://www.bamb2020.eu>
Madaster. 2018 (accessed 29 September 2018) <https://www.madaster.com/en>
von Richthofen A, Wei Z, Shiho A, Burkhard R, Heisel F, Müller Arisona S and Schubiger S. Urban Mining - Visualizing the Availability of Construction Materials for Re-Use in Future Cities. In *Proceedings of IV2017 - 21st International Conference on Information Visualisation* (London); 2017.
- [23] Smeets A, Wang K, Drewniok MP. Can Material Passports lower financial barriers for structural steel re-use? In: IOP Conf Series: Earth and Environmental Science. Brussels, Belgium: IOP Publishing; 2019. p. 012006. (225).
- [24] Lützkendorf TP. Product data and building assessment – flow of information. In: IOP Conf Series: Earth and Environmental Science. Brussels, Belgium: IOP Publishing; 2019. p. 012038. (225).