A GUIDANCE TOOL FOR CIRCULAR BUILDING DESIGN

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ABSTRACT

Circularity and the Circular Economy (CE) are gaining ground across different industries, including the building sector. However, these terms are not clearly defined and there is a lack of proper guidance for architects to effectively implement these concepts into their designs. In this paper, the research question: "How can architects, non-expert to the CE, be stimulated and systematically guided towards circular design?" is answered through the development of a guidance tool for circular buildings. Firstly, the key principles of circularity are identified. Second, a list of 'circular design' and 'circular material usage' strategies, appearing in literature, is compiled and structured. These strategies, accompanied by relevant reference projects, are comprised into a framework (guidance tool). Last, this framework is reflected on, in terms of its capability to answer the research question.

KEYWORDS: *Circular Economy, CE, circularity, architecture, building design, design for circularity, guidance tool, framework, circular design strategies, circular material usage strategies*

I. INTRODUCTION

Ever since the Industrial Revolution, a Linear Economy (LE) model was adopted, supported by an abundance of resources. Considering the earth as a closed system, it becomes apparent that this model is restricted (Braungart & McDonough, 2002, p.103-105). Due to an increase in population and global prosperity, a turning point was reached around the year 2000. From this moment on, resource prices started increasing rather than decreasing as we came to face the limitations of our planet (EMF, n.d. c). Since the 1950's, conceptual frameworks have been developed to try to limit the destruction of the earth, such as: *Regenerative Design*, *Performance Economy*, *Cradle-to-Cradle*, *Industrial Ecology*, *Biomimicry*, *Green Economy*, *Blue Economy* and *Bio-Based Economy*. Many of these ideas are included in the Circular Economy (CE), a new economy model based on circular principles relating to environmental, social and financial assets (Verberne, 2016, p.12). There is both a moral obligation (towards future generations) and an economic incentive for the adoption of a CE model, as businesses that implement the CE can profit from efficiency gains and reputation gains (Reike et al., 2017, p.4).

In the building industry, historically, the reuse of materials has been high. However, in the past decades, the amount of demolition waste has increased significantly (Hobbs & Adams, 2017, p.109). In recent years, the concept of circularity has been gaining traction. However, as the building industry is relatively complex and generally conservative, the transition towards a CE has been slow (BIS, 2013, p.81). Recently, the focus of sustainable building design has been more on energy consumption than on materials. As the building industry remains a key contributor to resource depletion, climate change, pollution, and related problems, there is an opportunity for a better integration of the CE in the building industry (Leising et al., 2017, p.976-977).

The CE is complex and not unanimously defined. As the term 'circularity' grows in popularity, without proper backing of a clear definition or metric, its meaning becomes vague, like 'sustainable' and 'green'. Moreover, the way to achieve circularity in a building or product is subject of debate. There is an increasing amount of examples of buildings that have been labelled 'circular', but the quantity of restoration of material flows is not maximised, so the term 'circular' only applies to an (unspecified) extent. The aim of this research is to provide insight in the different aspects of circularity and the CE in architecture, and to provide a guidance tool for architects who wish to improve the circularity, as a specific attribute of quality of the building design.

1.1. Definitions

1.1.1. Circular Economy

There is no standard definition for the CE model, but major organisations share the same ideas on the concept. All definitions have in common that the CE is opposed to the LE model: "make-take-waste" (Saidani et al, 2017, p.3). The strength of the CE is the compatibility of sustainable development and economic benefits (value creation and savings by resource input reduction), environmental benefits (impact reduction) and even social benefits (job creation) (Saidani et al, 2017, p.1-2). The ultimate goal is sustainable development, achieved through the improvement of resource efficiency by circularity (Linder et al., 2017, p.546).

1.1.2. Circularity

Circularity is the quantity of restauration of resource flows (EMF et al., 2015b, p.5). It can be considered at different systemic levels. There generally are four levels of circularity: *macro* level (city, province, region, nation), *meso* level (eco-industrial parks), *micro* level (single company or consumer) and *nano* level (buildings, products, components and materials) (Saidani et al, 2017, p.4-5). The levels influence and interact with each other: the higher levels are based on the lower levels. The shift towards a CE requires changes at each of these levels (Linder et al., 2017, p.546). Circularity at nano level consists of two aspects: *circular material usage* and *circular design* (Geldermans, 2016, p.301; Loppies, 2015, p.44):

- Circular material usage: Materials are selected based on circularity: materials that are renewable (biological cycles) or reusable after usage (technical cycles);
- Circular design: Products and components are designed and manufactured to easily be disassembled at the end of their use and can be applied in a new situation again.

For buildings, circularity can be perceived and measured on a scale of 100% linear to 100% circular, as a single attribute of building quality (Linder et al., 2017, p.546-547).

1.1.3. Circular Building Design

There are various circular design strategies at nano level, focusing on products, components and materials. Circular building design is a *Design for Circularity* (DfC) strategy that is specific to, or compatible with buildings. In the field of architecture, circular design can be described as: "*a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles*" (Pomponi & Moncaster, 2017, p.711). This includes optimising the buildings' useful lifetime and integrating the end-of-life phase in the design (Leising et al., 2017, p.977).

1.2. Relevance of Research

In its long tradition, the CE has only recently gained traction, as the urgency has become more apparent due to population growth and global wealth increase (Reike et al., 2017, p.4). In addition, regulation and certification for circular performance in buildings is under development by the European Commission, increasing the incentive to develop circular design methods and business models (Hobbs & Adams, 2017, p.111). As such, the CE presents risks and opportunities for businesses. According to the EMF, one of the main transitions that should take place for a successful implementation of circular models is rethinking product design in order to facilitate the recovery of components and materials (EMF et al., 2015a, p.7). As circularity is complex, effective circular design strategies should be suggested to designers, non-expert to the CE (Saidani et al, 2017, p.13). The guidance tool proposed in this research aims to provide architects with design strategies, material selection criteria and relevant reference projects.

1.3. Scope of Research

This research aims to stimulate the transition towards a CE in architecture. In this research, building circularity is considered with the following focus and limitations:

- System boundaries: In this research the focus is on the building (nano) level and its sub-levels: building systems (Brand, 1994, p.13), products/components and materials. Circularity is considered as closed loop or potential for connected open-loop cycles at a higher systemic level;

- Focus on circularity: As explained, the transition towards a CE has technical, environmental, economic and social motivations (Saidani et al, 2017, p.1-2). However, in this research, only circularity as a combination of circular design and circular material usage (Geldermans, 2016, p.301; Loppies, 2015, p.44) is considered. Other aspects of circularity in buildings require additional research.

1.4. Research Questions and Methods

This research aims to answer the question: "*How can architects, non-expert to the CE, be stimulated and systematically guided towards circular design?*" Systematic guidance requires the framing of the key principles of circularity, using a 'logical argumentation' method (Groat & Wang, 2013, p.379). The research seeks to give logical order to the concept of circular building design, by the development of a framework for a usable guidance tool for architects, non-expert to the CE, who wish to develop a circular building design. This is done in four steps:

- Step 1: Identification of key principles of the CE and circularity. This is done through (academic and non-academic) literature on the fundamentals of the CE and circularity and on assessment methods for circular performance;
- Step 2: Exploration of existing design and material usage strategies of the CE and circularity. This is done through (academic and non-academic) literature on design methods for the CE and circularity and through architectural and non-architectural case studies of circular design;
- Step 3: Development of a framework. This is done using the knowledge gained in the literature and case study research into a usable guidance tool for the targeted users, by combining theoretical principles with practical strategies and reference projects;
- Step 4: Conclusions are drawn and recommendations for future research are made.

II. KEY PRINCIPLES OF CIRCULARITY IN BUILDINGS

The butterfly diagram by the Ellen MacArthur Foundation (EMF et al., 2015b, p.3), presented in Figure 1, is one of the most acknowledged and used CE models in businesses, as well as in academic articles (Saidani et al, 2017, p.3). The diagram illustrates the continuous flow of technical and biological materials through the 'value circle' (EMF, n.d. a).

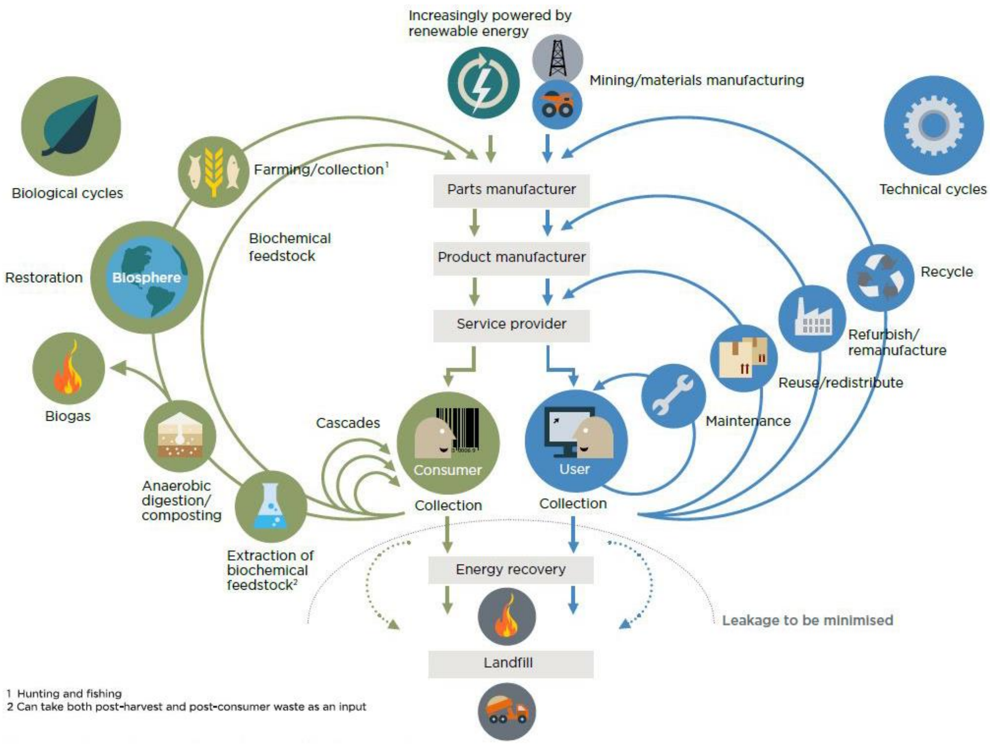

Figure 1. The *Butterfly Diagram* (EMF et al., 2015b, p.3)

Circularity is achieved through a combination of *circular material usage* and *circular design* (Geldermans, 2016, p.301; Loppies, 2015, p.44). As the CE aims to increase economic incentive for sustainable development by incorporating circularity into feasible business models, circularity can be thought of as a way of maintaining value of products, components and materials (EMF et al., 2015a, p.15). In accordance with the previous distinction, product value (or building value) has to be divided into *material value* (the value of the raw materials) and the *added value* (of the composition or arrangement of the materials in a product) (Circulardesignguide, n.d.). Circular material usage aims to prevent material degradation, and provide opportunities for material regeneration, as to protect and maintain the material value. Circular design aims to provide opportunities for tight restoration cycles, such as reuse and remanufacture, in favour of recycle, because this way, the highest amount of added value is maintained (Hobbs & Adams, 2017, p.109).

Circularity is a combination of *lifecycle thinking* and *system thinking* (Balanay & Halog, 2016, p.228; Saidani et al., 2017, p.11). *Lifecycle* phases are represented in the butterfly diagram, based on the product and material lifecycles common to the LE model (from mining to landfill), which can be abstracted to the development phase (input), the utility phase (use) and the end-of-life phase (output) (Köhler et al., 2013, p.6). Strategies for circularity should consider the entire lifespan of the product, component or material, as it is achieved by regenerative cycles that aim to prolong the use phases and eliminate the end-of-life phase (Moreno et al., 2016, p.2). *System* levels are represented in the cascading of the regenerative cycles, the tighter the cycle, the more system value is retained (EMF et al., 2015b, p.2).

2.1. Circular Design Principles

2.1.1. Lifecycle Phases

Every manufactured object has a technical, functional, aesthetical and economic lifetime with different cycle lengths, depending on the object (Verberne, 2016, p.34-35). According to Rau (VPRO Tegenlicht, 2015), in the LE, the service lifetime of products usually is dictated by the shortest of them all, as designers and manufacturers use the concept of planned obsolescence to sell more. In contrast, in the CE, there is an economic incentive to extend the service life. Circular design strategies are developed to make this possible.

2.1.2. Cascading of Hierarchical Systemic Levels

As discussed before, circularity can be achieved at different systemic levels that interact with each other (Linder et al., 2017, p.546). In this research, the level of a single building (nano level) is considered. However, to achieve circularity at this level, the building should not be seen as a single entity, but as a dynamic structure that is constantly adapting to the needs of the present (Verberne, 2016, p.34). Therefore it is necessary to think of the building as a combination of *building system*s or *levels*, such as proposed by Habraken (1961), in the ‘theory of levels’ and Brand (1994, p.13), in the theory of ‘sharing layers’. Brand proposes a model of six layers, each with its own typical service life: *site* (eternal); *structure* (30-300 years); *skin* (20 years); *services* (7-15 years); *space plan* (3-30 years); and *stuff* (<1 year). Circularity is more relevant for systems with a shorter lifetime, than for systems with a longer lifetime (Verberne, 2016, p.69).

Each of these building systems, in turn, are comprised of a selection of *products* or *components*. Again, each of these has its own service life and its own level of circularity. The systemic levels interact with each other. As an architect, selecting or designing more circular products and components will increase the level of circularity of the building system and ultimately that of the building. The lowest systemic level: *materials*, is considered in the next part.

2.2. Circular Material Usage Principles

Aside from circular design in buildings, the material usage (selection of the material and material processing method) is the final determining factor for the level of circularity.

2.1.1. Lifecycle Phases

Like circular design, circular material usage is concerned with three distinct phases: development (input), utility (use) and end-of-life (output) (Köhler et al., 2013, p.6). Material recovery is a viable circular strategy for the material input and output, but it is considered ‘the loop of last resort’

(Circulardesignguide, n.d.). When targeting the use phase, circularity strategies concern material durability (Verberne, 2016, p.41).

2.2.2. Systemic Spheres

The material usage is divided in the *technoshpere* and *biosphere*. The technosphere consists of materials that can be restored through recycling, whereas the biosphere contains all ecosystems on the planet, including all life forms and their environment, that can be naturally regenerated (EMF et al., 2015a, p.15-17). Hybrids of the two should generally be avoided (Braungart & McDonough, 2002, p. 98-117).

III. EXISTING CIRCULAR BUILDING STRATEGIES

The CE has its origins in different schools of thought, as explained by the EMF (EMF, n.d. b). These schools of thought have resulted in different frameworks for circular design. Some of them are specific to buildings, such as Buildings As Material Banks (Mulhall et al., 2017), some are more general, but can be applied to buildings, such as ReSOLVE (EMF, 2015, p.21), and others are non-building specific, but can provide inspiration for building design nonetheless.

In general, there is a discussion between the schools of thought based on eco-efficiency and those based on eco-effectiveness. The first takes the LE as a starting point, and sets out to improve it (doing more with less), while the latter takes the CE as a starting point (doing the right thing) (Braungart & McDonough, 2002, p.45-91). For something to qualify as being circular, it should make use of circular principles in the input, use and output phase. A building, system, product or component that is developed for an excessive lifetime (use phase), but ends up either as energy recovery or as landfill is not circular but is a slow linear process (Verberne, 2016, p.63).

3.1. Circular Design Strategies

The circularity cycles that characterise the CE are strategic options to deal with possible scenarios in the future, which is uncertain. The butterfly diagram (Figure 1) presents a number of options, such as maintenance, reuse, refurbish and recycle; in the order of value retention. *Design for Circularity* (DfC) is the general term for facilitating options for value retention and value recovery for the future, by means of clever, anticipating design. *Design for X* (DfX) paradigms are developed to increase the design's circular performance in regard to X, which can be any aspect of circularity, such as any one of the circularity cycles (Design for Reuse), or more general kinds of strategies (Design for Disassembly) (Verberne, 2016, p.40). The strategies are complementary rather than mutually exclusive and there is no strictly defined set of strategies, as in literature many different terms are identified. Generally, however, some kind of systemic hierarchy is adopted based on the concept of maintaining the added value (Reike et al., 2017, p.8).

The circular design strategies for the development phase are concerned with the refuse and reduce of the input (Reike et al., 2017; Verberne, 2016; Moreno et al., 2016). Concerning the use phase, circular design is generally about making the cycles longer and always using the tightest loop (highest in hierarchy) possible, as to maintain the most added value (Reike et al., 2017; Saidani et al., 2017; Moreno et al., 2016; Verberne, 2016; Köhler et al., 2013). The circular strategies of the end-of-life are concerned with the recovery of outputs, through cascading of systemic levels (Hobbs & Adams, 2017; Reike et al., 2017; Leising et al., 2017; Luscuere, 2016a, 2016b; Moreno et al., 2016; Saidani et al., 2017; Verberne, 2016; Köhler et al.). A table structuring the various circular design strategies is included in Appendix A, an explanation of the strategies is included in Appendix B. A building, system, product or component that is designed to anticipate future scenarios best will be suitable for all regeneration strategies. This ensures that in every possible scenario, the tightest loop can be used.

3.2. Circular Material Usage Strategies

Material usage is divided in the *technosphere* and *biosphere* (EMF et al., 2015b, p.2). Circular material usage strategies concerning the development phase, aim to limit the amount of virgin material input, while maintaining quality (Braungart & McDonough, 2002, p.92-117; Reike et al., 2017, p.13; Moreno et al., 2016, p.1-10). Concerning the use phase, the usage of durable materials is advised. Strategies for the output phase concern precautionary principles: materials that are chosen with consideration for future impacts and that have high quality will retain value and/or be more feasible for reuse and recycling (Verberne, 2016, p.41).

Recycling is the common term for material recovery in the technical cycles, but it occurs in granular levels: *downcycling* (converting materials into new materials of lesser quality and reduced functionality); *recycling* (recovering materials to their original quality and functionality); and *upcycling* (converting materials into new materials of higher quality and increased functionality) (EMF et al., 2015a, p.15-17). Currently in many European countries recycling is commonplace. However this is not done at high levels of application and the amount of reuse is minimal (Luscuere, 2016a, p.25). Materials in the biological cycle can be renewed through a natural process (Braungart & McDonough, 2002, p.105-109). A table structuring the various circular material usage strategies is included in Appendix C, an explanation of the strategies is included in Appendix D.

The biosphere and technosphere are both good sources for reclaiming materials. However, in practice, many times they are wrongly combined into *hybrids*. This has disastrous effects that are often unidentified by the manufacturer or user. When a biological material is inseparably combined with a technical material, the ability for natural breaking down or safely combusting of the biological part is lost. It is contaminated with elements from the technical cycle and will cause pollution or even toxicity. Besides, the technical part cannot be recycled to its original quality because it is contaminated with biological elements that will weaken it. As such, these hybrids should be avoided (Braungart & McDonough, 2002, p.98-117).

3.3. Theory Versus Practice

As mentioned before, the strategies for DfC are complementary and the inclusion of all or more of the strategies increases the circularity potential of the object of design. However, in practice it is not always possible to ensure the design provides options for every circularity loop, or some of the strategies are not relevant for the particular case, given the expected future scenarios. There are various CE business models that each focus on a specific set of cycles. Moreno et al. (2016, p.10) have identified five architype circular business models, based on circular supplies; resource value; product life extension; extending product value; and sharing platforms. In practice, the future scenarios of a product, component or material are determined by the business model that it is developed for, therefore its design should focus on these specific cycles.

Architectural as well as non-architectural case studies of circular design show prioritising towards one or several strategies, based on their respective business model. For example, the 'Design Out Waste' project by The Agency Of Design (The Agency of Design, n.d.) demonstrates this in three conceptual designs for a toaster, each designed for its own specific circular business model. This has resulted in three completely different designs, exploiting different strategies for circularity. These approaches may be applicable to other industries, such as in building design, while other approaches could be developed so suit a circular business model in such an industry specifically. In architecture, a few cases have been developed for the concept of Buildings As Material Banks (BAMB). The aim of this approach is to recover value from buildings, which are designed to facilitate that recovery (Luscuere, 2016a, p.25). For example, the extension of the city hall in Brummen, The Netherlands, by RAU, is comprised in such a way. Through lease contracts for products, components and materials, the building is ensured to be disassembled, and recirculated after its initial use. The value retention prospects of these products, components and materials have dictated much of the design, as part of this design for circular business model (RAU, n.d.). Further explanations of the circular design and circular material usage case studies is provided in Appendix B and D respectively.

IV. GUIDANCE TOOL

4.1. Development of the Tool

In order for the guidance tool to answer the research question: "*How can architects, non-expert to the CE, be stimulated and systematically guided towards circular design?*" a set of requirements was defined, aimed at 1) systematic guidance; and 2) stimulation for architects, non-expert to the CE. These requirements were implemented into a framework for the guidance tool (Figure 2). The requirements for the tool in terms of 1) systematic guidance are:

- It should comprise all the key principles of circularity in buildings;
- It should provide guidance for different circular strategies, aimed at all lifecycle phases of the design and specific to all hierarchical levels of the design;
- As the field of circularity in buildings is in development, the tool should be non-static;

And in terms of 2) stimulation for architects, non-expert to the CE:

- It should be user-friendly and comprehensible for architects, non-expert to the CE, during the design process, therefore it should combine theoretical principles with practical strategies and reference projects, using visual traits.

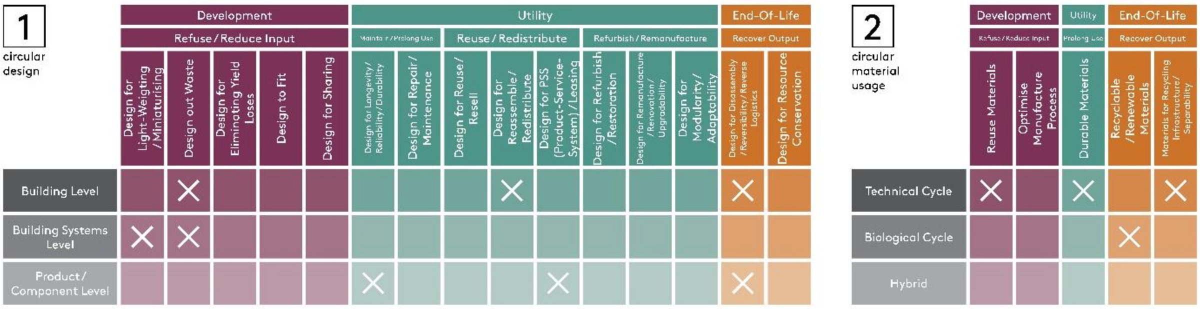

Figure 2. Framework for the circular building guidance tool (own image)

4.1.1. Development of the Framework

In the preliminary research, the appropriate format for the guidance tool was developed. In order to systematically guide architects towards circular design, a 'logical argumentation' method was chosen. The spectrum of logical argumentation spans from 'formal/mathematical' (using equations and software programs) to 'cultural/discursive' frameworks (using treatises), with 'mathematical/cultural' frameworks (using models and analytical tools) in between (Groat & Wang, 2013, p.379-411). As architects are visual people (Groat & Wang, 2013, p.25), the proposed framework is positioned at the 'cultural/discursive' side of the scale and makes use of visual traits.

The key principles of circularity in buildings, as discussed in Chapter 2, dictate the lay-out of the framework. First of all, a division was made between a *circular material usage* part and a *circular design* part, in line with the concept of *material value* and *added value*. Secondly, for both parts a matrix was comprised combining *system thinking* (rows) with *lifecycle thinking* (columns). Represented in the rows, the hierarchical systemic levels of circular building design are: *building*, *building systems*, *products/components*, while the lowest systemic level: *materials* is part of the circular material usage part. Lifecycle phases with their general circular strategies: *development* (refuse/reduce), *utility* (maintain/prolong, reuse/redistribute and refurbish/remanufacture) and *end-of-life* (recover) are included in the columns. These categorisations are based on the cascading cycles of the butterfly (EMF et al., 2015b, p.3), and on the work of Reike et al. (2017, p.13).

4.1.2. Selection of the Circularity Strategies

The circular building guidance tool includes *circular design* strategies and *circular material usage* strategies, appearing in literature by Braungart & McDonough (2002), Hobbs & Adams (2017), Reike et al. (2017), Leising et al. (2017), Luscuere (2016a, 2016b), Moreno et al. (2016), Saidani et al. (2017), Verberne (2016) and Köhler et al. (2013). A selection of strategies was made, based on relevance to building design and by reduction of similarities/duplications (tables of strategies appearing in literature are included in Appendix A and C). These strategies were structured into the framework, as is shown in Figure 2 (larger images are included in Appendix E and F). They are represented by functional colouring and contain inspiring images of precedents in order to stimulate architects.

4.1.3. Future Developments of the Tool

The framework proposed in this paper is the bases for a guidance tool for circular buildings. For it to be operational, it needs a user-friendly interface, easy accessibility and it should contain (at least) one relevant reference project in every cell. As one of the requirements, the guidance tool proposed is non-static and can be improved and expanded in the future. For these reasons, a dynamic webpage seems to be the suitable format for the final version of the guidance tool. This way, its accessibility is guaranteed and an easy interface can help users (architects) find relevant circular strategies and precedents. The content of the guide (Appendix B and D) can be updated and expanded by moderators. Additional functions, such as *circular energy usage* strategies, *circular business model* strategies and strategies to *eliminate negative externalities* (such as pollution, depletion, toxicity and human and animal mistreatment) can be added to the tool in the future. Further stimulation for architects can be achieved through additional visual traits such as icons and schematic images of circular solutions.

4.2. Guide To Use the Tool

The tool can be used by architects at different stages of the design process and for different purposes. It can serve as an exploratory guide to circular building strategies, by browsing through the different categories and learning about the different design strategies, supported by inspirational precedents. It can also serve as a tool to help make a specific design decision or to a come up with a specific design strategy, based on the object of design's hierarchical level and the targeted phase of the lifecycle.

V. Conclusions, Discussion and Recommendations

5.1. Conclusions

To answer the research question: "*How can architects, non-expert to the CE, be stimulated and systematically guided towards circular design?*" a framework for a circular building guidance tool was developed using a 'logical argumentation' method. The framework contains specific strategies for circular design and circular material usage, combined with relevant reference projects, which are structured by hierarchical systemic levels and lifecycle phases. This organisation is derived from the key principles of circularity in buildings, as defined through (academic and non-academic) literature research on the fundamentals of circularity and the CE, and on assessment methods for circular performance (Chapter 2). The circular strategies were identified through (academic and non-academic) literature on design methods for circularity and the CE, and through architectural and non-architectural case studies of circular design (Chapter 3). A selection was made based on relevance to building design and by the reduction of duplicates (Chapter 4). The result is a framework that combines theoretical principles of circularity in buildings with practical precedents, using visual traits (functional colouring and inspirational images). The framework serves as a basis for the development of a non-static circular building guidance tool, using the format of a dynamic webpage.

5.2. Discussion

The research question allows for a multitude of possible answers, of which the presented guidance tool is only one. Further research could be done to validate the effectiveness of this tool in terms of its ability to 1) *systematically guide*; and 2) *stimulate* architects towards circular design. The guidance tool is a good start for architects to become aware of possibilities for circular strategies, however, this is just one step in the transition towards a CE. Other key developments include: 1) innovative business models; 2) new reverse logistics; and 3) CE oriented system conditions; in a combined effort (EMF et al., 2015a, p.7). Therefore, the guidance tool should cooperate with other tools for these developments. In addition, circularity in architecture needs assessment metrics to quantify the circularity performance. This way, the guidance tool, as well as the individual strategies included, can be validated and improved on.

5.3. Recommendations

For the guidance tool to be operational, the following steps should be taken:

- Validation of the working of the guidance tool, through one or more test case design studies;
- The development of a user-friendly interface using the format of a dynamic webpage for easy accessibility;
- Additions to the content of the tool: at least one relevant precedent for each cell;
- A moderating system has to be developed in order to make future adjustments to the tool based on new research on circular buildings and new precedents of circular strategies.

Added functionalities to improve the applicability of the tool can be developed in the future, including:

- Validation of the effectiveness of the tool to *stimulate* and to *systematically guide* architects towards circular design;
- Increase the applicability to specific architectural design challenges, by further dividing the categories of the hierarchical levels into sub-categories. The building systems level could be split up in six different systems, as described by Brand (1994, p.13), while there are many possible further sub-categorisations for the products/components level.
- The compatibility of the tool with models for guidance of other aspects of circularity, including business models; circular energy usage and other negative externalities, such as pollution, depletion, toxicity and human and animal mistreatment;
- The inclusion or compatibility with assessment metrics of circularity in architecture, in order to validate and improve circularity strategies.

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APPENDIX A – DESIGN STRATEGIES STRUCTURED

		Guidance Tool Circular Design	Hobbs & Adams, 2017	Reike et al., 2017	Leising et al., 2017	Luscuere, 2016a	Luscuere, 2016b	Moreno et al., 2016	Saidani et al., 2017	Verberne, 2016	Köhler et al., 2013
Development	Refuse / Reduce Input	Design for Light-Weigting / Miniaturising						Design for light weighting, miniaturizing p.7			
		Design out Waste		Design out waste p.13				Design for circular supplies p.10			
		Design for Eliminating Yield Loses						Design for assembly / Design for eliminating yield loses / material / resources / parts / packaging p.3, 7	Design for assembly p.13		
		Design to Fit								Design to fit p.19	
		Design for Sharing						Design for swapping, renting and sharing p.7	(Design for) connectivity p.10		
Utility	Maintain / Prolong Use	Design for Longevity / Reliability / Durability		Design for longer p.3				Design for slowing resource loops / Design for reliability / Design for long life use of products p.1, 3, 10			
		Design for Repair / Maintenance						Design for maintainability p.3	(Design for) preventative maintenance / maintainability p.10, 13		
	Reuse / Redistribute	Design for Reuse / Resell	Designing for high reuse potential p.112	Creating loops for reuse p.4				Designing for multiple lifecycles p.6			Design for reuse p.2
		Design for Reassemble / Redistribute		(Design for) re-assemble / redistribute / recreate p.8							
		Design for PSS (Product-Service-System) / Leasing						Design for Product Service Systems (PSS) p.5			
	Refurbish / Remanufacture	Design for Refurbish / Restoration								Design for refurbishment p.20	
		Design for Remanufacture / Renovation / Upgradability		Design for remanufacturing p.13				Design for remanufacture / Design for upgrade p.3	(Design for) upgradability / remanufacture p.10, 13		
		Design for Modularity / Adaptability	Design for deconstruction and adaptabillity p.110					Design for modularity p.3	(Design for) modularity p.10, 13	Modular design / Design for adaptivity p.33, 40	
End-Of-Life	Recover Output	Design for Disassembly / Reversibility / Reverse Logistics	Reversible building design p.111	Design for disassembly p.13	Design for disassembly p.981	Reversible building design / Building design for reversability p.25	Design for disassembly p.176	Design for disassembly p.3	(Design for) easy disassembly p.10, 13	Design for disassembly p.20, 40	
		Design for Resource Conservation						Design for resource conservation p.1, 3, 10			Design for recycling and/or use of renewable resources p.2

APPENDIX B – CONTENT FOR GUIDANCE TOOL CIRCULAR DESIGN

1. Design Strategies for Development Phase

1.1. Refuse / Reduce Input	**Design for Refuse and Design for Refuse and Reduce is aimed to reduce the resource use of buildings, systems, products and components, while maintaining performance. This can be achieved in design by using regenerated inputs, by efficient design and by the increase of utility, through sharing economy and collaborative consumption.**
Design for Light-Weigting / Miniaturising	Optimised design in order to save material through weight-saving strategies and size reduction strategies.
Design out Waste	Reuse waste streams by recovering systems, products and components into the design.
Design for Eliminating Yield Loses	Strategies to reduce and eliminate resource losses in the manufacture process, and packaging (Moreno et al., 2016, p.7).
Design to Fit	Design to Fit is designing on demand or on availability as a way of optimising systems rather than component (Verberne, 2017, p.19).
Design for Sharing	Strategies to increase the utility of the object of design, by more intense use (by multiple users) and flexible functions.

2. Design Strategies for Utility Phase

2.1. Maintain / Prolong Use	**Design for Maintain/Prolong aims to maximise the technical, functional, aesthetical and economic lifetime, by slowing down loops and anticipating for easy maintenance.**
Design for Longevity / Reliability / Durability	Design to last for the appropriate technical (robustness), functional (timeless functionality), aesthetical (timeless aesthetics) and economic (cheap maintenance) lifetime (Verberne, 2016, p.34-35; Moreno, 2016, p.7).
Design for Repair / Maintenance	Design for easy repairs and maintenance, to extend the technical, functional, aesthetical and economical lifetime.
2.2. Reuse / Redistribute	**Design for Reuse is to prepare for reuse of a building, product or component to be reintroduced for the same purpose and in its original form, following minimal maintenance and cosmetic cleaning (EMF et al., 2015a, p.13). Sometimes, in order to remain functionality, redistribution is required.**
Design for Reuse / Resell	In designing to facilitate consecutive use, a level of adaptability is required, in particular versatility (shape/space lends itself for alternative use); redundancy (structural elements can bear larger loads than were originally imposed) (Verberne, 2017, p.41-42).
Design for Reassemble / Redistribute	lDesign for Reuse in a different location. Transport is key, therefore reassembly strategies could be considered.
Design for PSS (Product-Service-System) / Leasing	Designing for dematerialising products by facilitat-ing leasing, swapping, renting and sharing services, in order to increase utility and reuse (Moreno, 2016, p.7).
2.3. Refurbish / Remanufacture	**Design for Refurbish/Remanufacture aims to facilitate getting objects back to good working condition, good as new condition or even improved.**
Design for Refurbish / Restoration	Design for Refurbishment (or restoration in architecture) is the anticipation for returning a product to good working condition by replacing or repairing major components that are faulty or close to failure and making cosmetic changes to update the appearance of a product, such as changing fabric or painting (EMF et al., 2015a, p.13).
Design for Remanufacture / Renovation / Upgradability	Design for Remanufacture (or renovation in architecture) is the anticipation for disassembly and recovery at the sub-assembly or lower hierarchical level. Functioning, reusable parts can easily be taken out of a used product and rebuilt

	into a new one. This process provides quality assurance and potential enhancements or changes to the components (EMF et al., 2015a, p.13).
Design for Modularity / Adaptability	Design for Modularity is a strategy of standardisation to improve the flexibility of the product by ensuring its adaptability to suit different requirements in the future. Principles include versa-tility (shape/space lends itself for alternative use); redundancy (structural elements can bear larger loads than were originally imposed); independence (features that permit removal or up-grade without affecting the performance of connected systems). Modularity also facilitates in-terchangeability, allowing for reuse of parts elsewhere (Verberne, 2017, p.41).

3. Design Strategies for End-Of-Life Phase

3.1. Recover Output	**Design for Recover aims to substitute the end-of-life phase by recovering strategies for the outputs, in order to eliminate landfill (Moreno et al., 2016, p.2). This is done by anticipating the reuse of the outputs through cascading of hierarchical levels. If a building cannot be reused as a whole, individual systems, products or components can be reused / redistributed in a functional way and as a last resort the materials can be recycled (EMF et al., 2015a, p.13).**
Design for Disassembly / Reversibility / Reverse Logistics	Principles for Design for Disassemby include (visual, physical and ergonomical) accessibility of connections; elimination of chemical connections (binders, sealers and glues) in favour of mechanical connections (bolted, screwed and nailed connections); separation of (mechanical, electrical and plumbing) systems; and design to the worker and labour of separation (using manageable scale components) (Verberne, 2017, p.41).
Design for Resource Conservation	Reuse of the outputs through cascading of hierarchical levels is ensured by designing for easy end-of-life cleaning, collection and transportation of recovered parts and materials (Moreno et al., 2016, p.7).

4. Reference Projects For Circular Design

Design for Light-Weigting / Miniaturising - Building Systems Level	**RAU - Liander Headquarters (office building renovation)** The resource input for the steel roof structure over the existing buildings was reduced through clever engineering by rollercoaster engineers (lightweight structure experts).
Design out Waste – Building Level	**ABT - The Circular Garage Box (garage building reassembly)** As an experiment for reassembly of existing buildings, this project started with deconstructing and moving the garage boxes, which would otherwise be demolished, to the new site. There, the building was reassembled by reusing the harvested components. During this final step lessons were learned about the reuse of materials, for example the usage of old electricity cables. After completion, The Circulair Garage Box will function as an office, workshop and storage for project of the TU Delft (stichtingmilieunet.nl).
Design out Waste – Building Systems Level	**Doepelstrijkers - Haka Recycle Office (interior office building)** Both waste materials from demolition sites and waste products from production processes were harvested, transported and processed in the HAKA building to form the new interior elements (doepelstrijkers.com).
Design for Longevity / Reliability / Durability - Product / Component Level	**The Agency of Design - Optimist Toaster (product design)** This toaster aims to overcome the obsolescence of products. It is meant to last for generations. Therefore it is made from sturdy materials and everything is very simple so that it does not break. The toaster can come apart very easily to replace components if necessary. It is styled to age well and has some specific features to celebrate its age, like a toasting counter.
Design for Reassemble / Redistribute – Building Level	**MoodBuilders - Heijmans One House (house new build)** The house is designed to be used temporarily, to quickly reduce the demand in a temporarily available area. It can be reassembled and can be transported in large parts over the road.

Design for PSS (Product-Service-System) / Leasing - Product / Component Level	**The Agency of Design - Pragmatist Toaster (product design)** This toaster utilises the direct connection between manufacturer and consumer. It is modular so it can be any size needed. If a part fails, the rest of the toaster still works, the user can send the broken piece to the manufacturer and it will be replaced. Each part is designed to fit in a mailbox so that this process is easy. It should never end up in a bin. As the ownership shifts to the manufacturer, this leads to a very clear set of design requirements: simple construction, reusable parts and standardised materials. The toaster only uses one type of polymers so that it can be recycled up to nine times. On the bottom a tag shows the user how many of these cycles have passed (agencyofdesign.co.uk).
Design for Disassembly / Reversibility / Reverse Logistics - Building Level	**ARUP - Circular Pavilion (pavilion building new build)** The aim was to design a building where after its use all the materials could be re-used, re-manufactured or re-cycled. Wet fixations were avoided throughout. Instead clamp fixations are used, for example for the a self-supporting insulated wall-panel system (circularbuilding.arup.com).
Design for Disassembly / Reversibility / Reverse Logistics – Product / Component Level	**The Agency of Design - Realist Toaster (product design)** This toaster is aimed at the bottom of the market. After its use, it can easily be separated using a vacuum chamber, so that as little labour as possible is required for recycling.

APPENDIX C – MATERIAL USAGE STRATEGIES STRUCTURED

		Guidance Tool Circular Design	Braungart & McDonough, 2002	Reike et al., 2017	Moreno et al., 2016	Verberne, 2016
Development	Refuse / Reduce	Reuse Materials	Waste equals food p.92	Design out waste p.13	Design for reduce resource consumption p.7	
		Optimise Manufacture Process			Design for eliminating yield loses material p.7	
Utility	Prolong Use	Durable Materials				Select materials using the precautionary principles: materials that have high quality
End-Of-Life	Recover Output	Recyclable / Renewable Materials	Design for recycle: avoid chemicals and additives p.56		Design for biodegradability p.7	
		Materials for Recycling Infrastructure / Separability	Prevent the use of monstrous hybrids p.98-117			

APPENDIX D – CONTENT FOR GUIDANCE TOOL CIRCULAR MATERIAL USAGE

1. Material Usage Strategies for Development Phase

1.1. Refuse / Reduce Input	**Refuse and reduce the virgin material input by substituting it with recycled materials. In some cases, remining (gathering feedstocks from landfills) can be considered as a material source, but for this process human health has to be considered (Reike et al., 2017).**
Reuse Materials	Refuse and reduce the virgin material input by substituting it with recycled materials. In some cases, remining (gathering feedstocks from landfills) can be considered as a material source, but for this process human health has to be considered.
Optimise Manufacture Process	Reduce the virgin material input by selecting (materials that exploit) an efficient manufacture process, in order to minimise losses in the process of harvesting, transportation and manufacture.

2. Material Usage Strategies for Utility Phase

2.1. Prolong Use	**Use materials that can last the required lifespan, given the expected conditions of use.**
Durable Materials	Use materials with limited degradation and wear/decay, in order to provide the required functional, technical, aesthetical and economical lifetime.

3. Material Usage Strategies for End-Of-Life Phase

3.1. Recover Output	**Select materials using precautionary principles: materials that are chosen with consideration for future impacts and that have high quality will retain value and/or be more feasible for reuse and recycling (Verberne, 2017, p.41). The biosphere and technosphere are both good sources for reclaiming materials. However, in practice, many times they are wrongly combined into 'hybrids'. When a biological material is inseparably combined with a technical material, the ability for natural breaking down or safely combusting of the biological part is lost. It is contaminated with elements from the technical cycle and will cause pollution or even toxicity. Meanwhile the technical part cannot be recycled to its previous quality because it is contaminated with biological elements that will weaken it. As such, these hybrids should be avoided (Braungart & McDonough, 2007, p. 122-145).**
Recyclable / Renewable Materials	Use technical materials that can be recycled (recovered for the original purpose or for other purposes). Avoid downcycling (a lower quality residue is achieved), but pursue upcycling (increase the material quality) instead. The materials recovered feed back into the process as crude feedstock. Recycling excludes energy recovery. In the biological cycles, non-toxic materials are restored into the biosphere while rebuilding natural capital (renew) (EMF).
Materials for Recycling Infrastructure / Separability	Use materials that can be easily identified and separated. Anticipate the recycling infrastructure, at general demolition sites only few materials are separated to be recycled.

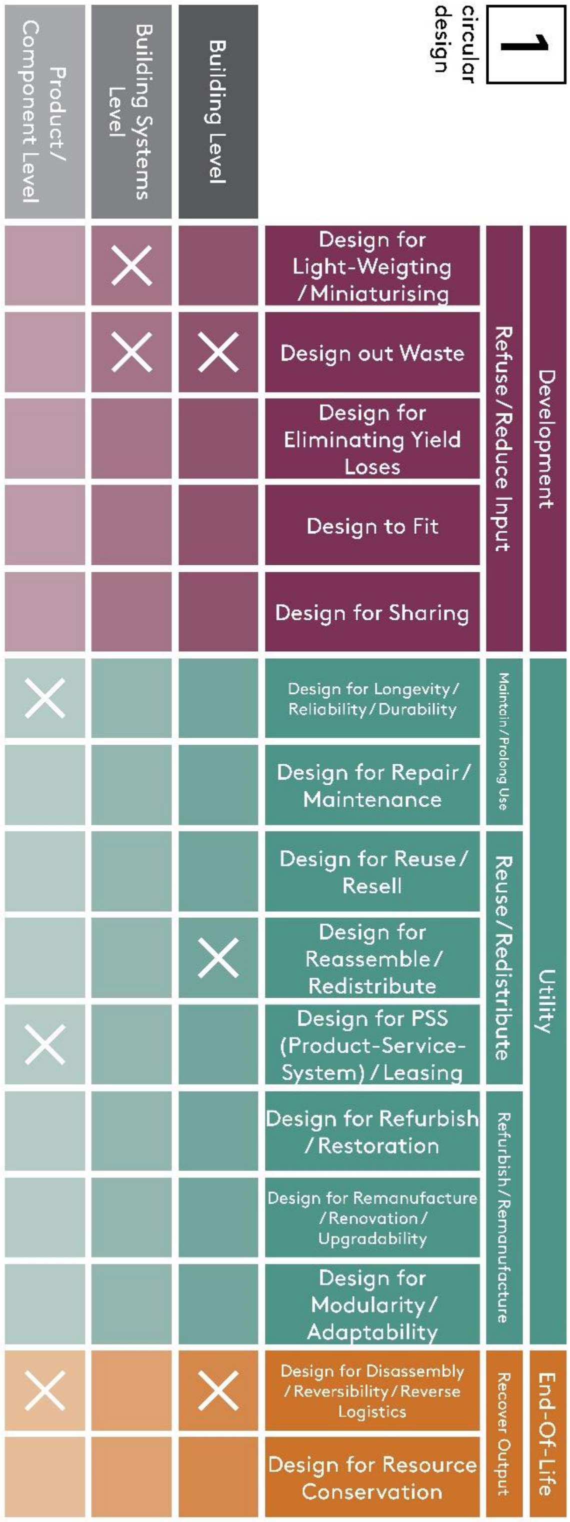
4. Reference Projects For Circular Material Usage

Reuse Materials – Technical Cycles	**Dirk Vander Kooij – Endless Chair (furniture design)** Using a self-engineered 3D printer, design furniture is manufactured from 96% recycled plastics (coming from old refrigerators). As this feedstock comes in different colours, every piece is an industrially produced 'one-of-a-kind' (dirkvanderkooij.com).
Durable Materials – Technical Cycles	**The Agency of Design - Optimist Toaster (product design)** This toaster aims to overcome the obsolescence of products. It is meant to last for generations. Therefore it is made from sturdy materials and everything is very

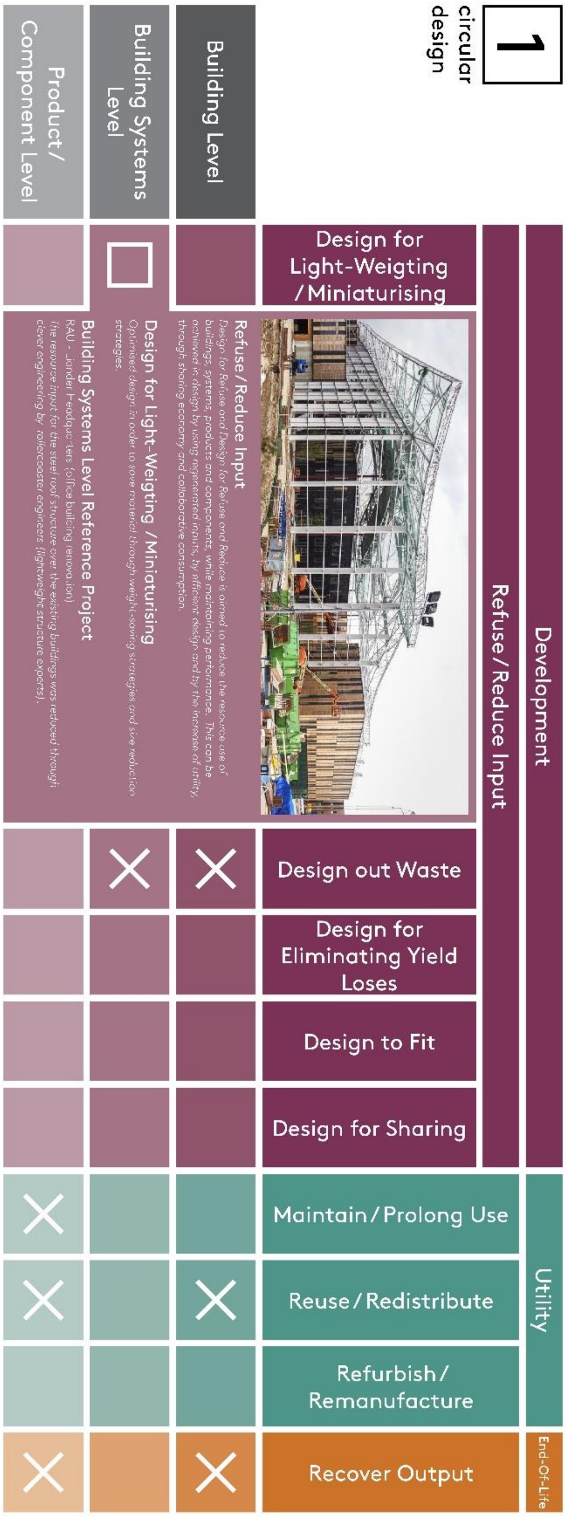
	simple so that it does not break. The case is made from (recycled) cast aluminium as it is very well recyclable and will hold its value far into the future.
Recyclable / Renewable Materials – Biological Cycles	**Finch Buildings - Finch Modules (house new build)** The house was designed to be high quality, affordable, durable housing for semi-temporary use. The units are made mostly of wood, the structure is cross-laminated timber, the cladding western red cedar wood. This way, they are renewable. It is supposed to be fully circular.
Materials for Recycling Infrastructure / Separability – Technical Cycles	**The Agency of Design – Pragmatist Toaster (product design)** This toaster utilises the direct connection between manufacturer and consumer. It should never end up in a bin. As the ownership shifts to the manufacturer, this leads to a very clear set of design requirements: simple construction, reusable parts and standardised materials. The toaster only uses one type of polymers so that it can be recycled up to nine times. On the bottom a tag shows the user how many of these cycles have passed.

APPENDIX E – IMPRESSION OF THE GUIDANCE TOOL FOR CIRCULAR BUILDINGS

1. Framework for the Circular Design Guidance Tool

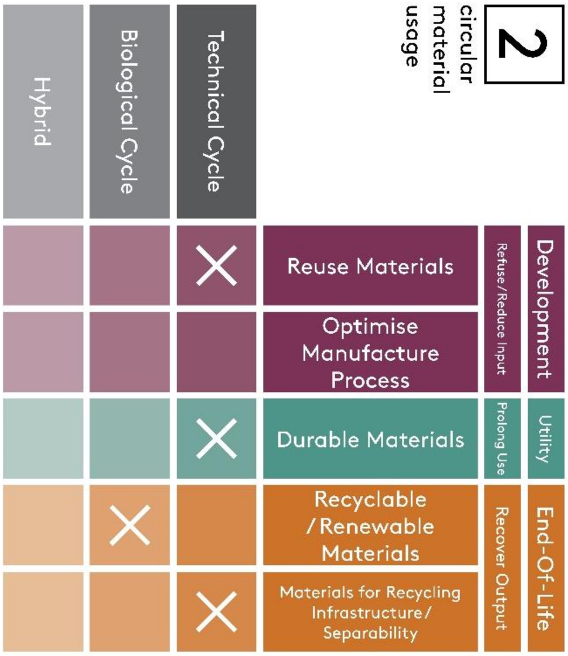


2. Circular Design Reference Project



Appendix F – Impression of the Guidance Tool for Circular Buildings

1. Framework for the Circular Material Usage Guidance Tool



2. Circular Material Usage Reference Project