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Design for change and circularity – accommodating circular material & product flows in construction

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Abstract

Circular building concepts, as proposed within e.g. Circular Economy and Cradle-to-Cradle frameworks, imply radical changes for the construction sector. Cradle-to-Cradle® in particular has put forward the idea of buildings as *material banks*, radically altering the way material flows need to be managed. The notion of material banks (temporary storage of materials that comprise the building assemblies) sheds new light on the value of building materials and products, and how to maintain and restore this. The basics are straightforward: high quality, pure material use and anticipated material regeneration routes. The implications for the supply and value chain, however, are significant, and research in this direction has only recently taken off. To smoothen the path to implementation, circular building principles may be combined with Design-for-Adaptability (DfA) guidelines, as developed over the last decades. DfA guidelines are rooted in enhanced resilience of the built environment on the one hand, and the associated constructive implications on the other. Synergy between the concepts of *circularity* and *adaptability*, with regard to the Dutch context, is at the heart of this paper. The main research question is: what are prerequisites for an effective performance of materials, products, services and buildings in the case circularity is a leading ambition? The research is structured around four interdisciplinary expert workshops in which knowledge and experiences were shared, discussed, tested and redefined, leading to a set of preconditions for circular building material and product flows. A key finding is that circularity-values emerge at the intersection of specific *intrinsic properties* (material and product characteristics) and *relational properties* (building design and use characteristics), whilst combining multiple parameters. In separation, neither intrinsic nor relational properties have decisive significance with regard to circularity; it is on the crossing where fulfillment is created. This paper finishes by discussing the findings from the perspectives of lifespan, monitoring, ownership, and standardization.

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1. Introduction: Circular material flows & Flexible buildings

1.1. Circular material flows

In the light of large global and local challenges relating, amongst others, resource scarcity, the European Union shows a shift in focus from linear to circular systems, whilst regarding waste as a resource [1]. Not only offers a circular approach an escape from depleting and wasting valuable resources, it is also linked to reduced dependencies on other countries for the supply of resources and to the creation of jobs [1,2,3]. However, circular resource flow systems usually imply higher levels of complexity, due to large changes in the way actors are interconnected, be it related to water, materials, top-soil for food production or energy systems [4]. For example, regarding decentralized decision-making, extended producer responsibility and reverse logistics. So far, many envisioned design solutions for the implementation of circular material flows have fallen short due to their relatively one-sided nature i.e. being too technocratic and too static, taking insufficient account of how environmental, social, technical, economic and temporal factors are integrated in practice [5,6].

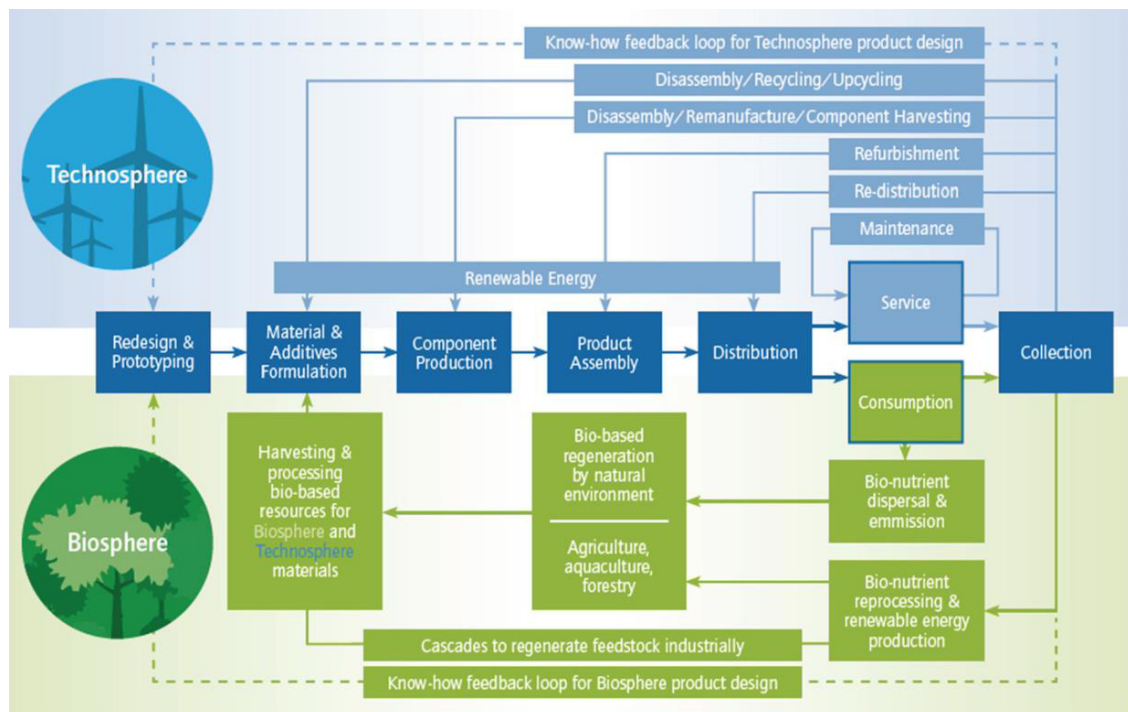


Fig. 1. Material flows in a circular economy [Source: EPEA & Returnity Partners]

With regard to architectural practice, valuable methods have been developed in the last decades to anticipate high-quality reuse of recovered materials beyond ‘end-of-pipe’ design solutions that only postpone the waste phase. *Design for Disassembly* (DfD) and *Design for Recycling* (DfR) are two such methods that gained ground in the building sector [7,8]. DfD and DfR focus on recyclability from a technical design point of view, aiming to reduce the negative environmental impacts of construction. Whether components and materials are actually used, reused and recycled in the intended way falls beyond the scope, but these are crucial indicators for the success of envisioned material loops. In essence those concepts are born out of a ‘mitigation tradition’ i.e. to lessen the effects of human activities, without exploring the potential of how those activities could actually generate positive environmental and social impacts. In

that respect there is dire need for regenerative frameworks and approaches. A few concepts lead the way in this field, for example *Cradle-to-Cradle* [2,9], *Regenerative Design* [10,11], *the Blue Economy* [12], and *Circular Economy* [3]. Those concepts open up new ways of thinking relating circulation and storage of valuable materials. The notion of *material banks* (temporary storage of materials that comprise the building assemblies), as put forward by Cradle-to-Cradle®, sheds a new light on the quality of building materials and products, and how to maintain this quality. The basics are straightforward: high quality, pure material use and anticipated reuse routes – redistribution, remanufacturing, recycling, etc., see Figure 1. The implications for the supply and value chain, however, are significant, and research in this direction has only recently really taken off.

1.2. Flexible buildings

In the last decades, the notion of urban planning has gradually been enriched with the realization that bottom-up, evolutionary growth can lead to “the most lively and successful parts of our cities” [13]. The notion of *self-organization* as a quality indicator in the formation of urban space is increasingly acknowledged within urban development theory [14,15,16]. Self-organization can be understood as the opposite of top-down planning: where self-organization is virtually limitless in its outcomes, top-down planning has inherent limiting effects on diversity [17,18]. These limiting effects can be linked to both aesthetics and function of urban form.

CHARACTERISTICS	
Long lifespan	Short lifespan
Fixed	Variable
Architecturally strong	Demountable
SCOPE	
Main structure	Partitioning walls
Collective spaces	Kitchen, bathroom
	MEP services
	(Possibly façade elements)
DECISION SPHERE	
Investor	User
CIRCULARITY RELATION	
Retained or increased value	Adapts to change
Long lifespan	Less waste
	Facilitates circular reuse

BASE BUILDING

FIT-OUT

Fig. 2. Distinction between Base building and Fit-Out.

Meeting the needs of its inhabitants is one of the main tasks to sustain vibrant, liveable cities. Housing quality is one of the main factors here [19]. In the Netherlands, as in many other countries, housing estates came up rapidly after WWII to meet the large demand for housing. The uniformity of such housing estates was met with criticism of, amongst others, John Habraken, who centred his book *‘The supports and the people – the end of mass housing’* [20] on this criticism. Habraken’s main point was that architecture failed to do justice to the heterogeneous nature of society, by internalizing design decisions that occupants, now and in the future, should really make themselves. Co-creation of the private living environment – the non-structural and individual elements – was hardly facilitated by the structural and collective ‘hardware’, thus organic growth towards successful living environments was also compromised. Rooted in this observation, Habraken suggested a division between two domains: the structural support or *base building*, decision area of the investor, and the changeable infill or *fit-out* where the user has decision power, see Figure 2. This ‘open building’ approach is often seen as the basis for Design for Adaptability (DfA) concepts, in

which a strong sense of flexibility is paramount [21]. To anticipate occupancy changes and avoid the building to become obsolete, one would imagine the notion of flexible, open design to be part of the – sustainable construction – equation. However, although important steps are made in singular innovative projects, such aspects are far from common ground and not implemented on a large scale in the Netherlands.

1.3. Research questions

From the introduction above derives the ambition to explore whether there can be a synergy between facilitating circular resource flows on the one hand, and building quality through open and adaptable approaches on the other. This is based on the assumption that a shift towards adaptable buildings has significant advantages for investors: by adding long-term value to investments, as well as users: by adding value through extensive customization possibilities. It could radically alter the way buildings – and the neighborhoods they occupy – evolve with regard to vacancy rates, deterioration, aesthetics, social cohesion and sustainability. Moreover, circulation of building products and materials at user tailored moments in time is enabled by adaptable capacity on the one hand, and autonomy over infill configurations on the other. In order to assess this synergetic potential from a technical and design point of view, preconditions and guidelines need to be defined. This objective leads to the following research questions:

1a: What are preconditions for the performance of materials, products, services and buildings in the case circularity is a leading ambition?

1b: How can those preconditions be integrated in design guidelines for circular building- and renovation projects?

2. Methodology

The research is structured around a series of four workshops in which knowledge and experiences have been shared, discussed, tested and redefined. The interdisciplinary core group, present at each workshop, existed of researchers, architects and consultants from Delft University of Technology, University of Applied Sciences Rotterdam, Briqs Foundation, and Knowledge Platform for Sustainable Resource Management. Next to this core group, external experts were invited for their specific disciplinary or project related knowledge. Lessons learned during the workshops resulted in a set of preconditions, which were then integrated into a stepwise design approach known as the New Stepped Strategy [22].

2.1. Four workshop sessions

The workshops revolved around four interrelated themes that the core group estimated to be key with regard to the task. These themes are described below.

I: Circular Building basics. The aim of the first workshop was to get grip on the concept of Circular Building. What is the role of resources, materials and products in it? Who are the current stakeholders and how may this change in the future? How does circularity relate to adaptable and open building concepts? What are the main obstacles? And which key themes can we define? Three angles were explored: freedom of choice, preservation of quality, and management of resources.

II: Adaptability & Flexibility. The second workshop was dedicated to the Flex 2.0 framework [23], based on the notion that adaptable capacity defines the future value of a building, alongside sustainability and financial performance. To a certain extent, circular building demands for flexible and adaptable buildings in order to facilitate change without loss of material quality. However, for circular building the focus lays on the materials used and their quality, recyclability and health. Adaptable building – from the viewpoint of Open Building – primarily defines the quality relating to decision power between support/infill domains, but not the actual material component quality itself.

III: Materials, Products & Standardization. The third workshop concerned resources, materials and products. What kind of materials and products are traditionally being used in the building industry and how will this change when

moving towards a circular building industry? The aim of the discussion was to define properties and conditions that stimulate circularity. What is the reuse-potential of a certain material or product? How can it maintain its quality after the lifespan of a building? The focus automatically shifted from materials to connections. Many questions arise when all connections need to be reversible and demountable. Can we still rely on custom made or should everything be universal and interchangeable? In other words: is standardization of elements the solution?

IV: Context & System Conditions. During the fourth and last workshop, the emphasis was on contextual opportunities and barriers for the transition from a linear to a circular economy. Key subjects were: business models, procurement policies, laws & regulations, and social added value.

3. Results

The research results are presented in the subsections below, addressing subsequently: key findings from the workshops, identified intrinsic properties of circular materials and products, identified relational properties of circular materials and products, defined preconditions for circular building, links between building *design layers* and material/product *regeneration flows*, and a stepwise design approach for circular building.

3.1. Workshop findings

Figure 3 displays key discussion points and findings that emerged from the workshop sessions.

3.2. Intrinsic properties

Materials and products need to fulfill some criteria in order facilitate circularity. We can distinguish intrinsic properties and relational properties. With regard to intrinsic properties, a material or product should be:

1. Of high quality (functional performance),
2. Of sustainable origin, able to ‘reincarnate’ sustainably (after every iteration),
3. Non-toxic (only healthy materials are used),
4. Consistent with biological cycle and cascade, or one or more technical cycles.

Of all the sustainable and non-toxic materials or products applied in a building, the composition and quality performance should thus be defined, as well as the use- and reuse paths. Complex products with multiple short maintenance or redistribution cycles are not necessarily better or worse than homogeneous recyclable products with a high purity and concentration. Furthermore, one should be aware of the fact that the administration required to register all these properties is a learning process rather than a one-off; interventions to the material or product in time will all need to be registered.

3.3. Relational properties

Besides their intrinsic qualities, a material or product should relate to the design and use of buildings. These relational properties concern anticipation of unknown future user scenarios. Technically, this can be defined by:

- a. Dimensions (taking into account dynamic *capacity-demands*),
- b. Connections (dry and logical),
- c. Performance time (defining the lifespan).

Again, similar to the intrinsic properties section, all relevant interventions – e.g. changing partitioning walls – need to be registered.

Session I: Circular building basics
Regenerative capacity implies: no loss of quality or value.
If we manage to substitute all resources, a circular economy comprises few incentives.
Clear definitions are required of which components belong to which 'shearing layer', with specific attention for intersection-zones.
Distinguish between legal & economic ownership, in relation to who has decision power in making changes (investor – user).
Session II: Adaptability & Flexibility
Dimensions and connections are two main 'Design for Adaptability' themes strongly related to circular building.
Adaptability and flexibility are not the goal but means to an end, and instrumental in generating quality and adding value (or save costs).
Flex 2.0 scores are arbitrary and as yet not useful for comparative analyses.
User awareness is key: in order to appreciate and apply adaptable, extendable or demountable design solutions.
Session III: Materials, Products & Standardization
By standardizing materials, you define conditions for recycling. By standardizing products you define conditions for connections.
Standardization is not always an effective option, e.g. in case digital production techniques can regulate demand for customized elements in a material-efficient way.
If the connections between elements are standardized, the (dimensions of the) elements do not necessarily need to be.
Defining the use and performance span of a building has to be part of the design process in order for material- and product choices to be adjusted to it optimally.
Session IV: Context & System Conditions
High-quality data (availability) on materials and related supply chains has advantages in every stage, for all stakeholders.
The transition from a linear to a circular economy takes place in two directions: bottom-up and top-down.
Law & regulations need adjustment, regarding intrinsic material qualities (e.g. toxicity, purity, etc.), and tendering procedures (e.g. contract methods, procurement, etc.).
Regeneration technologies and processes need to be improved and diversified in order to make significant - not only incremental -next steps.

Fig. 3. Key findings from the workshop sessions.

3.4. Preconditions for Circular Building

From a circular design point of view, the real value of a product is at the intersection of intrinsic and relational properties. This value, defined by multiple parameters, is not absolute. A few examples of different values are: use- or user value (how does the user value the building component of which the product is part?), reuse potential (how easy can the product be demounted? Can it be easily restored?), Circular Economy value (to which extent can the product function within the designated Circular Economy iterations of Figure 1?), market value, and cultural value.

In separation, neither intrinsic nor relational properties have decisive significance with regard to circularity; it is on the crossing where fulfilment is created. This accentuates the fact that circular construction comprises a dynamic, trans-disciplinary assignment. Below, seven data categories are listed that can be distinguished with regard to assessing the *circularity potential*:

- Exact composition of the material or product
- Performance quality of the material or product
- Intended (re) use path of the material or product
- Performance time of the material, product, component or service
- Connections applied between materials, products or components
- Dimensioning of materials, products or components
- Quality of the registration system and process

3.5. Circular Building Matrix

A next step is to specify the links between material and product-cycles on the one hand, and building design on the other. Figure 4 visualizes a basic inventory matrix linking building *layers* to biological or technical *regeneration routes*, proposed within the Circular Economy and Cradle-to-Cradle frameworks. Two primary fit-out layers (service system and setting) are highlighted. The distinction in building layers follows the so-called shearing layers of change [24], in the adapted version of McDonough & Partners [25]. In brackets, on the left, the average associated material turnover rates in a building's performance cycle are indicated. To complete the matrix, the layers can be further unraveled in sub categories, up to the smallest units of change relevant for the regeneration routes in question.

The New Stepped Strategy is taken as a starting point for applying the pre-conditions defined in the former section, because of its straightforward nature, and its track record with regard to sustainable building design and development concepts since its introduction in 2008. The New Stepped Strategy (NSS) is based on three steps: *1. Reduce resource demand (passive, smart & bioclimatic design)*, *2. Reuse resources (waste heat, waste water, waste materials)*, and *3. Apply regenerative – circular – solutions with regard to the remaining resource demand*.

GROUP (turnover rate)	SUB CATEGORY EXAMPLES	PART	Bio-cascades	Bio-feedstock	Maintenance	Redistribution	Refurbishment	Remanufacturing	Recycling
STUFF (8x)	...	COMPONENT, PRODUCT, MATERIAL							
SERVICE SYSTEM (4x)	Piping & wiring	COMPONENT							
	HVAC units	PRODUCT							
	Sanitary equipment	MATERIAL							
SETTING (3x)	Partitioning walls	COMPONENT							
	Connections	PRODUCT							
	Insulation	MATERIAL							
SKIN (2x)	...	COMPONENT, PRODUCT, MATERIAL							
STRUCTURE (1x)	...	COMPONENT, PRODUCT, MATERIAL							
SITE (0x)	...	COMPONENT, PRODUCT, MATERIAL							

Fig. 4. Example inventory matrix of building layers, material turnover rates and regeneration routes.

3.6. Stepwise approach Circular Building

Preconditions for circularity can be integrated into the NSS, albeit with important adjustments. To begin with, differentiation between planning and building design on the one hand, and materials and products on the other is required. Next, there is an area of tension with regard to the step ‘Reduce the demand’: from a circular point of view this is all about intelligent dimensioning, linked to an intended lifespan (see Figure 5). Furthermore, there are multiple routes imaginable, which makes the hierarchical order more complex. The stepwise approach for circular building projects is further explained below.

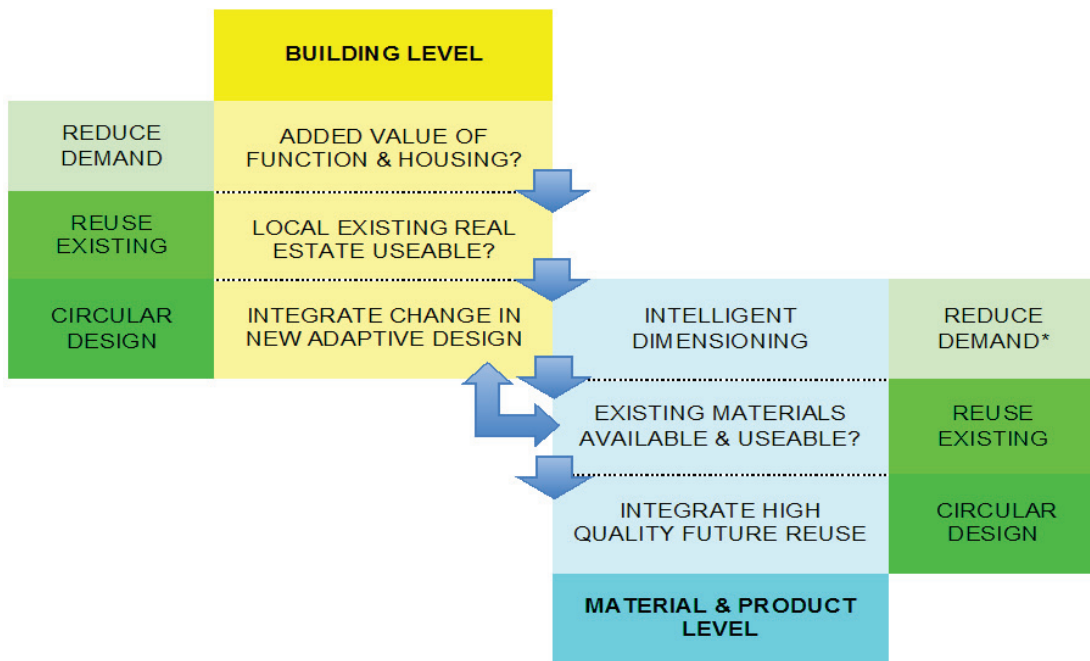


Fig. 5. Stepwise approach Circular Building.

Step 1: Evaluate the added value of the intended functions and their materialization e.g. is a new office building necessary or can extra workspace be generated by new ways of working, whilst reorganising the space?

Step 2: Explore current and future vacant buildings with regard to availability and usability. If possible, make use of local or regional data inventories regarding vacant real estate.

Step 3*: Integrate *change* in a new adaptable design. Distinguish generic elements with a long lifespan and high architectural value and specific changeable elements with a varying, shorter lifespan. Connections and dimensions are leading principles in the design and construction of the building, e.g. integrating cut outs in load bearing walls for future functions. *If local sourcing is a leading principle in the design, then step 3 may be preceded by step 5.

Step 4: Apply *intelligent dimensioning*. Measures and capacities should be suited for the planned function, performance and lifespan. In order to facilitate future changes in function or use, over-dimensioning can be an option, whilst implying a surplus material use rather than lean design. The notion to 'reduce the demand' should therefore be linked to an intended lifespan: increased material demand upfront can actually mean a reduction of material demand in the total lifespan of the building.

Step 5*: Explore the availability and usability of existing materials. Which materials in proximity to the building site can be recuperated? Define a radius for the maximum distance for which collection of materials is still beneficial. A 'harvest map', showing planned construction activities, is a useful tool in this respect. *This step can also be leading in the design, in which case it should move forward in the sequence.

Step 6: Integrate high quality future reuse. Include *change* as a design principle, while anticipating biological and technical regeneration routes. Design for disassembly and flexibility, and use material and products that keep or increase their value.

4. Discussion

Technical and design aspects are only one side of the story: organizational, cultural and legal aspects, for example, are at least as important. From that viewpoint, several considerations are introduced below.

4.1. *Intended use and lifespan*

For a material to be reused continuously in high-grade cycles, it is required to anticipate intended lifespan and use within a building. A building is not a static physical object but a collection of functions, processes and stakeholders that are subject to change over time. As such, buildings can increasingly be approached as complex systems, rather than complicated, but logical – linear assemblages of components. Inherently, this reveals multiple areas of tension with regard to keeping the initial intentions intact and advancing over time.

4.2. *Monitoring*

In a circular model it is inescapable to assemble high quality data on the applied materials and products; their composition, supply chain and properties. A systematic quality control of these data – and registration method – is equally important in order to keep up to date with developments (in know-how, user experience, change in demand, etc.). There are no readily available instruments on the market to facilitate this. Building Information Modeling (BIM) is referred to as a likely candidate, due to its inherent qualities as an interface between stakeholder data, and its position in the market. However, the use of BIM is far from being common ground in the field. Moreover, the possibilities it offers for material ‘track & trace’ needs further exploration from the perspective of circularity, for example regarding level of detail and transparency of product data.

4.3. *Ownership*

Bottom-up initiatives can mean a lot in the transition from linear to circular economic models. However, a large shift has to come from top-down regulations, since a legal change is required to facilitate and organize circular economic models. Regulations for procurement and contract methods need revision in this respect. Legal and economic demarcation is required regarding ownership of the support on the one hand, and the infill on the other. The demarcations have to be determined and communicated unambiguously: a basic rule to facilitate the different, and partly unknown, user iterations. Implementing this rule will vary according to typology; a hospital will need a different approach than an office or apartment building. Lessons learned from demonstration projects have validated, disproved or adjusted certain guidelines, but the typological differentiations, and shifts in ownership that come with those, will have to be further developed.

4.4. *Standardization*

A certain level of standardization is inevitable in a circular building industry – it ensures that materials and products can be reused in multiple buildings or systems without significant adjustments. Standardization of connections is found to be key in this respect, particularly (dry) connections in the infill domain. The design freedom of the architect and the need for diversity in our built environment are aspects that should be respected and considered when talking about standardization on a big scale. The role of the architect will shift to designing the support, whilst avoiding obstructions for the infill plan to change over time. Moreover, occupants may well commission architects to guide the infill design process.

5. Conclusion

This study underlines that implementation of circular principles for product- and material use in buildings demands radically different, integrated approach in all stages: before, during and after the performance span. Key

preconditions and guidelines are put forward to stimulate technical adjustments of the current building practice. At the intersection of intrinsic and relational aspects abides the relative ‘circularity value’. Facilitating and sustaining circular processes requires the adherence to multiple criteria and the input of multiple stakeholders. Appropriate tools for quality control are currently lacking, even if software such as BIM shows potential. Through a stepwise approach the implications for the design process on the building level and material/product level are illustrated. Successful implementation, however, depends greatly on contextual factors, comprising critical changes in e.g. value-chain relations and regulations. A major innovation on multiple fronts is thus required, and the challenges in cultural, legal and financial domains seem more profound than in the technical ones. This research shows the necessity to distinguish two types of clients, with each their own demands and perspective: the investor and the user. Clear demarcations will have to be agreed upon to determine which decisions are to be made by which stakeholder.

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