Circular Material Systems: anticipating whole-system design in architecture and construction

G Hubmann[1*] and V van Maaren[2]

[1]Technical University of Berlin, Straße des 17. Juni, 10623 Berlin
[2]C-Creators, Overhoeksplein 2, 1031 KS Amsterdam

*Corresponding email: g.hubmann@tu-berlin.de

Abstract. The construction sector is one of the most resource intense and environmentally damaging industries in the world. A promising approach to counteract this is to use principles of the Circular Economy (input reduction, reuse, and recycling) to ensure the continuity of value of a building's materials. Thus, we translated the learnings of an in-depth case study analysis including four buildings and their construction processes into a definition and framework for circular construction. We conceptualise buildings as circular systems that produce reusable components or biodegradable materials by practices operating across a building's lifecycle. These practices do not only include material and design aspects to close biological and technological loops, but also immaterial practices such as knowledge and expertise, locality, management and skills, and information. We argue that these organisational aspects that go beyond the current state of the art are critical enablers for circularity in construction. This perspective is relevant for practitioners in the field and allows for a new and holistic look at buildings as 'waste generators' or, in a positive scenario, as 'material depots'. Designing for recycling and reuse will require architects to build collaborations and knowledge across and beyond material value chains.

Keywords. Circular Construction, Sustainable Architecture, Circular Economy, Built environment, Whole-system Design.

1. Introduction and background

Urbanisation and climate change are two of the major concerns for humanity today. Rates of urbanisation are rapidly increasing and the effects of climate change impact ecosystems, economies, and communities around the world [1]. In this context, the construction, use, and demolition of buildings play a critical role. Conventional buildings consume massive amounts of energy, have an enormous material intensity, and produce exorbitant levels of emissions during their entire lifecycle. Globally, construction is the single most energy and emission intensive sector responsible for at least 39% of all Greenhouse Gas (GHG) emissions [2]. Besides that, the construction industry creates vast amounts of waste. For example, in Germany, 52% of the total waste produced is caused by construction and demolition [3], and across the globe about 35% of waste from construction goes to landfill [4]. Thus, buildings cause serious ecological externalities that manifest in both emissions and waste. In order to provide healthy and sustainable livelihoods in the future, approaches for architecture and construction are required that respect the planetary boundaries.

The relevance for increased sustainability in buildings is underlined by the recent proposal of a New European Bauhaus, an initiative under the umbrella of the European Green Deal that is in pursuit of a paradigm change for living spaces based on beauty, sustainability, and inclusion. The New European Bauhaus defines not only an environmental or economic approach but suggests a cultural project with aesthetic ambitions to transition to alternative models of construction [5]. At the same time, at city or regional levels of governance, initiatives that support lower emissions and less waste in construction are observable. For example, the adaptation of the building code in Berlin (Germany) to enable increased use of timber in public buildings [6] or the planned introduction of wide-spread digital material passports to transform the building stock into a material depot in the Netherlands [7].

There is widespread agreement among practitioners and scientists that the construction sector requires fundamental change regarding its production of emissions and waste. The question is how, when, and with what pace this transition will take place. Answers reach from *make do*, an approach practised by Pritzker-Prize winners Anne Lacaton and Jean-Phillipe Vassal that suggests to never demolish existing structures but to add, transform, and reuse them; *re-materialising*, keeping products in the cycle through regenerative design proposed by the cradle-to-cradle inventors William McDonough and Michael Braungart; *dematerialisation*, an argument for reducing the amount of physical substance that goes into the built environment – supported, amongst others, by R. Buckminster Fuller; to a *global building moratorium*, initiated by Charlotte Malterre-Barthes and colleagues [8].

Central to all the above-mentioned concepts is the continuity of value of a building's materials and the reduction of materials as such. This is in line with the principal ideas of the Circular Economy (CE). Generally, an economy that operates in a circular way should not have negative effects on the environment; rather, the damage done in resource acquisition should be restored while as little waste as possible is generated [9]. CE enables thinking in cycles and aims at keeping the valuation of materials in closed loops instead of having an open-ended conception of value chains. When designing products, this requires including the notions of input reduction, reuse, and recycling [10]. In other words, virgin material or energy inputs to the system and waste as well as emission outputs from the system should be reduced [11]. However, the CE discussion regarding definition, objectives, and forms of implementation is highly fragmented but there is an opportunity to use it as a tool for transformative change because it has become widely adopted in academic and non-academic sectors [12]. Yet, to make CE applicable for practitioners in construction, it requires a translation to the domain of architecture.

The CE is primarily focused on products and their lifecycles. A building is a very specific 'product' since it provides services, is usually made from a complex set of materials, and includes layers with different lifecycles. The concept of Circular Construction is trying to link the CE with construction by emphasizing recycled and renewable materials and by using design methods to make components reusable after a building's end-of-life [13]. This enlarges the traditional view of a building's lifecycle with for example modular design, secondary material use, and digital innovation (See Fig. 1).

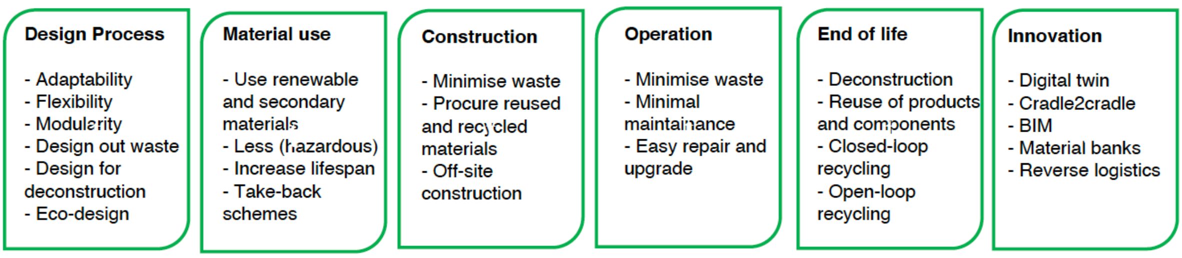

Figure 1. Key dimensions of a building's life cycle in Circular Construction, adapted from [14]

2. Methodology and overview

The aim of this paper is to learn from practice. We will develop a definition and framework for circularity in construction based on the in-depth analysis of four buildings and their construction processes that included circular thinking. The goal is to give guidance for practitioners in the field on how to implement circular processes in construction while enriching the current literature with case-based insights. Bearing in mind a building's entire life cycle, the question of this paper is how to prevent waste and keep construction materials in the value chain.

Therefore, we firstly carried out a literature review to give a short overview of the existing literature for Circular Construction and to identify current knowledge gaps. Methodologically, we used a Google Scholar search with the key words 'Circular Construction' and filtered peer-reviewed articles published in scientific journals. Our interest was to take into consideration a holistic idea of the construction process that includes all lifecycle stages of a building's materials. Therefore, we defined the following four categories that cover the processes from sourcing a material to reusing it. The categories under which we then sorted the papers are: 'Materials & Supply Chains', 'Design and Construction', Operation and Use', and 'Deconstruction and Repurposing'. Altogether, we identified 21 relevant papers that are related to or include a definition or a conceptual framework for Circular Construction. In a next step, we dismissed 8 papers because of a lack of applicability or a misleading focus, and eventually included 13 papers to create a classification (See Table 1).

Secondly, to analyse the case studies, we worked with an accepted definition of the CE literature that addresses closing resource loops for the biological and the technological cycle. For the former that means to design products in such a way that it is possible to biodegrade materials after its end-of-first-life in order to start a new cycle. For the latter this means to design products in such a way that materials can be continuously recycled into new materials or products [15]. Based on this, we thirdly carried out a case study analysis that includes four best-practice cases. The selection criteria for the cases were: located in Europe, different building typologies, related to the Circular Construction paradigm, and fulfilling resource-conscious strategies as outlined in Fig.1. The idea behind selecting cases with outstanding performance regarding closed resource loops lies in the potential to get a deep understanding how already realised projects incorporated circular thinking in construction processes. The in-depth analysis of the buildings was based on interviews with their architects or engineers and the analysis of the building's plans, thus included both quantitative and qualitative elements. The following aspects were considered: a material inventory of the building, the carbon footprint using a Life Cycle Assessment (LCA), a mapping about the localisation of supply chains behind single materials or components, an analysis of the planning approach as well as describing the necessary processes (stories behind the system) that have contributed to establishing closed resource loops.

Fourthly, based on the learnings of the case study, we developed our own definition of Circular Construction and a conceptual framework that makes the material use in buildings more explicit to give architects, designers, and builders clear guidelines for improved sustainability in construction. This framework combines material practices that are based on both the choice of materials and design decisions with immaterial practices, which were identified as a critical part of establishing circularity in construction. Finally, the paper closes with a discussion of the results, a conclusion, and an outlook.

3. Literature review and state of research

The Circular Economy (CE) has started to enter architectural design as a promising concept for resource-conscious construction practices but the research about Circular Construction remains in its infancy [16]. There is increasing awareness about the utility of the CE for construction, especially regarding closing the biological cycle. For example, the use of bio-based materials in construction replacing steel and concrete is seen as a solution to extensively store carbon in buildings and to answer the challenge of urgent climate action [17]. For future construction, it is necessary to not only produce less emissions during the production of building materials but also to sequester carbon in them to mitigate climate change [18]. However, the current framing and definition of Circular Construction implies only certain aspects within the scope of the building sector, which leads to a rather fragmented application of strategies in practice [12]. For example, extensive studies have focused on resource use and waste management while neglecting whole life cycle costing and building designs [16]. Currently, a systems perspective including how new business models might enable materials to retain high residual values is missing [14]. Another level of analysis that is lacking is the building as an entity per se [13]. Yet, there was an urge identified to find frameworks and methods to "foreground material stocks and flows in order to further the objectives […] of truly sustainable construction" [19].

Table 1. Results of the literature review.

Materials and Supply Chains	Design and Construction	Operation and Use	Deconstruction and Repurposing
Amiri et al. (2020)	Eberhardt et al. (2020)	Stephan & Athanassiadis (2018)	Furlan et al. (2020)
Churkina et al. (2020)	Hildebrand et al. (2017)		Ginga et al. (2020)
Nasir et al. (2017)			Lederer et al. (2020)
Zabek et al. (2017)			Osobajo et al. (2020)
Geldermans (2016)			Siew (2019)

Our analysis of the most relevant literature in the field of Circular Construction confirms a high fragmentation. We found that the concept of Circular Construction is limited to the type of materials used and to the recycling of waste after the end-of-life of a building – the two opposite poles of a building's lifecycle. Thus, in the existing literature we found a misbalanced interest focusing only on the direct in- and outputs of material value chains. Out of the 13 papers analysed, 5 had a strong emphasize on the use of materials and 5 on the recycling of construction and demolition waste. Surprisingly, the roles of the designers, architects, engineers, and builders who potentially have significant responsibilities regarding the choice of construction materials and their recycling as well as aspects of operation and use of a building are only marginally represented in our literature review. Another conclusion is a lack of systemic perspective across the different stages of a building's lifecycle. This suggests that the links between different stages (e.g., links between material choice, design of the building, and options for reuse after the end-of-life of a building) are not sufficiently addressed. To conclude, the identified gap is a lack of discussing the roles of design processes and construction as well as a missing focus on the operation and use of a building. Taking into consideration the lack of systemic perspective as well as the missing emphasis on the building as a unit of analysis, our further analysis is targeted at buildings and their use of materials as well as on the question of how to implement whole-system thinking in construction processes.

4. Case study: analysing best-practice examples

In this section, we highlight four innovative buildings with strategies of significantly reduced waste generation and circularity of materials. Three of them use a substantial amount of biobased materials, while two consist to a great extent of reused materials. Two of the cases are based on the design for disassembly and reassembly (DFDR) approach and one is led by material-based design, in which the materials define the design.

4.1 Mjøstårnet, Norway

The first case is the high-rise building Mjøstårnet, located in Brumunddal that was designed by Voll Arkitekter AS. The analysis shows that this building consists of 68% biobased materials (Fig. 2). Apart from the biobased construction that is addressing the biological cycle, the modular prefabrication of building components as well as the DFDR approach are key elements that contribute to a circular material use regarding the technological cycle. Fig. 3 shows that hydropower was used for the steel production process, which decreases carbon emissions.

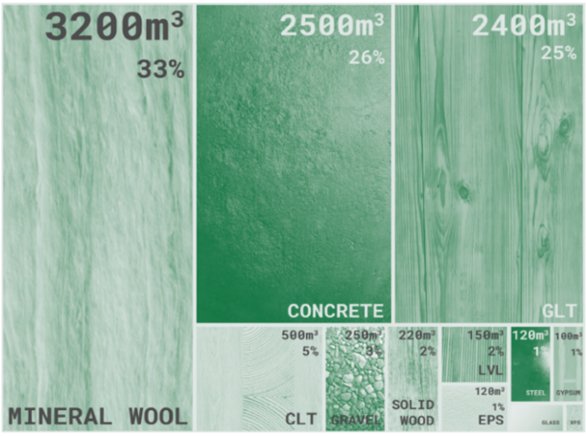

Figure 2. Material inventory of Mjøstårnet © by M. Quante and J. von Rinck.

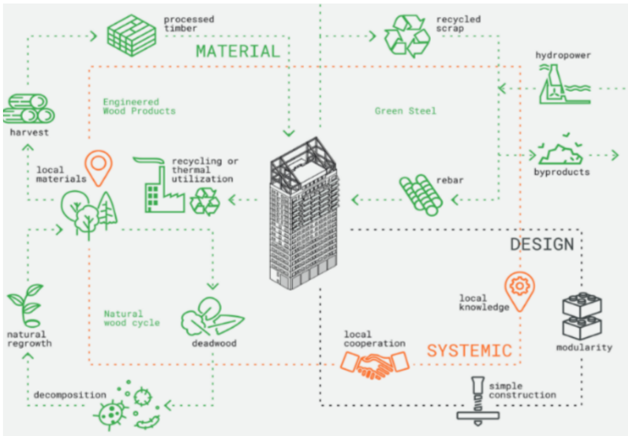

Figure 3. Circularity aspects of Mjøstårnet © by M. Quante and J. von Rinck.

In addition, most of the materials as well as most of the know-how on the production of these materials are local. Another important detail is that the willingness of the local authorities to cooperate on an all-timber structure accelerated the building permission process. Thus, the enhanced cooperation with stakeholders shortens the construction process, which results in positive environmental and economic effects.

4.2 Bombasei, Switzerland

The second case is the Bombasei Areal, located in Nänikon that was designed by Atelier Schmidt. It consists of three independent residential buildings. The material inventory highlights the high amount (65%) of biobased materials in these buildings addressing the biological cycle (Fig. 4). This together with the prefabricated modules, which created efficiencies in the construction process, leads to a very low carbon footprint for the buildings (technological cycle). Furthermore, the territorialisation of the construction material's supply chains makes the local sourcing and processing of these explicit (Fig. 5).

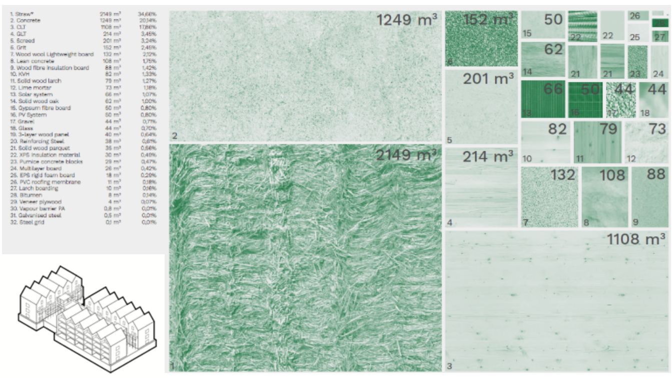

Figure 4. Material Inventory of Bombasei Areal © by P. Müller and L. Sedlmayr.

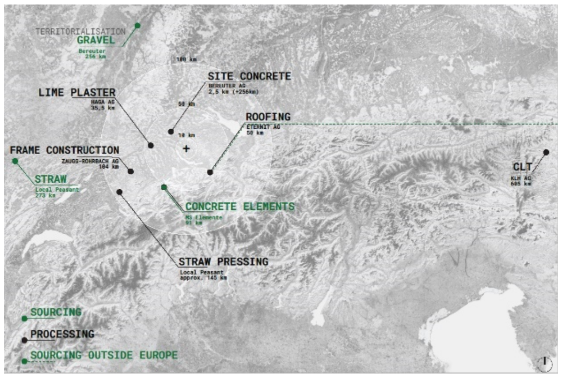

Figure 5. Mapping of the originations of construction materials for Bombasei © by P. Müller and L. Sedlmayr.

This case study reveals the potential of the residual material flow straw since approximately 20% of the straw produced annually in Germany's agriculture is not used. This would be enough material for the thermal insulation of up to 350,000 single-family homes, underpinning the architect's statement of the underused market potential for straw [20].

4.3 K118, Switzerland

The third case is K118, a three-storey extension of an old warehouse in Winterthur, designed by baubüro insitu. This construction predominantly consists of salvaged and biobased materials, addressing both the biological and technological cycle. In the preparation phase of the building, it was vital to find reused building components that only need minimal reprocessing for their new use. According to the architects, this approach resulted in a 60% saving of carbon emissions and the avoidance of 500 tons of virgin materials in comparison to designing a new building in the same size and function [21].

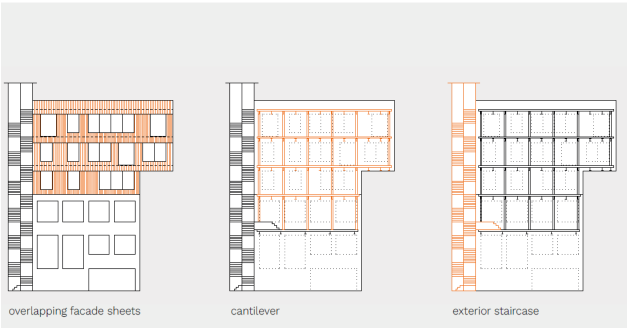

Figure 6. Form follows availability: a material-based design method © by J. Möller and M. Zountsa.

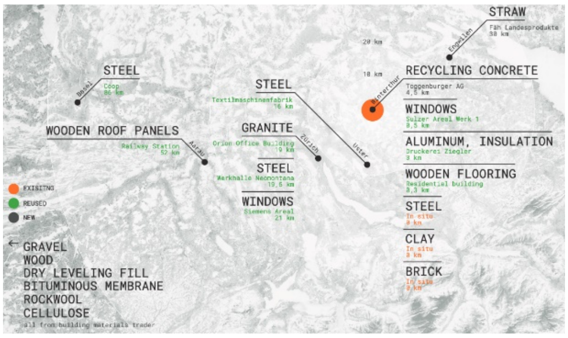

Figure 7. Local reuse of building components for K118 © by J. Möller and M. Zountsa.

The reused components from nearby demolition sites were defining the design (Fig. 7). Their availability required flexibility in the design process, resulting in a material-driven design method that had impacts on the form and function of the building (Fig. 6). The reused components are inexpensive but require significant amounts of manual labour to reinstall them. The architects underline the necessity for a material passport or a digital platform that matches supply and demand of construction materials.

4.4 Résilience, France

Designed by Archipel Zéro, Résilience, the fourth case is the head office of Novaedia, a food cooperative located in the proximity of Paris. This building addresses the biological and technological cycle by mainly using biobased materials in combination with reused materials. This resulted in a very low carbon footprint of only 41 kgCO_2eq per m^2. Biobased materials are in the façade (wood prefab composite walls with compressed straw, coated with rammed earth), floors, and insulation of the roof. The glazed façade was made from reused windows that came from a social housing complex just 4 km away. Apart from the material use, the design is completely dismountable as all elements are assembled through bolting.

Remarkable was the participative work (including 150 participants), in which the suppliers and contractors learned new construction techniques on site. Apart from that, the architect points out the necessity for a flexible design process that anticipates the availability of materials and their use in the project but also foresees a plan B in case of unexpected adaptions (Fig. 8).

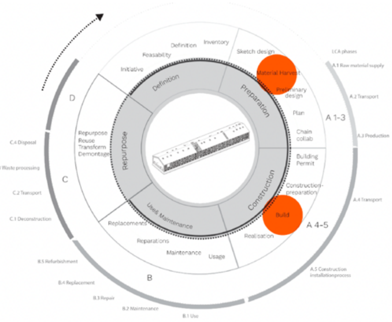

Figure 8. Thinking across lifecycle stages using a flexible design process in the case of Résilience © by M. Ponthieu and E. Toth.

5. Discussion

In the light of the Circular Construction paradigm and the question how to reduce waste and emissions in the construction of buildings, we analysed how these buildings contribute to closing resource loops on the levels of biological and technological cycles as suggested in the literature. We found that three out of four analysed cases consist of more than 60% biobased materials that potentially can be biodegraded after the building's end-of-life. At the same time, this is a significant factor for low carbon footprints of the buildings (partly only around 12 $kgCO_2eq$ per m^2). Additionally, in the case of Mjøstårnet, a strategy was employed to consciously prevent emissions during the production of the steel for the building. Thus, the choice of bio-based materials is significant to close the biological cycle but low carbon footprints as well as CO_2 prevention strategies during the production and construction might be relevant supporting mechanisms. The technological cycle was addressed mainly by the following methods: DFDR using dry connections and prefabricated modules as exemplified by Résilience and Mjøstårnet, constructing with reused materials, and using a material-based design as shown by the K118 project. In summary, the material practices mentioned in this paragraph are relevant examples for the construction industry to close resource loops.

However, the most striking result of the analysis was that immaterial practices on an organisational level that we identified as systemic enablers play a significant role in establishing circularity for the biological and technological cycles. Next to directly designing for the biological and technological cycle, systemic enablers are relevant for construction processes targeted at less emissions and waste (See Fig. 9). We have summarised them in four categories.

Knowledge and expertise: In the case of K118, the architects gained a lot of knowledge during the process of material hunting and how to subsequently implement the reused components into the design. Currently, there is limited knowledge available about these practices that differ from traditional construction methods. The architects behind Mjøstårnet emphasize the importance of local know-how as the traditional local expertise on building with wood was imporant to construct the high-rise building. A similar know-how on local materials, which was used in combination with a participatory approach was rendered critical in the case of Résilience.

Locality: Especially in the cases that use reused materials, sourcing the components from the vicinity is key to avoid long transports and avoid emissions. In the case of K118, all the materials were sourced locally within a radius of 50 kilometres from the construction site. But also in the other projects, local sourcing and manufacturing plays a significant role. Additionally, working closely with local authorities, strengthening local economies as well as accumulating and improving local knowledge are some of the interlinked benefits demonstrated by the Mjøstårnet case.

Management and skills: Understanding the shift of skills needed in the construction sector, the K118 project exemplifies this by their explicit wish for a new job: a material hunter. That new jobs in circular construction are required gets underpinned by the recent Circularity Gap Report (22).

Information: The architects of K118 underline the necessity for both a material passport of a building that makes transparent the composition of components for the next cycle and a digital platform that matches supply and demand of construction materials. The availability of information is key to a circular approach in architecture. This was also expressed regarding building with straw in the Bombasei case.

	MATERIAL PRACTICES							IMMATERIAL PRACTICES			
	BIOLOGICAL CYCLE MATERIAL			TECHNOLOGICAL CYCLE DESIGN				ORGANISATIONAL SYSTEMIC ENABLERS			
	biobased materials	low carbon footprint	emission prevention	reused materials	Design for Disassembly	material -based design	prefab modules	knowledge & expertise	locality	management & skills	information
Bombasei	●	●					●		●		●
K118	●	●		●	●	●		●	●	●	●
MJØSTÅRNET	●		●		●		●	●		●	
Resilience	●	●		●	●		●	●	●		

Figure 9. Case study overview including material and immaterial practices, © by Vera van Maaren

6. Circular Material Systems: definition and framework

Before we develop the conceptual framework, we suggest expanding the definition we used initially with immaterial practices and subcategories for the biological and technological dimensions relevant for the domain of construction (See Fig. 11). This way, we provide a more tangible definition of circularity in construction that might be useful for practitioners. We see the choice of materials reflected in the biological cycle and the design aspects including strategies regarding design for disassembly and reassembly (DFDR) are reflected in the technological cycle. The former includes the subcategories 'use of bio-based materials', 'low carbon footprint' (of the building), and 'emission prevention during production and construction'. The latter includes the subcategories 'design for disassembly and reassembly', prefabrication of modules', 'material-based design', and 'use of reused materials'.

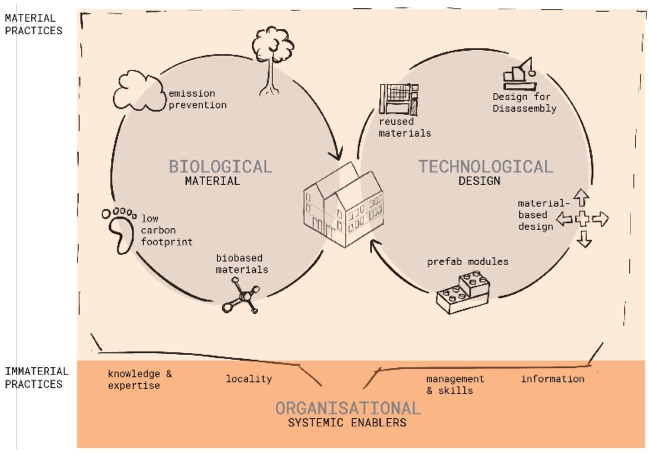

Figure 10. Immaterial practices are added to the definition of circularity in construction © by Vera van Maaren

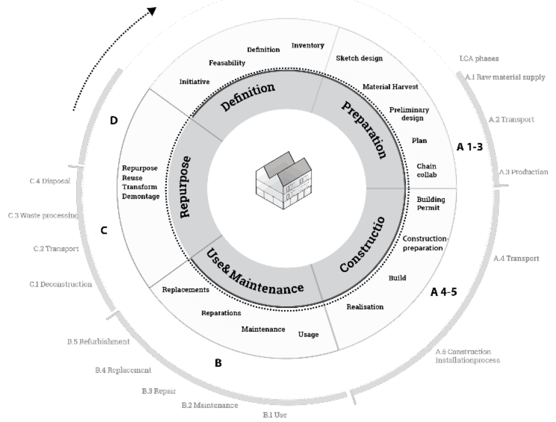

Figure 11. Holistic building development phases in comparison to the LCA phases.

This definition leads to three criteria that are necessary preconditions for establishing circularity at the building scale:

- **Materials and their use (biological cycle).** The use of biobased materials that store carbon on a long-term basis or the reuse of materials in their highest possible value as well as an emphasis on preserving already existing structures and the reuse of entire buildings through adaptation.
- **Design techniques and methods (technological cycle).** Construction methods allowing for flexibility, disassembly, separability, and deconstruction as well as material-based design techniques, in which the materials define the design.
- **Systemic enablers (organisational aspects).** A whole-system design approach focusing on keeping materials in the value chain. This includes planning aspects, digital enabling technologies, contracting and business models, and interfaces to stakeholders.

Based on the definition above, we propose a conceptual framework that we entitle Circular Material Systems (CMS). This concept sees a building not as a mere composition of different materials but as a material system. Borrowed from geomorphology, a material system defines the layers of soil and stones under the surface of the Earth. If applied to a building, this creates an overview of the amount and type of construction materials enclosed in the building. When adding the aspect of circularity, these materials should be predominantly bio-based and used in such a way that they can be fully biodegraded after the building's end-of-life to start a new cycle, or it is possible to reuse them continuously in new lifecycles. This level of circularity in a building can only be achieved by supporting immaterial practices (e.g., knowledge and expertise, locality, management and skills, information). Thus, CMS include a focus on both material (choice of materials, sourcing, design, construction techniques) and immaterial practices (planning, management, skills, knowledge) across the lifecycle of a building. We argue that the latter are a way to better connect the single stages of a building's lifecycle towards a whole-system design approach (See Fig. 12). This means applying CE thinking to all the stages of a buildings' lifecycle, which results in taking into consideration building materials and their supply chains; design methods and construction processes; organisational practices; operational aspects of buildings and their flexible use over time (e.g., maintenance, modularity, repair, refurbish) as well as the deconstruction stage and aspects of repurposing (including reuse, recycle, and remanufacture). For example, by considering the value chain of building components, the (un-)sustainability of a building's materialisation can be made visible and conclusions can be drawn about both the material and immaterial practices of construction. In summary, this perspective is relevant for practitioners in the field and allows for a new and holistic look at buildings as 'waste generators' or, in a positive scenario, as 'material depots'.

7. Conclusion

In this paper we addressed the serious ecological externalities of the construction sector (predominantly high levels of waste and emissions) by asking how to prevent waste along the lifecycle stages of a building and keep construction materials in the value chain. We identified the need to adapt the CE concept to the construction of buildings, which we addressed by giving a definition of circularity in construction that goes beyond the biological and technological cycle. The literature regarding Circular Construction is limited to the materials used and the recycling processes after the end-of-life of a building, thus a systemic perspective across a building's lifecycle is missing. Our focus was on the in-depth analysis of four buildings that took on board circular thinking, thus taking into consideration the building as a unit of analysis, which was previously lacking.

The most remarkable finding is the recognition that immaterial practices play a key role to ensure increased circularity in construction. Examples include circular business models, knowledge & skills regarding the prefabrication of timber elements, process of sourcing reused materials, the information layer in form of a building passport. These practices act as enablers for closing resource cycles on both the biological and technological levels while they have the potential to make cross-connections between different stages of a building's lifecycle to avoid the production of emissions and waste. Based on this, we developed the CMS framework that conceptually establishes architecture as a circular system. In short, this means that all the components of a building are selected, produced, and installed in such a way that they can stay in the value chain as long as possible or are biodegraded into a new cycle. But apart from only focusing on the biological and technological cycle, this requires combining material aspects such as the type of construction materials and design methods (e.g., DFDR) with organisational aspects such as the systemic enablers identified in this research (knowledge and expertise, locality, management and skills, information).

Our findings suggest that a radical shift is needed in the way we think, design, and use our buildings. What is missing today is a processual focus on the complete lifecycle of a building, something we address with the CMS framework. We want to emphasize the importance of a holistic approach in the construction process and the role architects and engineers can play in that. Through the analysed cases we noticed an enlargement of the traditional tasks of architects and engineers towards the management of additional processes. For example, material harvesting, organising leasing contracts with suppliers, or the capacity building for biobased construction techniques might lead to the creation of new jobs and skills such as 'the material hunter' who organises the sourcing of reused building components. What designing for recycling and reuse requires is building collaborations and knowledge across and beyond material value chains.

Acknowledgements
We would like to thank all the students of the two X-student research groups 'Circular Material Systems I+II for their hard work and the two anonymous reviewers for their valuable comments on earlier versions of this paper.

References

[1] IPCC, 2018: Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. P an, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

Lehmann, J., Mempel, F., & Coumou, D. (2018). Increased Occurrence of Record-Wet and Record-Dry Months Reflect Changes in Mean Rainfall. Geophysical Research Letters, 45(24), 13,468-13,476.

[2] Abergel, T., Dean, B., & Dulac, J. of. (2017). Towards a zero-emission, efficient, and resilient buildings and construction sector. In Global Status Report 2017.

[3] Müller, F., Lehmann, C., Kosmol, J., Ke ler, H., Bolland, T. (2017). Urban Mining. Ressourcenschonung im Anthropoz n. Umweltbundesamt. Bonn.

[4] Solís-Guzmán, J., Marrero, M., Montes-Delgado, M. V., & Ramírez-de-Arellano, A. (2009). A Spanish model for quantification and management of construction waste. Waste Management, 29(9), 2542-2548.

[5] https://europa.eu/new-european-bauhaus/about/about-initiative_en.

[6] https://www.parlament-berlin.de/ados/18/IIIPlen/vorgang/d18-2225.pdf.

[7] https://paspoorten.platformcb23.nl.

[8] Ruby, I., & Ruby, A. (2020). *The Materials Book*. Ruby Press. Berlin.

[9] Murray, A., Skene, K., & Haynes, K. (2017). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*(3), 369–380. https://doi.org/10.1007/s10551-015-2693-2, p. 371.

[10] Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124, p. 308.

Homrich, A. S., Galvão, G., Abadia, L. G., & Carvalho, M. M. (2018). The circular economy umbrella: Trends and gaps on integrating pathways. Journal of Cleaner Production, 175, 525–543. https://doi.org/10.1016/j.jclepro.2017.11.064, p. 526.

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. Renewable and Sustainable Energy Reviews, 68(October 2015), 825–833. https://doi.org/10.1016/j.rser.2016.09.123, p. 825.

[11] Korhonen, J., Nuur, C., Feldmann, A., & Birkie, S. E. (2018). Circular economy as an essentially contested concept. *Journal of Cleaner Production*, *175*, 544–552. https://doi.org/10.1016/j.jclepro.2017.12.111, p. 544.

[12] Calisto Friant, M., Vermeulen, W. J. V., & Salomone, R. (2020). A typology of circular economy discourses: Navigating the diverse visions of a contested paradigm. *Resources, Conservation and Recycling*, *161* (November 2019), 104917. https://doi.org/10.1016/j.resconrec.2020.104917, p.15.

[13] Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

[14] Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017, February). Circular economy in construction: current awareness, challenges and enablers. In *Proceedings of the Institution of Civil Engineers-Waste and Resource Management* (Vol. 170, No. 1, pp. 15-24).

[15] Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

[16] Osobajo, O. A., Oke, A., Omotayo, T., & Obi, L. I. (2020). A systematic review of circular

economy research in the construction industry. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/SASBE-04-2020-0034

[17] Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability*, *3*(4), 269–276. https://doi.org/10.1038/s41893-019-0462-4.

[18] Amiri, A., Ottelin, J., Sorvari, J., & Junnila, S. (2020). Cities as carbon sinks - Classification of wooden buildings. *Environmental Research Letters*, *15*(9). https://doi.org/10.1088/1748-9326/aba134

[19] Angélil & Siress (2020). The Matter of Construction: Systemic Overhaul or Tweaking the Status Quo?. In: The Materials Book, Ruby Press, p.12.

[20] Scharmer, D. & Kaesberg, B. (2017). FNR: Strohgedämmte Gebäude.

[21] Stricker, E. et al. (2021). Bauteile Wiederverwenden. Ein Kompendium zum zirkulären Bauen. Park Books.

[22] Circle Economy, (2022, June). Closing the Circularity Gap in the Dutch Built Environment.