Securing Healthy Circular Material Flows In The Built Environment

The Case Of Indoor Partitioning

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Securing Healthy Circular Material Flows In The Built Environment

The Case Of Indoor Partitioning

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by

Robertus Johannes GELDERMANS
Master of Science in Industrial Ecology
Leiden University/Delft University of Technology, the Netherlands
born in Beverwijk, the Netherlands

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	chairperson
Prof.ir. P.G. Luscuere	Delft University of Technology, promotor
Prof.dr.ir A.A.J.F. van den Dobbelsteen	Delft University of Technology, promotor
Dr.ir. M.J. Tenpierik	Delft University of Technology, co-promotor

Independent members:

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Ir. D. Bruggink	Orga Architects
Prof.dr.ir. L.C.M. Itard	Delft University of Technology, reserve member

Preface

We all want a private home with the fundamental right to shape it in any way we like. However, in the last century mass housing appeared all over the world in the form of buildings in which occupants have no say about the space-plan and infill of their dwellings. Those buildings have a fixed subdivision in units with standard layouts. But households are all different and change over time, and so do their needs and desires. The reasons behind alterations may range from fashion preferences and lifestyle changes to adjustments in family size or reduced abilities. Dynamic and subjective user experiences, however, are seldom anticipated in residential building designs. With this in mind, the Open Building concept, originating in the 1960s, proposed two levels of intervention and decision-making: the (collective) 'support' and (individual) 'infill'. Although the Open Building approach has been embraced conceptually, with a new wave of interest in the Netherlands at this very moment, it is largely overlooked in the actual design and construction of housing. Current attention for Circular Building (CB) puts, once again, the spotlight on Open Building (OB). This renewed attention is based on shared benefits around flexibility, and as such CB and OB are two sides of the same coin. Circular Building could thus prove to be a game-changer in inclusive sustainable architecture. This realisation formed the starting-point for my PhD adventure about 5 years ago. As a matter of fact, the seed was planted much earlier, preluding my submission to the Master track *Industrial Ecology* between 2007 and 2009. Ever since, in my work for Except Integrated Sustainability and the Ministry of Economic Affairs, as well as Delft University of Technology and the Amsterdam Institute for Advanced Metropolitan Solutions, I have been focusing on Cradle to Cradle®, Circular Economy and related concepts, with specific attention for material flows associated with buildings and cities. Regardless of the many exciting design and engineering challenges I encountered, there was always the realisation that social benefits were taken for granted. Most specifically, those social benefits that fall through the cracks of statistics, such as the aforementioned subjective user experiences. It was clear to me that my PhD trajectory needed to manifest itself on the intersection of social and technical territories, starting from the user of buildings: me, you, us, them. I hope I have succeeded in doing so. Either way, it has been an amazing, intense, and enriching experience, for which I am extremely grateful.

My deepest respect and gratitude go to the following people: my colleagues in general, who have supported, advised and inspired me along the way, and my promoters in particular: Peter Luscuere, Martin Tenpierik, and Andy van den

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Dobbelsteen. At the fnal stage of my dissertation, the independent members of my doctoral committee, and my proofreading hero Zoe, provided invaluable feedback as well, for which I am eternally grateful. Furthermore, several indirect colleagues and mentors have guided me along the way, both through publications and in conversations, notably: Frans van der Werf, Stephen Kendall and John Habraken.

At moments, a PhD trajectory can be a solitary adventure, specifically during the long months of writing. In such periods, music has always been an essential lubricant to keep mental processes going. Therefore I'd like to thank the following people and acts, even if I do not know them personally: Augustus Pablo, Bei Bei & Shawn Lee, Burnt Friedman, Chilly Gonzales, Clutchy Hopkins, Colleen, Dictaphone, Felix Laband, Four Tet, F.S. Blumm, Hermanos Gutierrez, Nils Frahm, Prins Emanuel, Richard D. James, Suzanne Kraft & Johnny Nash, and Woo.

Moreover, I owe many thanks for the support and love I received from my parents, as well as my brother and sister. Finally, none of this would matter if it wasn't for my wonderful wife and son: Zoe and Isaac, this is for you, I hope I have managed to stay sane enough throughout the years of its writing.

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Summary

Departing from two problem statements, one concerning circularity in the built environment and one concerning flexibility in the built environment, this dissertation sets out to answer two main research questions:

- **In an Open Building division of support and infill, to what extent can the infill contribute to sustainable circular material & product flows?**
- **Which qualitative and quantitative criteria and preconditions are central to integrating the notions of user health & well-being, circularity, and flexibility in infill configurations?**

In view on these research questions, this dissertation revolves around multiple topics and disciplines, addressing material properties, material flows, product design, and user benefits, relating to a specific building component: non-bearing partitioning.

The research follows a mixed-method approach, primarily qualitatively driven and supported by quantitative data and tools. Literature studies, workshops and expert consultations are applied throughout the trajectory to derive, test and adjust criteria, guidelines and design concepts. The dissertation is structured around four research chapters (each set-up as a separate academic article), preceded by a general introduction and background sketch, and followed by an overarching evaluation of the findings.

The results from the first research chapter (Chapter 3) concern the distinction of various intrinsic and relational properties, as well as an inventory matrix based on building layers and material reutilisation routes. In the next chapter (Chapter 4), a first set of criteria is derived (*Circ-Flex I*) in order to integrate flexibility, circularity and user benefits. In Chapter 5, criteria are further elaborated, including assessment guidelines that pinpoint health, well-being, and operational performance (*Circ-Flex II).* The following chapter (Chapter 6) is aimed at design aspects: a design conceptualisation trajectory is laid out, applying design preconditions rooted in the criteria that were shaped in the preceding chapters. Furthermore, a novel flow analysis and modelling method is utilised with respect to secondary raw materials: the Activity-based Spatial Material Flow Analysis (AS-MFA). This stage revolves around materialisation and operational propositions for an innovative partitioning configuration of side-panel and insulation. The innovations are based on renewable material and reversible adhesive technologies.

The following conclusions are derived from the research:

- Circularity in the built environment can only occur if flexibility is fully integrated in the whole building (component) value network, and conversely, flexibility in the built environment increasingly depends on the handling and management of materials designated for healthy, circular applications.
- Infill parts, implemented in an Open Building context, enable multiple short to medium length cycles within the longer service lives of multi-family building structures, following changes in user requirements. As such, this model accommodates more sustainable product and material flows. However, decisive success factors are the attitude of and interplay between actors in the value network, not least the end-user.
- Technical circularity potential of building products and materials resides at the intersection of intrinsic and relational characteristics.
- The differentiation of building layers and parts, in combination with differentiated reutilisation routes, provides leverage for more advanced approaches to circular building strategies, anticipating multiple handling and treatment processes.
- To bring circular building to scale in a socially engaged way, value models need to take account of actors' shared incentives around flexibility and health, as well as split incentives around circularity.
- Monitoring the operational performance is key for capitalising on the intrinsic health and circularity potential of building components during their service life.
- Research and design exercises into circular building concepts and products benefit reciprocally from data and experience in adjacent disciplines, such as urban planning and waste management, whilst integrating multiple sub-systems associated with value creation in circular models.
- Modifications associated with the innovative partition concepts occur above all in raw material sourcing, manufacturing, reutilisation logistics, and data-sharing, of which the latter should extend to the end-user.

Next to partitioning, the findings can be relevant for other infill components as well, such as: kitchen cabinets, stairs, furniture, and the interior side-sheeting and insulation of walls and ceilings in energy-renovations. Follow-up research and practical efforts should be aimed at the development and testing of products, as well as value propositions regarding ownership: from regular transactions in which ownership shifts to the customer, to more innovative models in which ownership stays with the supplier or shifts to an intermediary actor (e.g. pay-per-use, buy-back or deposit model).

Securing healthy circular material flows in the built environment cannot be the objective of one industry, let alone one organisation, but reshuffles whole value networks. This cannot be done without binding agreements and multi-criteria learning loops. The first emphasises legal frameworks. This is therefore another prime area for future action. The aspect of multi-criteria learning loops, finally, relates to the need for more sophisticated data-exchange, also engaging end- users, which is nowadays rare in housing.

Samenvatting

Vertrekkend vanuit twee probleemstellingen, één over circulariteit en één over flexibiliteit in de gebouwde omgeving, beantwoordt dit proefschrift twee hoofdonderzoeksvragen:

- **In een Open Bouwen indeling van drager en inbouw: in hoeverre kan de inbouw bijdragen aan duurzame circulaire materiaal- en productstromen?**
- **Welke kwalitatieve en kwantitatieve criteria en randvoorwaarden staan centraal bij het integreren van de begrippen gezondheid & welzijn, circulariteit en flexibiliteit in inbouw-configuraties?**

Met het oog op deze onderzoeksvragen draait dit proefschrift om meerdere onderwerpen en disciplines, gericht op materiaaleigenschappen, materiaalstromen, productontwerp en gebruikersvoordelen van een specifiek gebouwcomponent: de niet-dragende binnenmuur (scheidingswand). Het onderzoek hanteert een 'mixed-method' aanpak, primair kwalitatief gedreven en ondersteund door kwantitatieve data en tools. Literatuurstudies, workshops, en expert-interviews zijn toegepast om criteria, richtlijnen en ontwerpconcepten te testen en aan te scherpen. De dissertatie is gestructureerd rondom vier onderzoeks-hoofdstukken (elk opgezet als een afzonderlijk academisch artikel), voorafgegaan door een algemene introductie en achtergrondschets, en gevolgd door een overkoepelende evaluatie van de bevindingen.

De resultaten van het eerste onderzoeks-hoofdstuk (hoofdstuk 3) betreffen het onderscheid tussen verschillende intrinsieke en relationele eigenschappen, evenals een inventaris-matrix op basis van bouwlagen en hergebruikroutes van materialen. In het hieropvolgende hoofdstuk (hoofdstuk 4) wordt een eerste set criteria bepaald (*Circ-Flex I*) om flexibiliteit en circulariteit te koppelen aan het perspectief van de gebruiker. In hoofdstuk 5 wordt de Circ-Flex gedachte verder uitgewerkt in criteria en beoordelingsrichtlijnen die gezondheid, welzijn en operationele prestaties koppelen (*Circ-Flex II*). Het volgende hoofdstuk (hoofdstuk 6) is gericht op ontwerp: ontwerpvoorwaarden, geworteld in de criteria die in de voorgaande hoofdstukken zijn gevormd, liggen ten grondslag aan een conceptualisering-traject. Hierbij wordt onder meer een nieuwe stromen-analyse- en modelleringsmethode gebruikt gericht op secundaire grondstoffen: de Activity-based Spatial Material Flow Analysis (AS-MFA). De resultaten van deze ontwerp-fase draaien om de materialisering en operationalisering van een innovatieve scheidingswand (zijpaneel + isolatie), gebaseerd op hernieuwbaar materiaal en omkeerbare verbindings-technologieën.

De volgende conclusies zijn afgeleid van het onderzoek:

- Circulariteit in de gebouwde omgeving kan alleen optreden als flexibiliteit volledig is geïntegreerd in de hele waardeketen, en omgekeerd hangt flexibiliteit in de gebouwde omgeving in toenemende mate af van het gebruik en management van materialen die zijn ontwikkeld voor gezonde, circulaire toepassingen.
- Volgend op veranderingen in gebruik kunnen inbouw onderdelen, geimplementeerd in een Open Bouw context, meerdere korte- tot middelange cycli activeren binnen de langere service-duur van structurele componenten. Zo faciliteert dit model een duurzamer gebruik van producten en materialen. Echter, factoren van doorslaggevend belang zijn de houding van- en interactie tussen actoren in de waardeketen, niet in de laatste plaats eindgebruikers.
- Technisch circulariteitspotentieel van bouwproducten en materialen bevindt zich op het snijvlak van intrinsieke en relationele kenmerken.
- Onderscheid van bouwlagen en onderdelen, in combinatie met gedifferentieerde hergebruikroutes, biedt een hefboomwerking voor geavanceerde circulaire bouwstrategieën, anticiperend op verschillende verwerkingsprocessen.
- Om circulair bouwen op een sociaal geëngageerde manier op schaal te brengen, moeten waardemodellen rekening houden met de gedeelde belangen van actoren rond flexibiliteit en gezondheid, evenals gesplitste belangen rond circulariteit.
- Monitoring van de operationele prestaties is van cruciaal belang om te profiteren van het intrinsieke potentieel voor gezondheid en circulariteit van bouwcomponenten tijdens hun gebruiksduur.
- Onderzoeks- en ontwerpoefeningen naar circulaire bouwconcepten en producten profiteren wederzijds van kennis en vaardigheden in aangrenzende disciplines, zoals stadsplanning en afvalbeheer. In circulaire modellen komen meerdere subsystemen samen om waarde te creëren.
- Wijzigingen in de waardeketen, die verband houden met de innovatieve scheidingswand concepten, vinden vooral plaats op het niveau van grondstoffen, fabricage, hergebruikslogistiek en gegevensuitwisseling, waarvan dat laatste ook geldt voor de eindgebruiker.

Naast scheidingswanden kunnen de bevindingen ook relevant zijn voor andere inbouwcomponenten, zoals: keukenkasten, meubels en trappen, evenals panelen en isolatie van wanden en plafonds bij energierenovaties. Vervolgonderzoek en praktische inspanningen moeten gericht zijn op de ontwikkeling en het testen van producten, evenals op waardeproposities rond eigendom: van reguliere transacties

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waarbij het eigendom naar de klant verschuift, tot meer innovatieve modellen waarbij het eigendom bij de leverancier blijft of verschuift naar een intermediaire actor (bijv. pay-per-use, buy-back of deposit model). Het veiligstellen van gezonde circulaire materiaalstromen in de gebouwde omgeving is geen opgave voor één branche, laat staan één organisatie, maar herschikt de gehele waardeketen. Dit kan niet zonder bindende overeenkomsten en multi-criteria ‘leerlussen’. Het eerste legt de nadruk op juridische kaders. Dit is dus een belangrijk gebied om nadruk op te leggen in het vervolg. Het aspect van multi-criteria leerlussen, ten slotte, refereert aan de nood tot verfijndere data-uitwisseling, inclusief engagement van eindgebruikers, wat vooralsnog zeer zeldzaam is in de woningbouw.

Terms, Definitions & Abbreviations

Relevant terms, with abbreviations where applicable, and definitions adhered to in this dissertation are listed below.

- **Adaptability** – the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising value through life [1].
- **Amsterdam Metropolitan Area** (AMA) – City region around the city of Amsterdam, and a collaboration between 32 municipalities, 2 provinces, and the Transport Authority Amsterdam [2].
- **Biological cycle** - flow of biological materials that are ultimately used up during one or more product(ion) iterations, and that can safely return to the biosphere in the form of nutrients, from which new materials can be created. This can be referred to as an 'intended consumption pathway', as opposed to the 'service pathway' of a 'technical cycle' [3].
- **Circ-Flex** – approach towards design, manufacturing, construction, and operation of infill components, adhering to (1) healthy building and renovation concepts, while allowing for (2) space lay-out flexibility, as defined by the user, and (3) safeguarding the optimal circularity potential of associated materials.
- **Circular Economy** (CE) – an economy based on the renewability of resources, retaining or creating value at optimal rates and utility, while promoting positive systemic impacts on ecology, economy, and society at large, and preventing any negative impacts [adapted from 4,5,6].
- **Circular building** (CB) – (verb) the dynamic total of associated processes, materials and stakeholders that accommodate healthy renewable flows of building materials and products at optimal rates and utility, whilst promoting positive impacts and preventing negative impacts. (noun) the manifestation of the aforementioned in a – temporary – building configuration.
- **Circularity** – movement of parts – substances, materials, products, components – through a system and constituent sub-systems in shorter or longer loops, either avoiding (fatal) degradation of comprised materials and substances, or promoting bio-degradation by design [adapted from 4,5,6,7].
- **Circularity Potential** (CP) – the capacity to accommodate circular movement of parts – substances, materials, products, components – whilst avoiding (fatal)

degradation of comprised materials and substances or promoting bio-degradation by design [adapted from 4,5,6,7].

- **Co-creation** – a creative process that taps into the collective potential of groups to generate insights and innovation [8].
- **Component** – in general: constituting part of a larger whole [9]. In this dissertation notably related to subsets of buildings, as an independently functioning assembly of materials and products [adapted from 7].
- **Criterion** (multiple: criteria) – principle or standard by which something may be judged or decided [9].
- **Design for Disassembly** (DfD) – design approach in which buildings and products are designed intentionally for material recovery, value retention, and meaningful next use [10].
- **Ecosystem services** – services that result from the life processes of multi species assemblages of organisms and their interactions with the abiotic environment, as well as the abiotic environment itself. These processes ultimately generate services when they provide utilities to humans [11].
- **Flexible building** (FB) – a building (noun) – or set of building activities (verb) - designed to allow easy rearrangements of internal fit-outs and arrangements to suit the changing needs of its occupants [adapted from12].
- **Flexibility** – the ability to adjust and allow for change.
- **Goods** – items for sale or possessions that can be moved [9].
- **Health** – state of complete physical, mental and social well-being [13]
- **Impact** – a powerful effect that something, especially something new, has on a situation, person or group [9].
- **Infill** (also: Fit-Out) – the individual level within a building structure, conceptually originating in the dichotomy between collective support and individual infill of Open Building. The infill comprises, for example, the following parts: partitions; interior doors; piping and wiring (not exceeding the individual dwelling); non-structural ceiling and floor parts; kitchen and bathroom components; stairs; and indoor finishings. Technically, also facade parts could be categorized as infill [adapted from 14].
- **Linear economy** – economical and industrial system designed on a linear, one-way ‘cradle to grave’ model. Resources are extracted, shaped into products, sold, and eventually disposed of [adapted from 15].
- **Material** – in general: a physical substance that things can be made from [9]. In this dissertation mostly related to subsets of buildings, as a processed good that becomes a building element [adapted from 7].
- **Materialisation** – to come into perceptible existence; to give material form to [16].
- **Natural resource** – any of the materials that exist in nature, such as water, wood, and coal, that can be used by people [9]. Resource that occurs in the natural environment, that is, at the location where humans extract or harvest them [17].

- **Non-bearing Partition** – vertical structure, not bearing any structural load other than itself, that separates one (part of a) space from another.
- **Open Building** (OB) – an approach to building design that increases the variety, flexibility and quality of space, ensures the idea of choice and personalisation in living for the inhabitant [adapted from 18]. OB – first introduced by John Habraken in the 1960s – distinguishes various levels of control in the built environment, essentially split between collective and individual domains. With regard to buildings, the support (or base-building) represents the collective domain, while the infill or fit-out represents the individual realm [adapted from 19].
- **Operational** – relating to a particular activity; ready to work correctly [adapted from 9].
- **Post Occupancy Evaluation** (POE) – the process of obtaining feedback from stakeholders regarding a building's performance in use, assessing, for example, productivity and well-being [adapted from 20].
- **Primary raw material** – also 'virgin material': an unprocessed resource, directly extracted or obtained from primary natural sources (for example, mining or wood felling activities) [adapted from 21].
- **Product** – in general: an article or substance that is manufactured, refined or obtained by effort [adapted from 9]. In this dissertation notably related to subsets of buildings, as a processed assembly of two or more smaller elements [adapted from 7].
- **Property** – (1) things owned: 1a. object or objects belonging to someone; 1b. a built construction and/or area of land; (2) quality or characteristic of a substance, material, or product, especially one that means it can be used in a particular way [9].
- **Quality of life** – a subjective measure of well-being. Factors vary according to context. In the EU, 9 domains have been defined as an overarching framework for the assessment: material living conditions; productive or main activity; health, education, leisure and social interactions; economic and physical safety; governance and basic rights; natural and living environment; overall experience of life [22].
- **Raw material** – crude or processed substance that can be converted into a new – intermediate or finished – good [adapted from 23]. This base feedstock can thus be of a primary or secondary nature.
- **Remanufacturing –** the rebuilding of a product to specifications of the original manufactured product, potentially using reused, repaired and new parts [24].
- **Renewability** – the capacity of any resource, material, substance or good to be used and reused in a non depleting manner, that is, without (fatal) quality-degradation and without the addition of non-renewable resources for its production and utilisation. This is related to 'regenerative capacity', which is usually applied in reference to the renewal or reconstitution of a damaged or inactive state [adapted from 6,21].

- **Resource** – a source of supply that can be drawn upon when needed [9]. In this dissertation notably applied with regard to physical natural matter, extracted and used to man's advantage, for material products and energy, but also refering to water, air, or topsoil [6].
- **Reutilisation pathway** – the primary route selected to retain or regenerate value embedded in the material or product after a useful iteration. This follows a hierarchical order as applied in multiple Circular Economy or Cradle to Cradle related concepts, comprising, amongst others, direct reuse on-site; reuse off-site (i.e redistribution); remanufacturing; recycling; and biological cascading [adapted from 4 and 5].
- **Rural areas** – all areas outside urban clusters [25].
- **Secondary raw material** – waste and non-waste substances and materials that can be applied as primary materials via simple or more complex re-processing steps [adapted from 26].
- **Substance** – a material with particular physical characteristics and chemical constitution [adapted from 9 and 23].
- **Subsystem** – a group of interconnected and interactive parts that performs a task as a component within a larger system
- **Supply chain** – a system of organisations, people, technologies, activities, information, and resources involved in moving a product or service from supplier to customer. Supply chain activities transform natural resources, raw materials and components into a finished product [27].
- **Support** (also Base-Building) – a building's structural and collective level, conceptually originating in the dichotomy between support and infill of *Open Building*.
- **Sustainability** – the balanced and systemic integration of intra and intergenerational environmental, social, and economic performance [28].
- **System** – an interconnected set of elements that is coherently organised in a way that achieves something. A system must consist of three kinds of things: elements, interconnections, and purpose [29].
- **Technical cycle** – flow of man-made materials that are not used up during utilisation in a product but that can be reprocessed and used again in a new product. This is referred to as an 'intended service pathway', as opposed to the 'consumption pathway' of a 'Biological cycle' [3].
- **Toxicity** – the extent to which something is poisonous or harmful [30].
- **Urban** – characteristic of a town or city area. The term is distinct from 'rural' or 'peri-urban' built environments in terms of population-density, services, infrastructures, and uses, relationships, and complexity. 'Urban clusters' are clusters of contiguous grid cells of 1 km^2 with a density of at least 300 inhabitants per km^2 and a minimum population of 5 000 [adapted from 25].

- **Value** – the regard that something is held to deserve, that is, the importance, worth, or usefulness of something [adapted from 9]. Value can be expressed in various tangible or intangible units or terms.
- **Value network** – interacting set of actors that create and sustain value associated with a material, product or service through supply, use, reverse supply and reprocessing stages.
- **Waste** – any substance or object that the holder discards or intends or is required to discard [31].

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1 Introduction

Problem statements, Research questions, and Methodology

In this chapter, the problem statements are introduced that form the starting point for this dissertation. In Section 1.1, the focus is first on mankind's use of natural resources, from a general perspective, followed by a more specific reflection aimed at construction materials and the Dutch context. In Section 1.2, the focus shifts to the living quality of citizens, particularly regarding the indoor environments of Dutch social housing. Emphasis is put on the notion of flexibility to accommodate ever-changing needs and requirements. Such changing conditions can relate to current or new users as well as current or new functions.

Both Section 1.1 and 1.2 conclude with a problem statement. Section 1.3 elaborates on these, describing system boundaries, objectives and research questions. Lastly, in Section 1.4, the overall methodology is described and a brief introduction to the subsequent chapters is provided.

1.1 Circularity Problem Statement

1.1.1 Ecological Debt: Earth Overshoot Day

At the moment of writing, on 29 July 2019, it happens to be *Earth Overshoot Day* or *Ecological Debt Day*. On this day, according to the Global Footprint Network, nature's resource budget for the entire year 2019 has been used up by humanity [1]. We are depleting our natural capital. There is an increasing body of evidence to support this, be it with regard to biodiversity loss, soil erosion, or climate change [2].

Earth Overshoot Day (EOD) compares the planet's biocapacity with human resource demand, in hectares of land [1]. The metrics behind EOD are not uncontested, due to data-gaps and methodological choices that exclude some parameters, but it shows an undeniable trend [3,4,5,6]. If anything, EOD is said to underestimate rather than overestimate the status quo [4]. Wackernagel and Beyers state that overshoot can only be temporary, eventually humanity will have to operate within the means of Earth's ecological resources [1,3]. As of the 1970s, however, humanity has been consuming as if we have more than one earth. EOD is a global average, based on national footprint accounts. Figure 1.1 shows the global evolution of EOD between 1970 and 2019, and Figure 1.2 is a graph displaying EOD in relation to various countries (reference year 2019) [1]. For the Netherlands, this year EOD fell on May 4th.

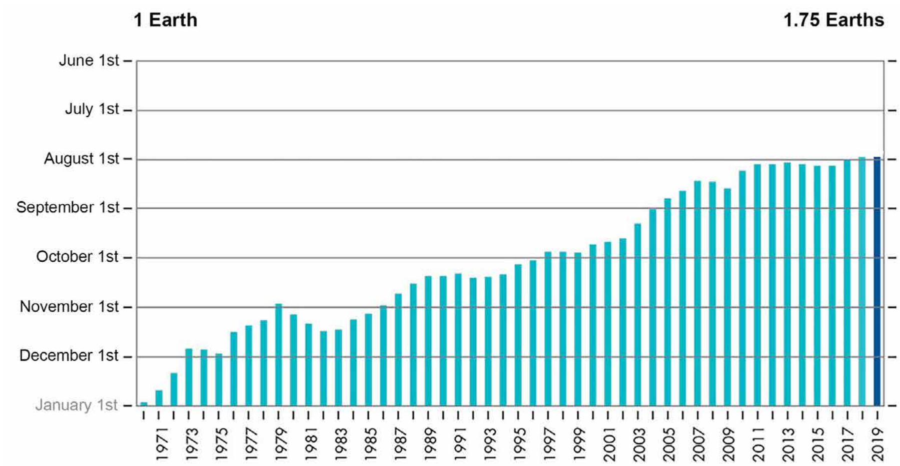

FIG. 1.1 Global Earth Overshoot Day from 1975 – 2019 [Source: Global Footprint Network]

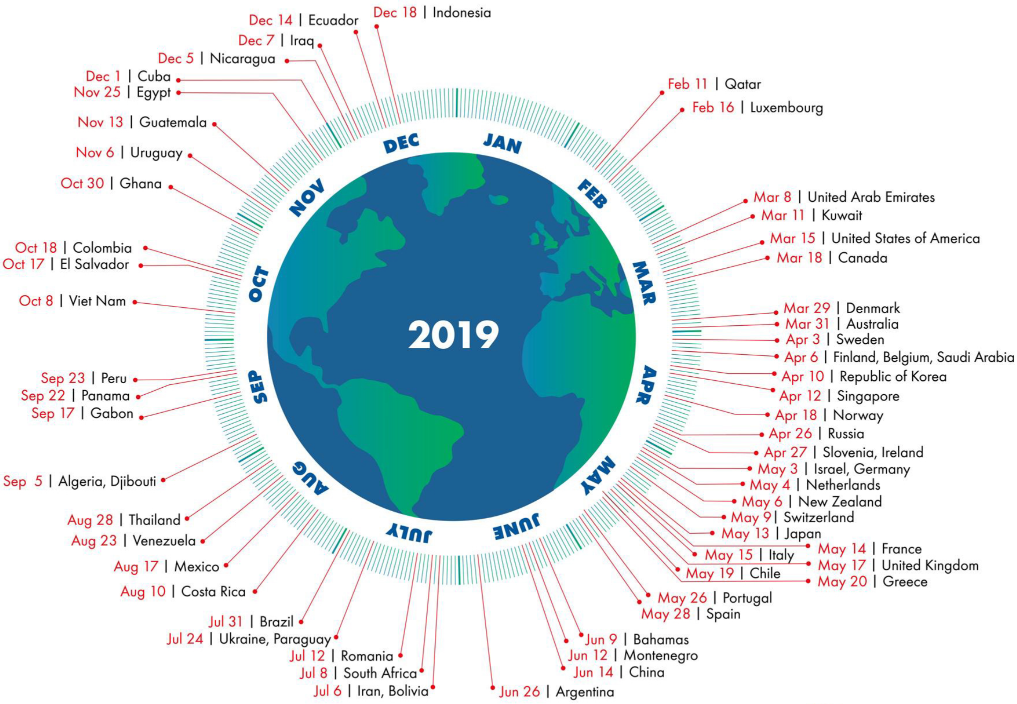

FIG. 1.2 Earth Overshoot Day in various countries. Reference year 2019 [Source: Global Footprint Network]

In order to avoid potential disaster, we thus need to restore the ecological balance by active intervention [3]. The key question is whether our actions today are laying the right foundation for this restoration. According to the Sustainable Development Goals report 2019, the answer is an unambiguous No: the natural environment is deteriorating at an alarming rate [2]. The general verdict is that, regardless of widespread progress in policies and instruments to support sustainable consumption and production, it is “abundantly clear that a much deeper, faster and more ambitious response is needed to unleash the social and economic transformation needed to achieve our 2030 goals” [2, page 2]. The global trend is that our material footprint is increasing, without any sign of decoupling between material footprint and population growth or Gross Domestic Product (GDP) growth, see Figure 1.3. Furthermore, the lifestyles of people in richer nations require significantly more resources than those in poorer countries, see Figure 1.4. In many cases, the resource requirements of the former heavily depend on extractions in the latter [2].

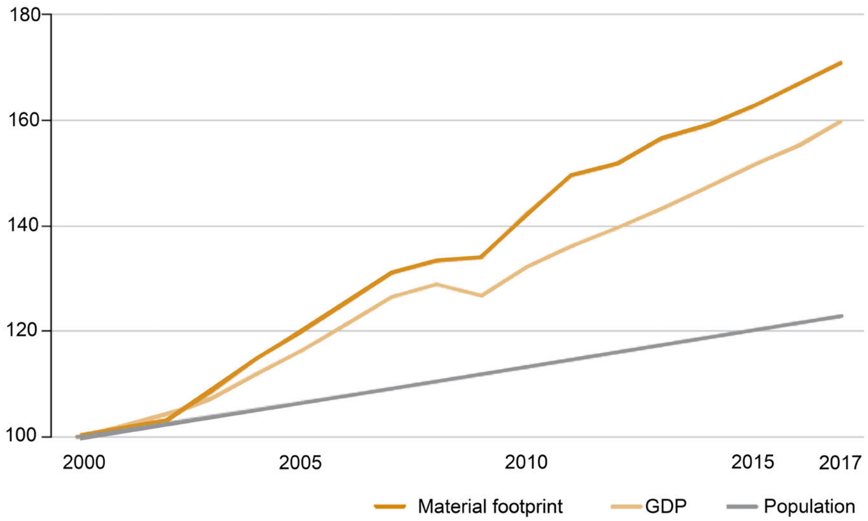

FIG. 1.3 Population, material footprint and GDP growth index 2000-2017 (Baseline 2000 = 100) [Source: United Nations]

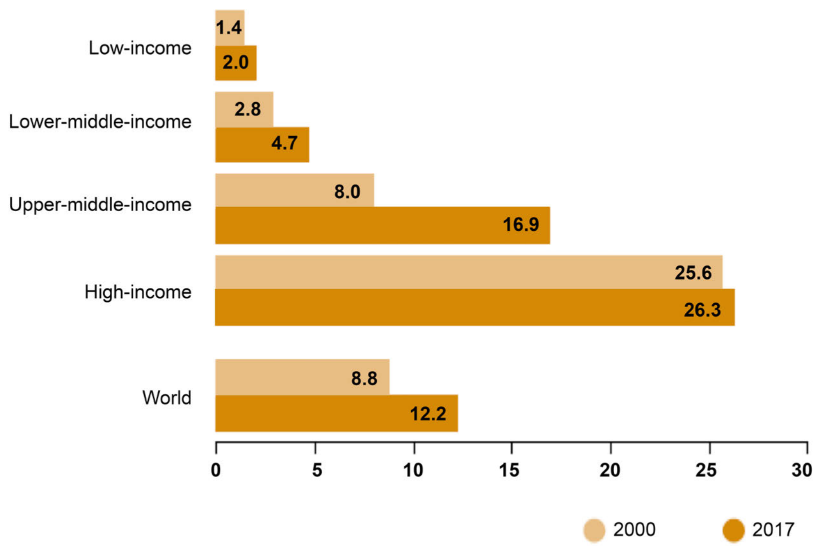

FIG. 1.4 Material footprint per capita 2000 and 2017 (metric tons per person) [Source: United Nations]

1.1.2 Circular Economy

In recent years, the circular economy has become increasingly prominent "as a tool which presents solutions to some of the world's most pressing cross-cutting sustainable development challenges" [7, page 1]. The Circular Economy can be defined as: "an economy based on renewability of all resources – energy, materials, water, topsoil (for food production) and air – while retaining or creating value as long as possible, promoting positive systemic impacts on ecology, economy and society, and preventing negative impacts" [8, page 5]. Not only does a circular economy approach offer 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 [9,10,11]. However, circular resource flow systems usually imply far reaching changes in the way actors are interconnected, and until now, technological innovations and designs for circular material flow systems have fallen short due to their relatively one-sided nature [12,13]. According to Vernay (2013), this is due to an approach which is too technocratic and too static, taking insufficient account of how environmental, social, technical, economic and temporal factors are integrated in practice [13]. Moreover, evidence-based data regarding the positive and/or negative impacts of a circular economy are still scarce.

In the Netherlands, broad attention for circular economy principles began in the 2000s. The concept struck a chord, most notably after an introduction of Cradle to Cradle® (C2C) on Dutch television in 2006 [14]. The founding fathers of C2C®, McDonough and Braungart, stated that the ecologically sound design of products and processes could and should generate economic and societal benefits, an idea which seemed to land well in Dutch industry as well as Dutch society at large [15]. This attention did not come out of thin air. At that time, Dutch policies already had a history with sustainable development, in line with the growing global awareness of the negative environmental impact of our industrial economy. The emphasis was initially on pollution control, shifting to pollution prevention in the late 1970s and early 1980s, triggered by the so-called 'Ladder van Lansink' [16]. The Ladder van Lansink introduced a waste management hierarchy with prevention as the highest aim and landfill the lowest. With each national environmental policy plan that followed, more attention was given to integrated chain management and long term transitions to shift to a sustainable society [16,17,18]. However, implementation of the ambitions has proven difficult, not least due to fluctuating political, societal and industrial support [19]. Furthermore, historically, the policies have a strong bond with sustainable development interpreted as eco-efficiency and decoupling economic growth from environmental impact [20]. In some ways, this historical link, and path dependency, is a barrier for the implementation of circular principles. Eco-efficiency (product or service quality divided by environmental impact) leans strongly

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on reducing negative impacts, and less so on eradicating or replacing products and processes with negative impact for those designed for positive impact [20]. Moreover, eco-efficiency runs the risk of neglecting strong sustainability phenomena, especially in relation to population and economy growth scenarios [21].

The awareness grows, in the Netherlands and beyond, that sustainability measures are thus far insufficient, and that more efforts are required, for example by embracing the circular economy [22,23,24]. But where eco-efficiency offers a compromise between environmental and economic gains, linked to a certain consensus between public and private parties, the circular proposition offers a different industrial operation system. Discrepancies and frictions in interests and interpretations of the stakeholders are inevitable, regardless of the shared appeal of the circular economy. For example, consensus between public and private parties needs renewal, based on systems thinking. In other words, we need to unlearn behaviour we take for granted, but which is degenerative, and begin to position our behavioural patterns from a holistic vantage point, aimed at synergies between environmental, social, and economic (sub)systems. What has been built up over decades in the Dutch policy framework deserves critical reflection and reassessment. An interesting test in this respect, is the way in which the Netherlands deals with transforming the energetic performance of the building stock, while simultaneously promoting circular operations of associated materials and other resources.

1.1.3 Circular Built Environments

The Dutch construction sector shows parallels with what is described above. Ecologically-aware methods have been developed and applied for several decades, in essence born out of a 'mitigation tradition' i.e. to lessen the effects of building-related activities. Explicitly exploring the potential of how those activities could generate positive environmental and social impacts, adhering to holistic circular principles, is a very recent development. This development is rooted in systems thinking, at the heart of approaches such as Cradle to Cradle®, Circular Economy, Industrial Ecology, Regenerative Design, and Blue Economy. Those approaches open up new ways of thinking, relating the role of society in general, and the man-made environment in particular, to facilitate the healthy circulation and storage of valuable materials [11,20,25]. The Netherlands takes a role at the forefront of this development, boasting some valuable practical examples and strengthening design guidelines as well as policy directives for the circular building transition. However, circularity principles have not yet been applied on a large scale in the Dutch building sector, certainly not with regard to housing [26,27]. Although several circular principles have found their way into design tools and methods, there is no consensus as to what circularity entails, and how systemic phenomena, such as spatial and temporal distribution, should be integrated.

Construction and demolition waste (CDW) constitutes about one third of the total waste in Europe [28]. This CDW mainly consists of concrete, masonry, and ceramics, but also large amounts of wood and plasterboard [29,30]. Adhering to the circular economy model, the EU as well as Dutch national and local authorities are promoting a shift in waste management practices. Direct reuse of buildings is an example of such a model, favouring renovation or transformation strategies rather than demolition, whilst avoiding (at least part of) the waste flow. Another example is the optimal application of waste management hierarchies to stretch the process of value loss. Buildings are, no matter how complex, similar to any other product in that respect, and straightforward rules of thumb apply, such as the inertia principle, see Figure 1.5 [31].

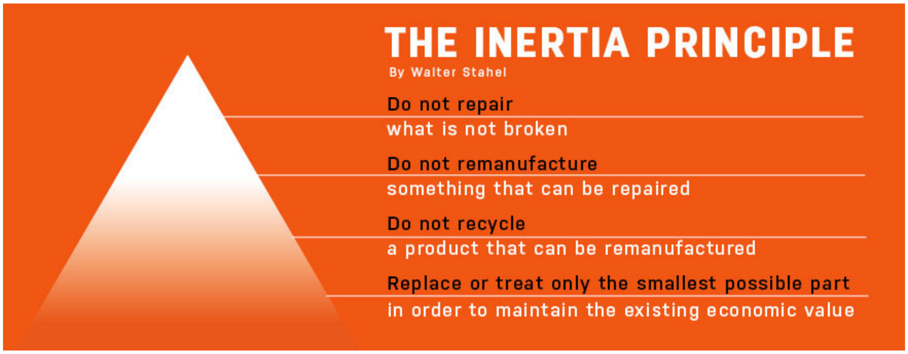

FIG. 1.5 The Inertia Principle [Source: TU Delft OCW]

Currently, direct building reuse is often compromised and overruled by other factors, such as aesthetics, refurbishment costs, and client satisfaction, with often an unambiguous linear economic bias [30]. The selective dismantling of buildings is in many cases simply seen as too costly and time-intensive. Reflecting on the Dutch context, Schut et al. (2015) observe a prominent flaw in the construction sector, namely that costs associated with the final stages of a building (dismantling, demolition, recycling, etc.) are not internalised in the upfront transaction and exploitation calculations and agreements [32]. Reuse is not (or insufficiently) integrated in the financial and regulatory frameworks that drive the construction sector, nor is the societal meaning of existing real estate [33]. Moreover, there is no consensus or clear evidence regarding the environmental impact in comparative assessments between renovation and newly built. Not least because the assumptions made and system boundaries chosen decisively impact the outcome [34]. Debacker et al. (2017) conclude that “building design and construction actors seldom take into account the end-of-use consequences when making design or construction choices” [35, page 52].

An essential aspect of circular building practice is retaining or regenerating the quality of resources, so that they become part of healthy and transparent technical cycles and biological cycles or cascades [22,27]. For building materials, this means that an integrated approach is required with regard to all stages of the value system, such as raw material sourcing, product manufacturing, supply and demand logistics, use, maintenance, reuse and reutilisation routes. The control of those stages is distributed over many stakeholders, as well as over time, which makes it a dynamic and transdisciplinary endeavour. This does not imply that each stakeholder must become an expert in all of those stages. It only means that each stakeholder needs to anticipate the fact that other stages and stakeholders are part of the pact. For some of the stakeholders this comprises more far-reaching responsibilities than for others. Consistent information flows and feedback loops regarding the intrinsic quality of the material in question thus need to be facilitated, in order to safeguard the *circularity potential* throughout the whole value case. In the Dutch building paradigm, this is not a common code of conduct, and very little experience exists with regard to systemic approaches. This also holds true for Circular Building, being an inherently systemic affair. The following definition of Circular Building is adhered to in this dissertation: *Circular building (verb) is the dynamic total of associated processes, materials and stakeholders that accommodate healthy renewable flows of building materials and products at optimal rates and utility, whilst promoting positive impacts and preventing negative impacts. A circular building (noun) is the manifestation of this in a – temporary – configuration.* The term 'renewability' thus refers to the capacity to be used and reused over and over again in a non-depleting manner, applying to both biological materials and technical materials.

Circular Building can become the prevailing paradigm only if networked actors and activities that constitute the circular value-case rigorously adhere to an integrated systems approach. This leads to the following problem statement:

CIRCULARITY PROBLEM STATEMENT

Retaining the quality of building components is hampered by design, manufacturing, and operation that fails to systematically integrate the renewability of applied materials

1.2 Flexibility Problem Statement

1.2.1 Social Debt: The Great Indoors

Ecological debt, as described in Section 1.1, inevitably implies also social debt, given that humans are dependent on the natural environment. This fact, however, is not the main social debt this dissertation aims at. Rather, the emphasis is on the living quality of the environment where most people nowadays spend most of their time: the built environment in general and the indoor environment in particular. The maps of Figure 1.6 visualise the rate of global urbanisation between 1950 and 2020 [36,37].

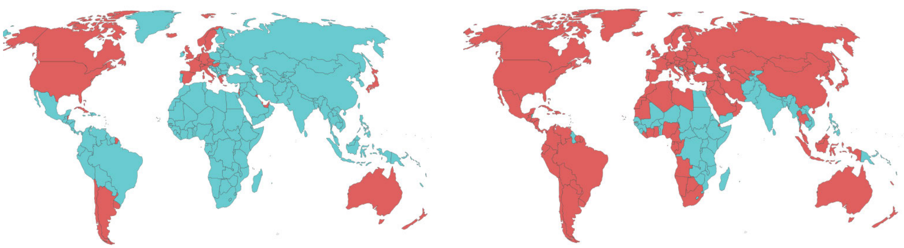

FIG. 1.6 Urbanisation: Majority rural (green) and urban (red) in 1950 (left) and 2020 (right) [Source: Our World in Data]

The graph of Figure 1.7 shows the average time spent indoors, according to an American study of the early 2000s [38,39]. The numbers in contemporary urban Europe are more or less similar, estimations range between 80-90% indoors, 5-10% outdoors, and 4-7% in vehicles [40,41].

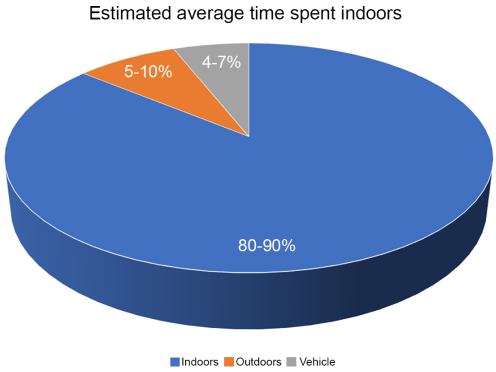

FIG. 1.7 Estimated time spent indoors (blue), outdoors (orange), and in vehicles (grey) in percentages [Source: Bob Geldermans]

1.2.2 Home

"Utilitas, firmitas et venustas" wrote Vitruvius in his books on Architecture, which may be translated as 'utility, firmness, and attractiveness (or: aesthetics)' [42]. As long as we remain true to those principles, we will manage to build meaningful buildings and cities. However, these terms are open to interpretation, especially concerning the latter: aesthetics. Moreover, our - industrialised - society changes over time, as does the built environment. The meaning of good architecture and planning is ever-evolving.

When articulating the importance of buildings in general, and our homes in particular, one could take multiple approaches. Objectively and technically, homes provide us with shelter and protect us from unwelcome external factors, and as a result we spend the majority of our time in them [43]. More subjectively, and complex, would be to describe the extent to which we feel 'at ease' in our home. This touches upon the experience and perception of safety, comfort, and joy, or any other desired emotion. A more philosophical reflection is that "we depend on our surroundings obliquely to embody the moods and ideas we respect and then

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to remind us of them” [44, page 107]. These surroundings blend from the private realm into the public, collective space, where the interaction with and influence of others increases with the level of scale. This organisation of built fabric – from the smallest unit, say a room, to the scale of a city or city region – could be seen as an organism, accommodating its inhabitants and their activities to the best collective benefit. Through the ages, changes in the built form occurred incrementally, at all levels, through acts of expansion, upgrading, renewal and repurposing, with no fixed final form [45]. However, this ‘gradual refinement’, as Habraken (2014) calls it, was disrupted in the 19th and 20th century, through a rapid reorganisation of urban areas, instigated by the industrial revolution and its accelerating effect on functional, social and technological change. Consequently, urban development and architecture shifted from ‘self-organisation’ to top-down planning, losing some vital building blocks for successful cities along the way [46,47,48,49]. Particular criticism has been levelled at social segregation and exclusion, resulting from housing policies and planning strategies that insufficiently addresses issues of inequality. An example are the 'banlieues' of Paris. Angélil and Siress (2012) state that “tensions between the banlieue and the city core are the result of social and spatial inequities that arise from class and ethnic territorial segregation” [50, page 58]. A well-known example in the Netherlands is ‘De Bijlmer’, a city-district in the South-East of Amsterdam. De Bijlmer was welcomed as a new model-district for modern city-dwellers, but failed to live up to that claim, due to, amongst others, mono-functionality and anonymity [51,52]. Over the last decades, urban planning strategies have been enriched with insights and tools to facilitate bottom-up, evolutionary development, aimed at “successful cities”, certainly in the Netherlands [46,53,54,55,56]. However, in practice, effective implementation of such insights and tools appears to be far from self-evident. According to Janssen-Jansen (2016), this relates to local authorities being primarily focused on the needs and expectations internal to their operational areas, often pursuing short-term financial gains [56]. Moreover, reflecting on an examination of the Dutch urban context, Karsten (2009) states that dominant urban discourses in the field of urban planning tend to overlook the daily life of residents and particularly of family residents [57]. From these observations follows that anticipation of change and diversity, as a means to retain the long-term societal value of urban real estate, is not secured by the current planning and housing development policies.

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1.2.3 Social housing

The question of housing-quality for the Dutch working class originated in late 19th and early 20th century Amsterdam, where the first (social) housing associations came into existence. Despite a gradual decline over the last decade, the share of social housing still represents about 30% of the total stock: 2.4 million out of 7.7 million [58,59].[1] These 2.4 million housing units, of which the majority concerns multi-family rental housing, are divided over 320 housing associations/ corporations.[2] The biggest share of social housing can be found in the four largest cities: Amsterdam, Rotterdam, The Hague and Utrecht. In those cities, waiting lists for social housing are long, with common waiting periods of 5-10 years. Roughly 27% of the overall stock is built before 1960, 58% between the years 1960 and 2000, and 15% is post 2000. In general, the quality of social housing is estimated to be lower than that of private housing, not least with respect to customisation and ownership: in a house you own, you are free to make modifications [60]. That said, housing corporations are investing in improving the quality of their stock, through renovations, demolitions, and new constructions. In the last decade, investment strategies have been increasingly linked to the energy transition, working towards a carbon-neutral stock by 2050 [61]. Establishing and sustaining human-centred, 'life-sized', cities in the Netherlands thus means multiple considerations relating to the quality of the social housing stock. Studies into the satisfaction levels of residents in multi-family housing indicate that roughly 75% is satisfied. Dissatisfactions relate to the parameters: size, layout, maintenance level, general atmosphere and outdoor space [62]. Although perceived value is subjective and hard to pin down, especially when taking into account changing perceptions of the housing unit over time, the aforementioned parameters provide a good starting-point for establishing an empirical basis for monitoring residential environmental satisfaction [63].

1 Dutch social housing can be defined as: Housing (mainly rental) with a maximum monthly rental price of € 710,68 (in 2018), meant for people with a low or middle income. Social housing is usually owned and exploited by housing corporations.

2 Within this dissertation, housing *corporations* are synonymous to housing *associations*, even if the legal status differs.

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1.2.4 Perceived value of real estate

According to Finnish architect and writer Juhani Pallasmaa, societal urban value is approached one-dimensionally. In relation to the functional and sensual perception of urban form, Pallasmaa states that the latter aspect, regarding the senses, is and has been neglected by architecture and cities. Pallasmaa refers to *ocular-centric design*, suggesting that there is too heavy an emphasis on visual aspects [64]. In a reflection on modernist design, he states the intellect and the eye are usually housed, while the body and the other senses, as well as our memories, imagination and dreams are left homeless [64]. This relates to a stronger human-centric approach to building design, that also underpins this dissertation. If we dwell on the aforementioned observations regarding self-organisation as a quality indicator of resilient urban environments, and gradual refinement of built form from smaller to larger scale, it follows that self-organisation, in all its diversity, must be facilitated.

‘Value’ is a contestable term. What is valuable to one, might be worthless to another. A city's ‘hardware’, say buildings and lands connected by infrastructures, become meaningless without people who attribute meaning to it through functional and sensual perception. Acknowledging and preserving qualities of the urban backdrop for human activities is thus a vital part of a thriving city. Just as there are many examples of urban form that is meant to exist only temporarily, there are many urban typologies that should define a city’s sensory profile more permanently. As such, it can become part of the citizen’s collective identity and individual engagement with their surroundings [65]. There are many examples of urban interventions that erase buildings from the face of the earth against the will of many, and against the building’s technical potential to continue for years to come. A recent example is the Tweebos neighbourhood in Rotterdam (600 pre-war housing units): no longer in line with contemporary housing and urban requirements according to the owner (Vestia) and the municipality, but a high value area from the perspective of architectural and social engagement according to others, not least the local residents. Opinions differ with regard to the technical state and renovation potential [66].

What is constantly changing, by definition, are social dynamics: both on a larger demographic scale and a smaller household scale. Developments that impact housing needs are, for example, migration and ethnic diversity, shifts in single or composed households, and the ageing population. With respect to the latter, Figure 1.8 displays the Dutch population over the age of 75 in total numbers and percentages, including the share of 75+ living in special care facilities [67].

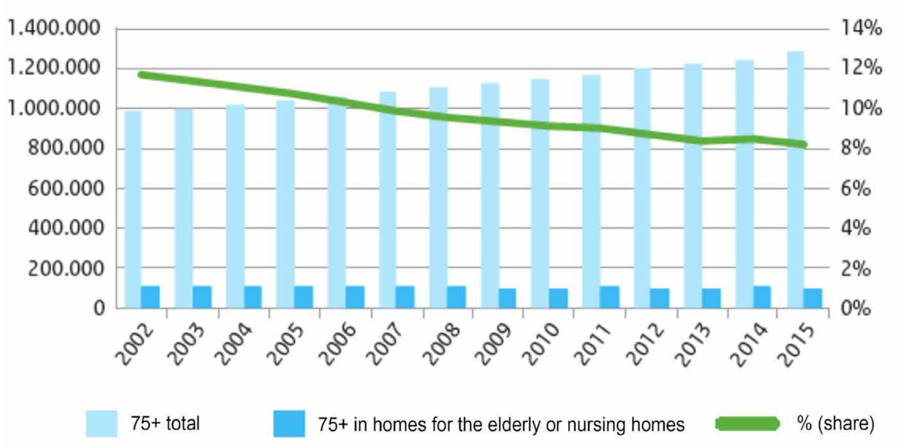

FIG. 1.8 Dutch population over the age of 75 in total numbers and percentages, including the share of 75+ living in special care facilities [Source: WoonOnderzoek Nederland 2015]

The needs of an urban society may change, under the influence of any social or technological trend or phenomenon, and the needs of a household may change because of modifications in the participants' life or lifestyle. The urban hardware should be an accommodating setting for those changes. This implies that 'flexibility' is a primary parameter in the design and operation of urban form. We don't know exactly which changes will arise, but we can expect changes to occur and anticipate that fact. With regard to the multi-sensual perception of value with which this section began, what would be a better place to explore than the interior? This is the domain where diversity thrives and the individual identity of people is most tangible.

1.2.5 The indoor domain

Driven by social and technological changes in the late 19th and early 20th century, new visions in architecture emerged that relate to the notion of adaptable and flexible housing. A highly influential representant of this 'modernisation' of architecture was French architect Le Corbusier, who developed a functionalist style in which structural columns and open floor-plans underscore the notion of infill freedom. Furthermore, the influence of the Dutch art movement De Stijl can be seen as a precursor for later considerations of flexibility in Dutch architecture, describing an architecture that is open, connecting inside and outside, while having a flexible interior lay-out [68].

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After WWII, a few movements emerged in architecture and urbanism, based on the realisation that human society is continuously in motion. In Japan, the Metabolists suggested an architecture in which megastructures and infrastructures are fused with ideas of organic, biological growth [69]. In the Netherlands, John Habraken criticised the uniform mass housing developments that were increasingly defining cities' identities, arguing in favour of a more participative approach that creates space for individual expression [70]. This Open Building (OB) approach is currently a reference point for notions of change, flexibility and user involvement in Dutch housing. Multiple interpretations of the OB approach have emerged over time, most prominently with regard to technical detailing of the building and with the industrial manufacturing of components, as in the aerospace and automotive industries [71]. OB distinguishes the support, that is the building's structure including all collective elements, and the infill, concerning everything behind the doors of individual housing units: lay-out, kitchens, bathrooms, service installations. Some building components could overlap the two domains, for instance parts of service installations or façades.

The anticipation of change through flexible infill systems has been applied on a larger scale in commercial typologies, such as shops, hotels and offices, where 'transient occupation' is common. For housing, customs differ. Usually, conventional pathways are followed by the stakeholders on the supply side: owners/developers, architects, engineers and contractors, offering the dwellings as complete products. The demand side, never mind the *future* demand side, is not actively part of the equation. Incentives to change this model have been scarce. Nonetheless, OB related principles continue to resonate in housing visions and plans; for example, factoring in participative design, developing housing in co-creation with residents or concerning infill-flexibility to make a building more future-proof. However, true division of decision power, in which structural design for collective use is fundamentally decoupled from infill design for individual use, has not significantly entered the everyday practice of the building sector [72]. Without this division, the notion of flexibility can never reach its full potential, concerning, for example, freedom of choice for users, establishment of an infill market, and prevention of premature obsolescence. This leads to the following problem statement:

FLEXIBILITY PROBLEM STATEMENT

The notion of infill flexibility is insufficiently taken into account in building projects, failing to do justice to social dynamics and leading to the premature obsolescence of real estate.

1.3 Delineation and Research Questions

With regard to the problem statements, formulated in 1.1 and 1.2, this dissertation puts the emphasis on specific aspects, which are introduced below.

1.3.1 Partitioning

First of all, the focus is on one building component in particular, namely: a non-bearing indoor partitioning wall. Indoor partitions are arguably the most prominent infill components when it comes to defining one's direct living environment. Christopher Alexander (1977) states that a house can only develop a personal character if the walls are welcoming to desired modifications [73]. For example, typical zones for expressing identity are found between 90 and 120 cm above the floor, boasting a variety of small-scale interventions, such as shelves, niches, objects, built-in furniture, lamps, etc. [73,74,75]. Pennartz (1981) confirms that small-scale modifications and deviations from standard layouts generate personal meaning [75]. Even if users of the space do not radically alter the floor-plan and the partitions stay where they are, they tend to personalise walls by decorating them and/or use them as the backdrop for furniture or other objects [74].

Partition walls thus address elaborations of functional use, as well as social perception and the attachment of significance to space [74]. Functional use concerns the division of space based on differentiation of activities, often with respect to considerations of hygiene, sound or vision. Furthermore, it relates to aspects that support such activities, for example the placement of shelves, sinks and cupboards. Social perception relates to socio-cultural-spatial behaviour. According to Tuan (1977), the organising "principles of space signify interpersonal relationships as much as they indicate the general state of mankind" [76]. Lifestyles tend to depend highly on one's ownership of a private space and privacy needs vary because of changing social customs [77,78,79]. In general, social perception is thus related to how rooms establish a sense of comfort and well-being for the user. This could be expressed in both closed off and (semi-)connected spaces, as well as in the infrastructure to move from one place to another. In that context, Hillier and Hanson note that architecture does not have a merely *symbolic* relation with social life, but a *direct* one, since architecture provides the material preconditions for the patterns of movement, encounter and avoidance which are the material realisation of social relations [80]. Directly related to the appropriation of private space is the way in which partitioning walls obtain meaning for the user, as described above. As such, partitioning walls can provide the capacity to resonate the user's character.

The focus on non-bearing partition wall components starts from the premise that the structural elements, supporting the infill, have sufficient quality to accommodate ongoing use of the building, even if functions and/or users change. The role of the structural elements in open, circular building strategies is a research topic in its own right and falls outside the scope of this dissertation. Here, the superstructure is the silent backdrop providing incentives for multiple renovation or transformation cycles. The materials and products used for the infill require qualities that differ from those of the support-structure, as they relate to different functions, with shorter service cycles. It is assumed that this aspect allows for a better match between retaining (raw) material and product values, on the one hand, and short to mid-term business models in the supply chain, on the other. Partitions are related to most other infill 'layers', such as doors, (lowered) ceilings, raised floors, kitchens, stairs and sanitary equipment, whilst having direct relevance for piping and wiring of electrical, information and communication technology (ICT) or sanitary functions, as these are often intertwined with the partitioning. The infrastructural aspects of service installations always follow the logic of their useful location. Changing floor-plan and partitioning requirements may thus have substantial implications for piping and wiring.

Lastly, in this research, the focus is on partitions that can establish a direct connection with the adjacent layers (most prominently ceiling and floor). Free-standing, temporary room dividers are thus not addressed. In order to safeguard the multifaceted set of performances beyond the function of room division alone, a partitioning wall may need to take into account sound or light-leakage, for example. Figure 1.9 displays various building layers, as based on Frank Duffy and Stewart Brand's pace layers of change [81], and Figure 1.10 shows two different partition elaborations.

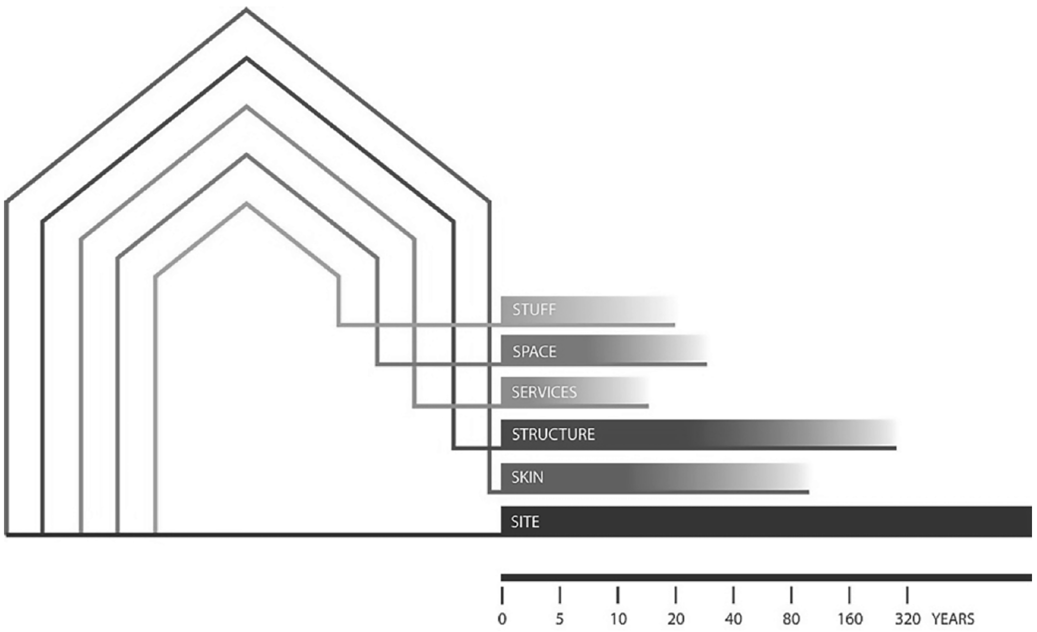

FIG. 1.9 Pace layers, showing six building layers with different service lives: from transient (stuff) to permanent (site) [Source: David Bergman based on 'How Buildings Learn', Stewart Brand, 1995]

FIG. 1.10 Conventional plasterboard partitioning (left) and a modern elaboration of brick partitioning [Source: Shutterstock/ Dezeen Magazine]

1.3.2 Materialisation

If circularity is a criterion, it is necessary to know which materials are "stored" in a product or building. In the current paradigm we get away with a rather rough estimation of those materials, and the corresponding waste management strategies are usually limited to low-grade applications. However, a more detailed examination of material quality is required if renewable models are anticipated. With circularity in mind, each level of detail - be it on the (raw) material or product level - demands for other choices. For example, homogeneity can be an important condition for a material in order to maintain quality in the next cycle, but may not necessarily be a preferred characteristic for reapplying a material into a new product.

With regard to the materialisation and manufacturing of non-bearing partitions, various materials and products apply. When the notions of renewability, circularity and infill-flexibility are part of the equation, the range of applicable materials and products is narrowed down. Raw materials may lose their sustainable circular capacity as soon as they are manufactured into any given product, and a potentially circular product may lose that capacity as soon as it is implemented into the building's context. Quality control throughout the whole operational cycle is thus required in use and reuse iterations, as well as recycling routes. Only prolonging service lives is essentially a linear process: the product's value may be maintained to some extent through short cyclic value models, but longer cycles, including high value recycling or upcycling, are not necessarily secured.

Within this research, the raw material stage is highlighted. This has implications for connections on all levels: how are materials connected to form a product? How are products connected in a building? How are stakeholders in the value-chain connected to safeguard product and material quality?

1.3.3 Dutch Residential Construction, Demolition and Renovation

This research focuses on residential typologies, in particular multi-family social housing. This concerns new building projects, but also renovations in the existing stock, representing the lion's share of the overall building stock. Multi-family social housing reflects a Dutch tradition of providing quality housing for people with lower or middle incomes and takes up roughly one third of the total national building stock. Those houses are usually owned by housing corporations. In the light of user-flexibility, mixed functions and functional transformations are relevant to this dissertation as well. The latter relates to, for example, converting idle or under-used offices to residential or mixed-use typologies. This ties in with an ongoing trend in the Netherlands, in response to an increasing amount of empty office space and an increasing demand for housing, particularly in larger cities [82,83]. Wilkinson and Remøy state that conversions are inherently sustainable, compared to demolition and new construction, as "embodied energy is retained and less waste material is created during construction works" [83].

With regard to construction and demolition waste (CDW) flows, the focus in this dissertation is thus on CDW associated with residential typologies. This ties in with both maintenance cycles on the collective scale (which are usually organised by or in close conjunction with the overarching organisation) and individual alterations executed by residents at their own chosen moments in time. Most of this household CDW is offered and collected separately, although there are also fractions found in coarse bulk waste [84]. On the collective scale, CDW is in many cases managed by specialised companies in close agreement with the main contractor. The diagrams of Figures 1.11 and 1.12 show, respectively, the history of separately collected waste flows from Dutch households between 1985 and 2018, and CDW generation and treatment in the Netherlands between 1985 and 2014 [84,85]. These figures indicate that each person in the Netherlands represents roughly 275 kg of separatedly collected waste per year, and roughly 140 kg of CDW per year.

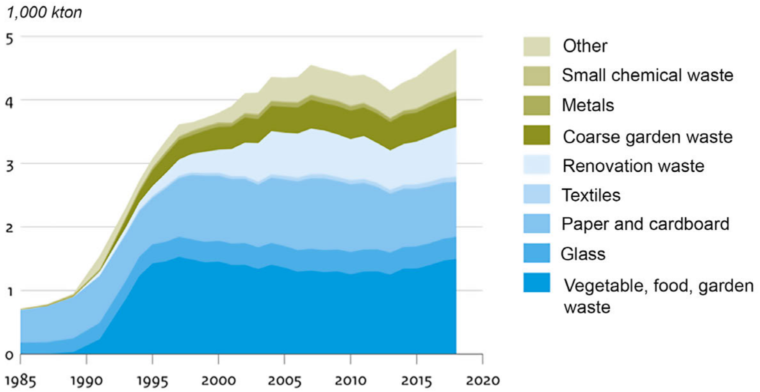

FIG. 1.11 Separately collected waste from households in the Netherlands [Source: Compendium van de Leefomgeving (CvdL)]

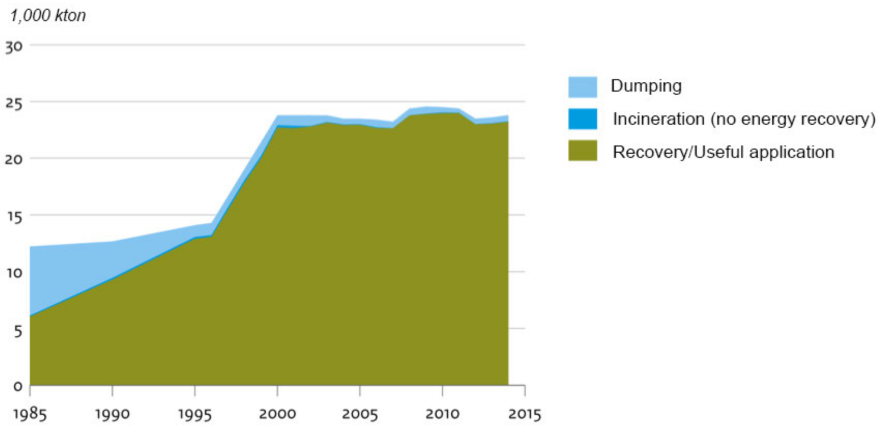

FIG. 1.12 Construction and Demolition Waste generation and treatment in the Netherlands [Source: CvdL]

Figure 1.12 shows that the lion's share of CDW in the Netherlands finds a recovery route or 'useful application'. In general, a waste management hierarchy is followed with regard to most preferred reuse or recovery routes. However, the term 'useful application' is contested, as it gives leeway to large-scale, low-value applications and to transboundary loopholes [86,87]. Waste incineration *with energy recovery* (not to be confused with incineration tout court, the darker blue flow in Figure 1.12) is a relevant phenomenon in this respect. Circular strategies require a more differentiated approach towards waste processing, distinguishing multiple treatment gradients before recovery of the calorific value takes place. This already resonated in the aforementioned Ladder van Lansink (Section 1.1.2) and is put forward by, amongst others, the Ellen MacArthur Foundation (see Section 2.2.5). Obviously, such strategies need to be accompanied by upfront design, manufacture, and operation processes that facilitate a shift from linear waste to circular resource management.

The total amount of CDW associated with the residential sector - integrating all collection routes - is roughly 15%, but difficult to define more precisely, due to the lack of coherent and reliable recent data [88]. For similar reasons, it is currently impossible to put exact numbers on specific material fractions. However, certain material flows are particularly relevant for non-bearing partitioning, such as gypsum – or plaster – board, wood-based panels, timber and insulating materials. Even though these flows are recognised as high potential, with regard to waste and resource management strategies, they usually end up in low-grade recovery routes [88].

1.3.4 User Health & Well-being

McDonough and Braungart's statement (2002) that none of the materials used in contemporary buildings are specifically designed to be healthy to people, underscores the fact that materials, products and buildings have become more and more heterogeneous and complex, introducing multiple substances and synthetics that pose potential threats to human health [89]. Although increasing attention for such health and safety aspects can be discerned in policies and guidelines, associated building standards seem to have difficulty keeping up with developments in materials and products for construction and infill organisation. In general, indoor environmental quality is not yet well integrated in assessment schemes and policy documents [90,91,92]. An example of concerns, relevant in the light of this research, are volatile organic compounds released from particle boards, paints and adhesives, amongst others. Such compounds are suspected carcinogens and immune system disruptors [93]. This topic implies a user-centred approach, which does not relate to physical health alone, but also to mental health and well-being, in line with the perceived value referred to in Section 1.2.4.

1.3.5 Systems integration: Operations

In response to holistic perspectives on cities as circular urban metabolisms, based on local cycles of energy and materials, the notion of 'systems integration' has been adopted from engineering discourses [12,94,95]. Systems integration can be defined as aggregated subsystems that cooperate to enable the overarching system's functionality [96]. With regard to urban (eco)systems, the focus is on the interplay between social and technical systems. Vernay (2013) proposes three interlinked elements of systems integration in the context of circular cities:

1. Linking separate technical configurations which connect previously unconnected networks of actors and the rules that guide their actions;
2. Increased interaction among actors, which leads to connecting previously separate technical configurations and the development of shared rules;
3. Changing rules, which lead to the coupling of previously separate networks of actors as well as the technical configurations they create and use [12].

An example of systems integration in a circular building context is the link between circular building product supply, real estate facility management, and secondary material treatment. Table 1.1 displays a matrix of indicators in relation to three forms of socio-technical interaction that increase in connective intensity. As such, Table 1.1 provides a typology for systems integration [12].

TABLE 1.1 Typology of systems integration using six indicators [Source: Based on Vernay, 2013]

	Connection	Junction	Union
Degree of technological sharing	Separate technologies	Shared or partly co-owned technologies	Co-owned technologies
Organisational form	Separate organisations	Some cross-boundary organisations	Joint organisations
Degree of interaction between actors of the systems	Limited interaction between actors	Moderate interaction among some actors of the systems	Intense interactions among actors of the systems
Rules shared	No shared rules	Systems share some common rules	Overarching sets of rules
Independent versus joint decision-making	Independent decision making	Some decisions are made in consultation with one another	Joint decision making
Operational relationships	Market and supply relationships	Supply and demand partly combined	Fully interconnected supply and demand

Multiple systems integration variations are imaginable with regard to circular building. Yet, for establishing effective configurations, critical links between value-chain partners are required that match best with the characteristics listed under the *junction* and *union* types of Table 1.1. This relates to the fact that circularity depends on the whole chain of custody [97]. Actor A might supply a building product that is developed for circularity, but it depends heavily on actors B, C, etc. to secure an appropriate cycle through storage, transport, use, maintenance, dismantling and reutilisation. By definition, this is never a one-actor affair, nor is it a static affair: it takes place over time and space. It is thus understandable that the discourse around circular building often revolves around material-ID documents and other forms of data-sharing.

Figure 1.13 visualises the interlinking subsystems adhered to throughout this dissertation.

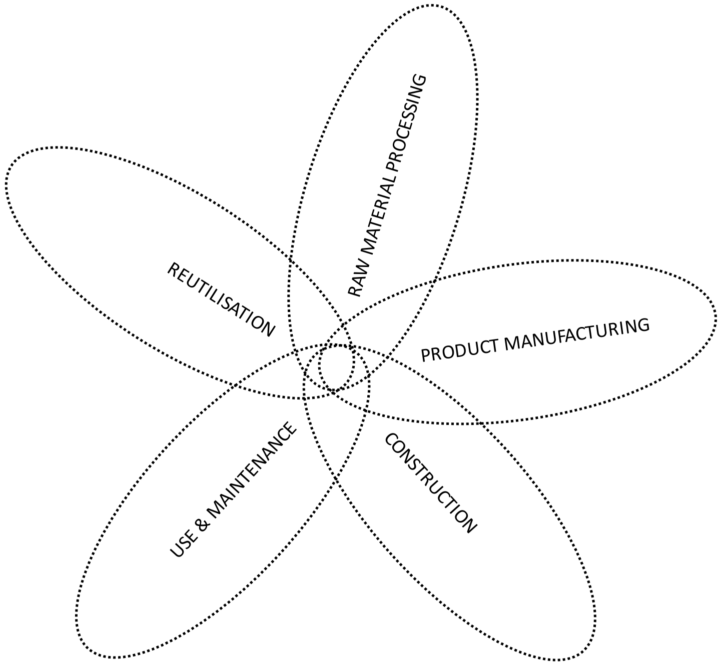

FIG. 1.13 Integrated value chain: multiple activities and stakeholders in spatially and temporally differentiated systems [Source: Bob Geldermans, 2019]

- Raw material processing means *processing* to a required state for further production. With regard to materials of a non-biological origin (see also Section 2.2.5), this concerns *re-processing*, implying that primary (virgin) raw materials are phased out.
- Product manufacturing concerns the assembly of parts out of raw materials, either intermediate goods or end-products.
- Construction refers to the implementation of a part into the building.
- Use & Maintenance concern the stage during which the part is utilised on-site.
- Reutilisation is the applied overarching term for a range of differentiated routes with shorter or longer cyclic characteristics, such as redistribution (including temporary storage), remanufacturing, recycling (retaining material quality) and upcycling (enhancing material quality).

Operational performance of a product or service thus depends on quality control throughout the integrated value chain, each partner being a cog in the wheel.

1.3.6 Research Questions

Based on the problem statements introduced in the former sections, the overarching research questions are formulated as follows:

- **In an Open Building division of support and infill, to what extent can the infill contribute to sustainable circular material & product flows?**
- **Which qualitative and quantitative criteria and preconditions are central to integrating the notions of user health & well-being, circularity, and flexibility in infill configurations?**

The diagram of Figure 1.14 shows the route from the problem statements, via delineation, to the main research questions.

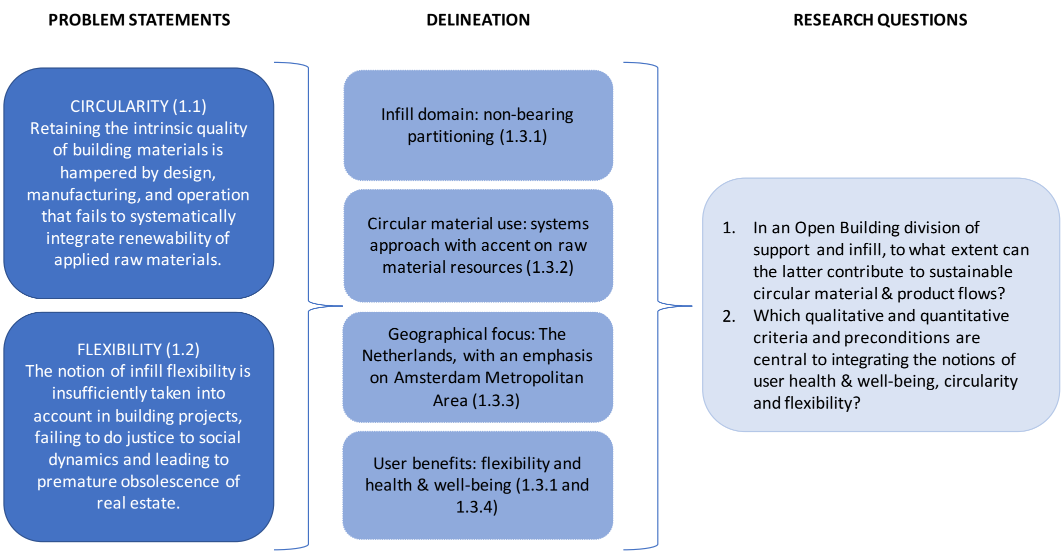

FIG. 1.14 From Problem Statements to main Research Questions [Source: Bob Geldermans, 2019]

In order to answer the main research questions, several sub-questions are addressed. These are formulated below and will be dealt with in, subsequently, Chapters 3, 4, 5, and 6.

1 What are the preconditions for the performance of materials, products, services and buildings in the case that circularity is a leading ambition? (Chapter 3)

2 Which aspects are key with regard to - the relationship between - flexible partitioning, circular material flows, and user benefits? (Chapter 3 and 4)
3 How can residential health & well-being be integrated in the design and performance assessments of indoor partitioning products adhering to a circular model? (Chapter 4 and 5)
4 How can materialisation be integrated in the design and performance assessments of indoor partitioning products adhering to a circular model? (Chapter 5 and 6)
5 How can operational processes be integrated in the design and performance assessments of indoor partitioning products adhering to a circular model? (Chapter 5 and 6)
6 What are notable disruptive innovations that have the potential to challenge the status-quo, enabling the implementation of appropriate, systemic circular value models? (Chapter 6)

1.4 Methodology

1.4.1 Mixed Methods

In response to the research questions formulated in Section 1.3, information and data needs to be collected in a variety of ways and from a variety of sources. The inherently interdisciplinary nature of the scope necessitates the application of multiple methods and tools. The approach adhered to in this dissertation is based on the evolving scientific body of work relating to Mixed Methods research and design methodologies [98,99]. Day and Gunderson (2018) state that built environment research problems often call for a combination of methods that span across multiple disciplines [98]. Teddie and Tashakkori (2009) argue that Mixed Methods (MM) research takes a pragmatic stance towards quantitative and qualitative approaches, and certain types of research necessitates both forms of data for verification and the generation of theory [99]. In view of the research questions this also holds true for this dissertation, bringing together topics such as material properties, product & material flows, and user benefits. This dissertation follows a qualitatively driven approach, and is thus, at its core, a qualitative study, supported and supplemented by quantitative data and methods. Literature studies, workshops, and expert consultations are applied throughout the trajectory to derive, test and adjust criteria, guidelines and models based on integrated perspectives. This is deemed essential with regard to the relatively new field of circular and user-inclusive building. In a design conceptualisation stage, findings are tested, using qualitative and quantitative data, the latter notably in comparison between technical specifications and relating secondary raw material flows. Where possible, primary, real time data are applied, complemented by secondary, statistical data. (see also subsection 1.4.2).

Moreover, zooming into the micro-level and zooming out again to the macro-sphere is applied to contextualise the findings, not least in anticipation of the communication between disciplines and communities that find themselves united within the goal to establish safe and sound circular systems. The MM approach adhered to should thus lead to findings, theories, and solutions that connect disciplines, and as such help to harmonize and mature the discourse around circular building, rather than increase the potential Babylonian confusion. Although inherently interdisciplinary, there are of course boundaries and focal points. Figure 1.15 positions this research in relation to the interdisciplinary scope of circular built environments, cutting through scale levels, whilst accentuating the field of ‘Flows & Resources’, in close conjunction with the fields ‘Society & Stakeholders’, 'Design' and ‘Technology’.

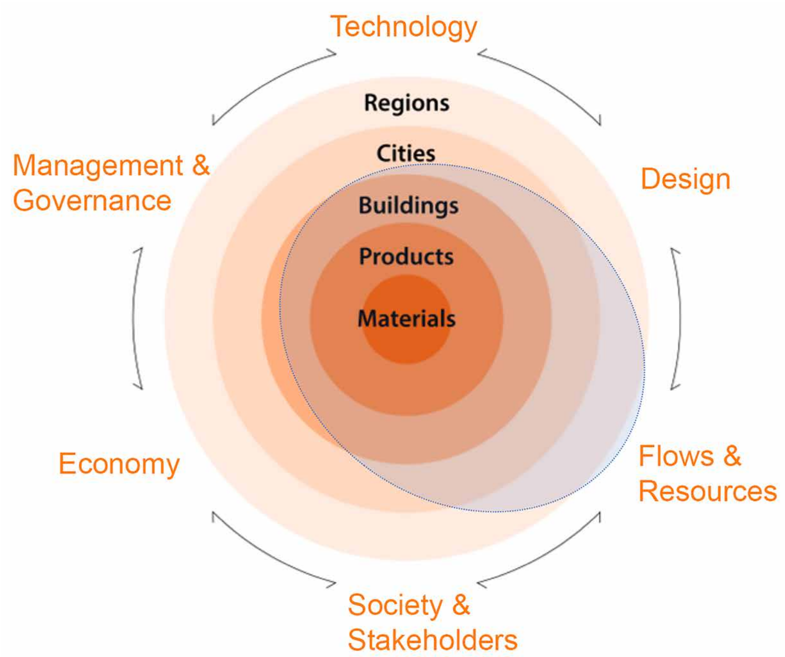

FIG. 1.15 Scope of this research, cutting through scales and disciplines, whilst accentuating Flows & Resources, Society & Stakeholders, and Design [Source: the CBE Hub, TU Delft]

The design component of this research underscores the aforementioned MM methodology. Design is “a knowledge-intensive activity, but also a purposeful, social and cognitive activity undertaken in a dynamic context”, aiming at “changing existing situations into preferred ones” [100,101]. Blessing and Chakrabarti (2009) argue that design – being a complex and multi-faceted phenomenon – involves “artefacts, people, tools, processes, organisations and the environment in which it takes place” [101]. Each of those facets is dealt with in specific disciplines. Design requires knowledge of the stakeholders and their intentions as well as the lifecycle of a product and/or service, that is, how it is to be produced, transported, installed, used, maintained and retired [101]. The Design Research Methodology (DRM) put forward by Blessing and Chakrabarti (2009) provides a useful framework. DRM adheres to a systematic research approach for supporting design innovations. Figure 1.16 displays the DRM framework. The systematic and iterative way of achieving goals, understanding, support, and evaluation, through steps of analysis and synthesis, runs through this dissertation in various chapters. Although my research loosely follows the stages indicated in Figure 1.16, the diagram should not be read as a set of stages to be executed rigidly and linearly [101]. Multiple iterations are likely in the reality of the research trajectory, in which specific stages can run in parallel or be emphasised. Various scholars have advocated that this is essential to increase the understanding and make the process more efficient [102,103,104].

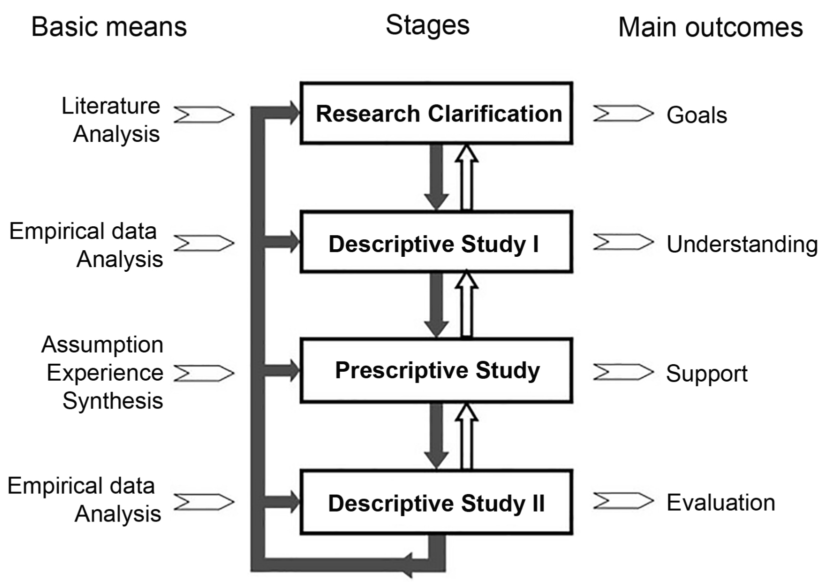

FIG. 1.16 DRM framework [Source: Blessing and Chakrabarti, 2009]

1.4.2 Methodology per chapter

Each chapter has a different sub-scope with varying methodological accents. The dissertation is built up out of two introductory chapters (Chapters 1 and 2), four research chapters (Chapters 3-6), culminating in an overarching evaluation in which discussion points are further elaborated in relation to specific state-of-the-art developments and future perspectives (Chapter 7) and a conclusive chapter (Chapter 8).

Figure 1.17 visualises the methodology, pinpointing the various means, stages and outcomes of my research, as well as the relation to DRM. Chapter 1 (Introduction) links explicitly to the DRM element 'Goals', whereas Chapter 7 (Discussion) concerns an overarching reflection, linking specifically to DRM element 'Evaluation'. Furthermore, Chapters 3-6 integrate all elements of the DRM.

Chapters 3, 4, 5, and 6 follow a 'relay' trajectory, through which criteria and guidelines are fleshed out, gradually working towards a more practical design approach to problem-solving (Chapter 6). The methodologies of Chapters 3-6 are outlined below and explained in more detail in the specific chapters.

In Chapter 3, the foundation is laid out, based on sub-questions 1 and 2, as formulated in subsection 1.3.5. I structured my research around a series of workshops that I developed to source, share, discuss, test, and redefine knowledge and experiences with a focus group of experts, in order to achieve guidelines for circular building. The aim of this chapter is twofold: (1) defining preconditions for the performance of materials, products, services and buildings in the case that circularity is a leading ambition, and (2) exploring key points with regard to the relationship between flexible partitioning, circular material flows, and user benefits.

In chapter 4, the focus is on the topic of residential user-integration, revolving around sub-questions 2 and 3 (see subsection 1.3.6). I combined literature study and semi-structured expert consultations to derive basic criteria for user-centred circular and flexible partitioning configurations (coined *Circ-Flex*). Next, I test these criteria in a quick-scan assessment of two partitioning variants. The aim of this chapter is to deepen the relationship between flexible partitioning, circular material flows, and user benefits, accentuating the integration of residential health & well-being in design and performance assessments of indoor partitioning products.

In Chapter 5, I put the emphasis on health & well-being, combined with operational aspects to secure healthy circular material flows, in response to subquestions 3, 4, and 5. My research methods include literature review, analysis of assessment-schemes, synthesis of criteria and guidelines, and validation of those in a test-case. Visits to manufacturing plants and conversations with experts provided additional data with regard to material sourcing, production and implementation of a state-of-the-art partitioning product. In this chapter, the basic criteria described in Chapter 4 (*Circ-Flex I* in Figure 1.17) are extended with an elaborated set of criteria and assessment guidelines that pinpoint health, well-being, and operational performance (*Circ-Flex II* in Figure 1.17). This chapter focuses explicitly on the rigorous integration of materialisation and operational aspects to guide the design and performance assessment processes.

Chapter 6 is aimed at design aspects, in response to sub-questions 4, 5, and 6. The design conceptualisation laid out in this chapter applies design preconditions rooted in criteria and guidelines that were shaped in the preceding chapters. Furthermore, in Chapter 6, additional data are generated – and analysed – through expert consultations, site-vists, and external lab-results. Moreover, a novel material flow analysis and modelling method is utilised with respect to secondary raw materials. The latter method (the Activity-based Spatial Material Flow Analysis: AS-MFA) is developed as part of the work package I coordinated in a separate project: 'Resource management in Peri-urban Areas' (REPAiR, Horizon 2020, 2016-2020).[3] The results of the design conceptualisation stage are directed at materialisation and operational value chains relating to a specific partitioning configuration of side-panel and insulation innovations. In Chapter 6, materialisation and operational aspects are taken a step further, deploying a design conceptualisation and study of innovative materials and value chains that have disruptive potential in the shift from linear to circular indoor partitioning systems, particularly relating to renewable materials and reversible adhesives.

Each of these chapters is set-up as a separate academic article, published in various journals (indicated in Figure 1.17). Because of this set-up, some overlap among those chapters does occur. My role concerned that of lead author and lead researcher, responsible for all aspects, notably: conceptualisation; data curation; formal analysis; investigation; methodology; project administration; and validation. Where applicable, co-authors and collaborators are mentioned per chapter.

3 Work Package 3: 'Developing and Implementing Territorial Metabolism based Representation and Process Models'.

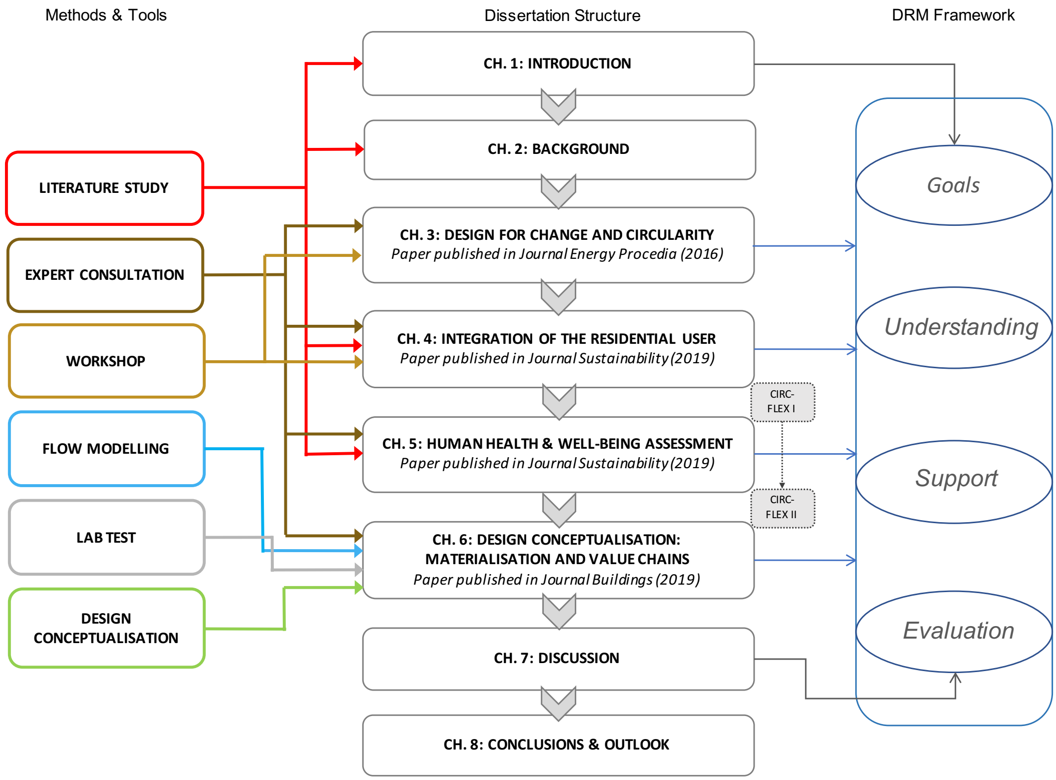

FIG. 1.17 Research methodology with mixed-methods and tools in relation to chapters and linked to components of the DRM Framework [Source: Bob Geldermans, 2019]

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2 Background

Housing and Environmental awareness

As introduced in Chapter 1, this dissertation synthesises two perspectives, being of an ecological and a social nature. In this chapter, I sketch out historical contexts. The first starts from social concerns in the 19th century regarding public housing conditions for city dwellers with very limited means, such as low-skilled workers who had come to the city for a job and better life expectations in general [1]. Section 2.1 continues with a paragraph on Dutch housing in the 21st century, and a description of Modernism and Structuralism in Architecture as a foundation for Adaptable and Open Building. Furthermore, notions of Prefab Architecture, Participatory Design, and, finally, Circularity in current housing developments, are addressed. The second perspective, described in Section 2.2, departs from the same period, focusing on environmental awareness and the implications of industrialisation from the 19th century onwards. Section 2.2 builds on the basis of environmentalism, looking into Sustainable Development, Systems Thinking, and Circular Economy, particularly in relation to the Dutch urban environment.

2.1 Housing

2.1.1 Introduction to Dutch public housing

To describe the historical context of housing in the Netherlands, I like to start with a few numbers concerning the Dutch population, which has grown substantially over time: roughly 700,000 people in the year 1300; 3,000,000 in 1850; 5,000,000 in 1900; 16,000,000 in 2000; and 18,000,000 people in 2030 [1,2,3,4]. Since the

14th century, the Netherlands has always been relatively urbanised, with a peak in 1670, when nearly half of the population lived in urban settings [1]. Urbanisation increased again in the second half of the 19tth century, in part related to industrial and technological developments. As of 1870, urban population growth surpassed that of rural areas [5].

The urban living and housing quality for the working class – the dominant social group – was generally poor in the 19th century, sometimes even referred to as primitive and destructive [5]. The living conditions, health and safety of this "lower class" was not a priority for the government [6]. Nonetheless, initiatives to improve them emerged as of mid-19th century, when the (private) 'association for the working class' (Vereniging ten behoeve van de arbeidersklasse in Amsterdam) was established in Amsterdam [6,7]. Increasing efforts to enhance the living quality for the working class in the second half of the 19th century eventually led to the 'Housing Act' (Woningwet), implemented in 1902. This underscored the shift from a predominantly liberal to a more socially engaged governmental policy, in which the state let housing associations and local authorities take the lead [7]. By the early 1920s, about 1350 associations had a combined property of 75,000 dwellings [8]. The housing shortage caused by World War II induced another increase in the construction of social housing, and between 1950 and 1980 the social housing stock tripled [9]. In this period, the role of both national and local governments became more dominant, implementing stringent standard designs to build large numbers and save on building expenses [8].

At the turn of the 20th and 21st century, a disengagement with responsibilities for housing on the part of the government began, more or less privatising the social housing sector [8]. This coincided with a general reform of the welfare state in the Netherlands, shifting towards a so-called 'participation society' based on individual responsibilities [10].

2.1.2 Dutch Housing in the 21st Century

The most common type of dwelling in the Netherlands is the terraced house ("rijtjeshuis"): a single-family home of two or three storeys, often with a front and a back garden, adjoined by several identical homes. 65% of all Dutch dwellings are single-family dwellings; the other 35% are multi-family apartments.

FIG. 2.1 Multi-family typology in The Netherlands [Source: Bob Geldermans]

In the more densely populated areas such as the Randstad, however, the division is reversed, as limited space makes for more compact homes. In Amsterdam, for example, more than 85% is multi-family [11].[4] Figure 2.1 shows a multi-family building typology in The Netherlands.

On a national scale, approximately 55% of the dwellings are owner-occupied, and 45% renter-occupied. The Randstad, again, paints a different picture: 73% renter-occupied in Amsterdam, for example, and 65% in Rotterdam. The lion's share of the renter-occupied homes are owned by one of the 380 remaining corporations, representing approximately 2,2 million households [12]. This gives the corporations an important role in maintaining and improving the quality of homes and neighbourhoods, keeping their stock both affordable and up-to-date with contemporary and future norms.[5] A main focus in this respect is the energy performance of their housing stock, in the light of national and European policies relating climate change. Moreover, according to Hoof et al. (2018) housing corporations are urged to reinvent themselves, moving from one or two competences to a multi-competence profile, in anticipation of trends such as: digitisation, an ageing population, the circular economy, transparency, co-creation, and user-centredness [13].

4 The Randstad is a *megalopolis*, home to approximately 7 million people, in the Western part of the Netherlands, including amongst others the cities Amsterdam, Rotterdam, The Hague and Utrecht

5 Recent and ongoing debates about the core tasks of housing corporations actually include the amount to which they should invest in liveability aspects beyond the housing estate scale.

2.1.3 Modernism and Structuralism in Architecture

The Modernism movement is rooted in the far-reaching changes in Western society in the late 19th and early 20th centuries. In general, it has been described as a revolt against the conservative values of *realism* [14]. Modernism offered an alternative perspective in anticipation of new social, economic and political realities in the industrialised world. The role of technology was central in this respect, not least in architecture: Le Corbusier, one of the most prominent figures of the movement, for example, approached buildings as 'machines for living', much as cars were machines for driving [15]. An analytical approach to function determined the form of modernist buildings, in which ornamentation and historical links were broadly rejected [16]. Moreover, an ideal of social living was projected on modernist architectural and urban designs, trying to raise the living conditions of the masses [17].

Criticism of the modernist approach in architecture resonates in the work of structuralists, amongst others, stressing its failure to sufficiently address the social and spatial needs of communities or families [18]. Structuralism first developed in linguistics, but transferred to numerous other fields, such as Architecture [19]. Structuralism in architecture is usually earmarked as a reaction to the functionalist bias within the Congrès Internationale d'Architecture Moderne (CIAM). This was an organisation founded to advance the principles of Modern Architecture. For most of its existence (1928 – 1959) it was hugely influential, assembling prominent architects of that time [20]. In the 1950s, the functionalist architecture and urban planning perspectives that dominated CIAM's vision was challenged by – most notably – Team 10: a CIAM subgroup. Team 10 claimed that 'CIAM-rationalism' overlooked the identity of inhabitants and urban form. This started the Structuralism movement, spearheaded by Aldo van Eyck and Jaap Bakema [21]. The resulting architecture could be described as a manifestation of relationships between equally valuable polarities: inside/outside, past/present, constancy/change etc., accommodating variable, individual functions in an invariable collective structural plan [19,22]. This approach resonates with the ideas of Claude Lévi-Strauss (1963), when postulating the existence of a structured collective unconscious capable of generating patterned cultural behaviours, including built form [23,24]. Such notions underscore the urge of Van Eyck, amongst others, to achieve a more humanist architecture doing justice to the vernacular sense of place [25,26]. A similar motivation can be detected in Christopher Alexander's work, whilst searching for a pattern design, or programming language, through which 'wholeness' (or as Alexander calls it: 'the quality without a name') can be understood [27]. Figure 2.2 visualises this [28].

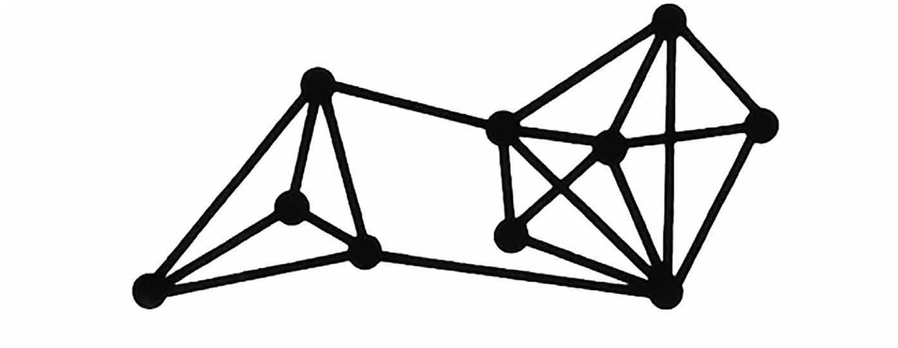

FIG. 2.2 The structure of a design problem—the un-self-conscious process modifies one node at a time, leaving the whole structure intact [Source: J. Kehl]

This notion of wholeness comes back in the work of Dutch architect and academic John Habraken. Habraken highlights time, change, and distributed control as the most essential factors. In his proposition, this leads to more decision power for the occupants regarding, most notably, space-plans and the interiors of buildings [29]. Habraken's approach to distinguish between support and infill is known as Open Building, see Section 2.1.4. One of the first concrete outcomes of that approach was the initiation of the Foundation for Architects Research (Stichting Architecten Research, SAR) in 1964, led by Habraken and the Bond voor Nederlandse Architecten (Association for Dutch Architects). The SAR dedicated itself to developing a new professional methodology replacing the one based on predetermined floor plans [30].

2.1.4 Adaptable and Open Building

As a concept in architecture, 'adaptability' could be defined as "a design characteristic that embodies spatial, structural, and service strategies which allow [...] a level of malleability in response to changing operational parameters over time. This strategic shift reflects buildings [...] as imperfect objects whose forms are [...] continuously evolving to fit functional, technological, and aesthetic metamorphoses in society" [31, page 2]. Some advocate that it is simply part of good design, to allow for change over time. This resilience, however, is not self-evident in our built environment. Adaptability is at the heart of OB. With regard to the physical structure, OB aims to "bolster the capacity for change to take place through an ease of tension between building components, notably the infill and the support" [31, page 7]. However, the concept is primarily rooted in social, not technical, considerations, induced by concerns about the uniformity of mass housing after World War II. OB departs from the desire to empower the user by decoupling the support and infill parts, in technical, organisational and regulatory sense, leading to new ownership and financial models [32]. This opens up possibilities for a separate fit-out industry, aimed at what users can control behind their front door [33]. As yet, the support-infill concept is more common in commercial typologies, such as shops and offices, than in the residential sector. The separation of support (or base building) and infill (or fit-out) offers a viable basis for control over building material and product flows. Figure 2.3 displays OB decision levels, from more collective to more individual domains, including estimated service lives [34,35].

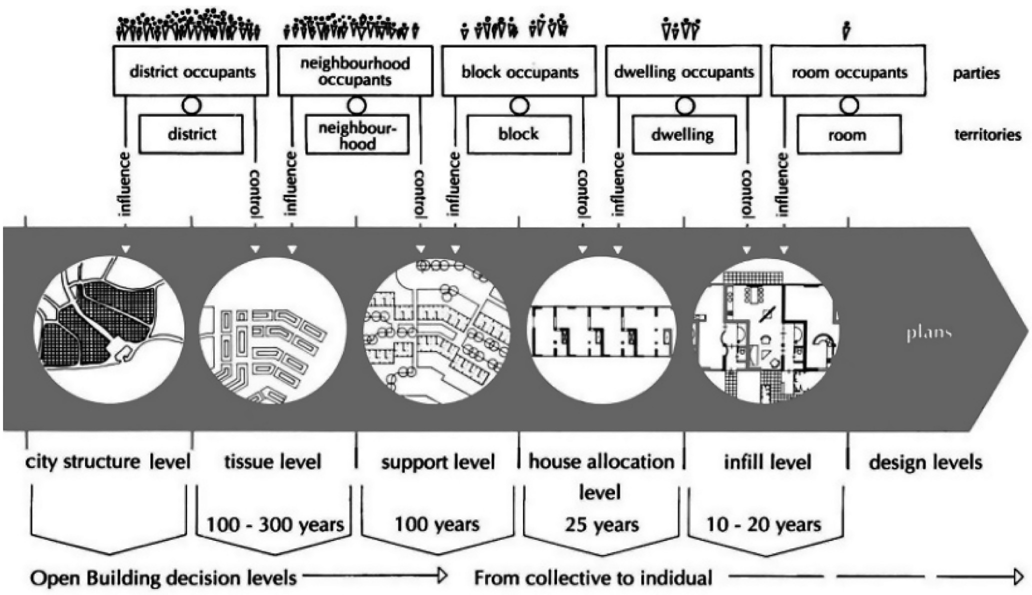

FIG. 2.3 Open Building decision levels from collective to individual, with service-life indications [Source: Van Randen]

In the past, several attempts were made to introduce infill products and concepts to the market, such as the Matura Infill System of John Habraken and Age van Randen. However, these attempts have not survived, due to various reasons: an important one being that there was insufficient leverage at the time for a viable market introduction [35]. OB principles, however, have found their way into multiple housing projects, both nationally and internationally. Prime examples in the Netherlands are Molenvliet (Papendrecht), Pelgromhof (Zevenaar), Beatrixlaan (Voorburg), Keyenburg (Rotterdam), and Solids (Amsterdam). Several of these examples will come back in Chapters 4 and 7.

FIG. 2.4 Clockwise from above left onwards: the NEXT21 complex; Open support structure before infill renovation; Unit 303 'Independent Family House' with open partition wall; Floor-plan of Unit 501 'Plus One House' [Source: Bob Geldermans]

A prime international example is NEXT21 in Osaka, Japan (see Figure 2.4). NEXT21 is an experimental, multi-family housing project built in 1993 by Osaka Gas Co. It showcases an integrated approach to sustainability through environmental protection, energy-saving comfort for residents, and the ability to satisfy evolving individual and societal needs [36]. NEXT21 secures the long life of housing through an open support structure and flexible infill. The architect in charge, Yositika Utida, invited thirteen other architects to design the 18 individual units, stating he did not want to make a building but a 3-dimensional urban design [37]. Each housing unit responds to a predefined household profile, addressing different types: singles, couples, couples with children, single parents with children, and other compositions. The floor-plans are adjustable, following a modular grid system. The subsystems can be adjusted with autonomy, avoiding interference with other housing units. Throughout its 25+ year existence, NEXT21 has been monitored on multiple parameters, such as energy performance, water use, biodiversity, and user perception. The latter is done through interviews with the temporary users, after a period of 5-7 years. The findings are in Japanese and for internal evaluation only. Likewise, beyond the general claim that Design for Flexibility principles increase the reuse potential of parts, no data are disclosed with regard to material (re-) use. Nonetheless, higher initial costs are said to be a barrier for replicating this approach in the current Japanese building sector [38].

Anticipating multiple building levels, and the way they may change individually over time, adaptable and open building approaches have a significant impact on the construction and deconstruction process. Conventional processes run short in this respect, as they are usually based on parallel rather than serial activities [39]. Lichtenberg (2004) highlights the differences between parallel and serial (or sequential) activities, particularly focusing on finishing processes and the integration of service installations. The complicated on-site interrelations between actors and activities in these stages lead to inefficiencies, failures, and the lack of infill-flexibility [39,40]. The proposed sequential process facilitates a more integrated and streamlined chain of activities, similar to, for example, the car industry. The diagrams of Figure 2.5 compare the parallel and sequential construction process [39,40].

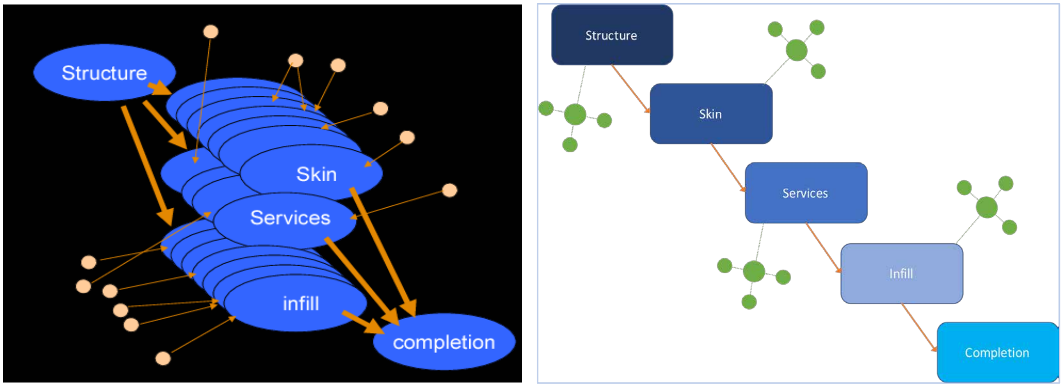

FIG. 2.5 Parallel (left) and Sequential (right) construction process [Source: Slimbouwen]

2.1.5 Prefab Architecture

There seems to be a paradoxical relationship between the aforementioned notions of place awareness and *genius loci*, on the one hand, and the industrial, repetitive and business-like connotations that come with the word prefabrication [41,42]. However, prefabrication can be instrumental in adapting to new functions and the requirements of a place in relatively in-obtrusive ways. As such, it often accompanies adaptable and open design concepts and practices.

Prefabrication (prefab) comes indeed from other industries in which well-integrated and coordinated design and supply-chain efforts are inextricably linked to the complexity and economies of scale inherent to manufactured products [39]. Think for example of the automobile, shipbuilding, and aerospace industries. Construction, on the other hand, has always been an on-site activity, or rather, set of activities. In the last century, when housing production needed to accelerate, the lack of efficiency with which the building industry was often confronted became more obvious. Over time, this has led to a larger share of prefab in the construction sector. Also in the Netherlands, prefab architecture has gained ground, with a boost in the 1990s, based on the awareness that a greater flexibility of the housing stock was needed. This was largely in response to demographic dynamics and associated relocation rates being at odds with buildings' technical service lives, leading to unnecessary waste of built capital. The Dutch government implemented the IFD-programme, in which IFD stands for Industrial, Flexible, Demountable. The IFD programme may have contributed to an innovation-boost, favouring prefab and modular manufacturing and building methods, however it has not resulted in enhanced flexibility and sustainability performance of the building stock at large [43]. Durmisevic and Binnemars (2014) state that "most modern buildings today are made of prefabricated components designed to be mountable but not demountable", marking one of the main barriers for deconstruction [44, page 76]. For the time being, prefab innovations that integrate assembly, disassembly and reassembly, are more common in typologies and business models with an explicitly temporary character. The traction of Circular Building in the Netherlands, however, is likely to positively impact the application of prefab techniques and methods on a larger scale. Moreover, young technologies, such as additive manufacturing (3D-printing), Computer Numerical Control (CNC) and Internet of Things (IoT), are estimated to have substantial impact on the way prefab will be integrated in construction [45].

2.1.6 Participatory Design

Participatory design could generally be described as an attitude towards creation and innovation occurring through a process of inclusive rather than exclusive decision-making [46]. With regard to the democratic principles behind it, this could be traced back as far as Plato's concepts of equal representation [46]. Participatory design or co-design as a model in architecture, however, only dates back to the 1960s, as a way to "redress the balance between architect and user" [47]. As such, it is deeply related to both Structuralism and Open Building, as described in the two former sections, albeit with diverging accents.

There are multiple degrees in which users can be empowered. These degrees are highly dependent on contextual aspects such as tradition and opportunity. This ranges from (1) self-build practices, in which the schooled architect is more or less by-passed, to (2) future-user involvement in design processes, and 3) adaptable design concepts that anticipate unforeseen future use.

The 1st – *self-build* – approach relates to, for example, vernacular architecture all over the world, or the hands-on and affordable self-build housing system proposed by Walter Segal (1907-1985), particularly employed in UK communities.

The 2nd – *future user involvement* – approach comprises multiple methods for user representation. Lee (2006) distinguishes four types, with varying levels of design participation: for a) innovation, b) collaboration, c) emancipation, and d) motivation [48].

The 3rd approach – anticipate unforeseen use – is interwoven with both other approaches. It finds an important distinction from the 2nd approach (future-user involvement approach) in the way designers could be excluded altogether concerning the private (technically, legally, and organisationally independent) fit-out domain. Subsequently, this demarcates the domain where the 3rd approach (self-build) becomes the key feature. A contemporary Dutch housing concept where participatory principles are either leading or integrated is 'Klushuizen' (DIY houses), initiated in Rotterdam in 2006, see Figure 2.6. This concerns vacant and derelict housing in gentrification neighbourhoods to be reactivated by new occupants. The municipality sells the houses for extremely low prices, but with a renovation obligation up to an agreed standard. Within those restrictions the new owners are free to customise the dwellings the way they desire [49].

FIG. 2.6 Klushuizen (DIY-houses) in Rotterdam, the Netherlands [Source: Klushuis.Wordpress]

2.1.7 Circular Housing in the Netherlands

In the Netherlands, several policies underscore the ambition to shift from linear to circular building approaches. Important programmes and agreements between the government and industry partners include 'Nederland Circulair 2050' (Netherlands Circular 2050, 2016), 'het Grondstoffenakkoord' (Raw Material pact, 2017) and 'Transitieagenda Circulaire Economie' (Transition-agenda Circular Economy, 2018) [50,51,52]. Construction is one of the main sectors in focus. The latter document (Transition-agenda) includes a strategy and guidelines to execute the intentions formulated in the former two documents, specifically regarding the building sector. The agenda's horizon is 2050, in line with objectives of the Dutch Cabinet to reduce primary raw material use by 50% in 2030 and by 100% in 2050, but the approach is stepwise: the first period concerns 2018-2021 [51,52]. Four points of attention provide structure to the agenda 2018-2021: market development; measuring; policy, law & regulations; know-how and awareness.

At this moment, practical experience with circular building is mainly being developed in commercial building typologies, much less so in housing, which is due to a lack of appropriate financial incentives and a lack of legal support, amongst others [53]. With regard to sustainability, the emphasis in housing (both renovations and new construction) has long been on energetic performance, but a shift towards a more integrated approach can be discerned, with increasing attention for building materials [54]. As of January 2018, an environmental performance calculation based on an MPG assessment (Milieu Prestatie Gebouwen: Environmental Performance of Buildings), is mandatory when applying for a permission to build, renovate, or demolish, which is likely to impact the building structure or environment [55]. In 2019, the MPG will be revised, whilst integrating circular principles [56]. In some Dutch municipalities pilot projects regarding circular housing have been or are being deployed with ambitions that are higher than the national regulatory framework dictates, e.g. Buiksloterham Amsterdam; Puraverde, Venlo; Superlocal, Kerkrade; and Woonbron Rotterdam. Several parties in the Dutch housing sector are thus building up experience with implementing circularity principles [57]. For example, the housing corporation Woonbron (Rotterdam) collaborates with a market partner (New Horizon) aiming at the circular dismantling of 600 units in the years to come. The dismantling trajectory and associated business model is outsourced to New Horizon, which "mines" for valuable secondary components and materials [58]. Another housing association, HEEMwonen (Kerkrade), integrates circular principles into a transformation project. In line with the declining population, 300 apartments (3 building blocks of each 100 apartments) are to be transformed to 125 high-quality social houses. The aim of this project - titled SUPERLOCAL - is to reuse materials locally, but also to re-value landscaping aspects, whilst deploying an inclusive and co-creative approach [59]. In Venlo, the project initiator and contractor Jongen BV develops 50 houses based on 5 pillars defined in close collaboration with the C2C Expolab (Venlo): healthy and safe materials; renewable energy; adaptable building; sustainable water management; air quality and diversity. The project (PuraVerde) is developed in close conjunction with the municipality and market partners. An important aim is to keep the total costs of ownership (TCO) lower than the standard. Finally, in Buiksloterham (a district and living lab for circular area development in Amsterdam), the project 'Schoonschip' deploys an integrated approach to circularity. Schoonschip is a residential neighbourhood of 46 houseboats and communal spaces where sustainability is safeguarded on all levels, emphasising the exploitation stage over the construction stage, due to the higher overall impact of exploitation [58].

The aforementioned examples show that circularity in housing, and construction in general, is approached both as a term to address high-quality cyclic material use, and a more 'holistic' expression of sustainability, integrating multiple themes as well as spatial and temporal levels. Related to this, is the topic of measuring circularity. In the transition from linear to circular built environments, measurability is increasingly part of the ambitions. It enables better management and monitoring of projects, the creation of level playing fields, and lay a foundation for replicability. From the multiple initiatives to gain more grip on measurability it can be observed that the inherent complexity is taken seriously, while deriving more manageable definitions that focus on subparts, such as materialisation [60,61,62]. Within the Dutch Transition-agenda for Circular Building, measuring is a main point of attention, aiming to establish a uniform method that can be integrated in standardisation and regulatory frameworks [56].

2.2 Environmental awareness

2.2.1 Introduction

In spite of – or thanks to – earlier theories and discourses concerning population growth and natural resources, particularly relating to Malthus' essays on the principles of population and Marx' thoughts on 'eco-socialism', it seems that environmental awareness, in the light of industrialisation, gained ground in the second half of the 19th century [63,64,65]. Intellectuals such as John Ruskin and

William Morris contested the urban conditions in England, resulting from industrial capitalism, in favour of rural virtues [63]. And something similar happened during that period in the United States of America, spearheaded by figures such as essayist Henri David Thoreau, and writer and nature preservationist John Muir. However, it wasn not until decades later that the notions of environment and economy firmly came together in relation to contemporary society [66].

An important precursor for environmental awareness was the advancement in science, which provided an evidence-base to problematic phenomena in nature, caused by man. Rachel Carson's *Silent Spring* (1962) has proved to be a key publication in that respect, in response to the wide use of chemical biocides toxic to the environment and humans. Carson was advocating responsible use of pesticides in awareness of the potential impact on ecosystems [67]. Despite heavy resistance and mocking from the (agro-)chemical industry (Monsanto published a parody in 1962 called "The Desolate Year", describing death and destruction in a world without pesticides), the book helped awaken a grassroots ecological awareness [68,69]. Moreover, *Silent Spring* poignantly revealed the schism between (main interests of) industry, science, and civil society. In doing so, it started a battle that is still ongoing today. Was it *dichlorodiphenyltrichloroethane* (DDT) at that time dominating the debate, today it is *isopropylammoniumsalt* (Glyphosate a.k.a. RoundUp).

2.2.2 Limits to Growth

About ten years after *Silent Spring*, another publication emerged that had a large impact on the discourse of modern life in relation to human and environmental health: *Limits to Growth* [68]. *Limits to Growth* (LTG) introduced a computational model based on five parameters: population; industrialisation; food production; pollution; consumption of non-renewable natural resources [70]. Although the predictions presented in the book were not uncontested, many proved to be relatively accurate, according to recent reflections [71,72,73]. Jackson and Webster (2016) stated "there is unsettling evidence that society is still following the 'standard run' of the original study, in which overshoot leads to an eventual collapse of production and living standards" [73]. Regardless of the computational accuracy-level in LTG, the foundations on which the models were based contain some facts that are hard to counter, particularly with regard to the exponential growth rates of variables relating the development of mankind (such as population, consumption, and pollution) versus the linear growth rates of natural resources. Of course, technological innovations and economic mechanisms can be decisive factors in sustaining the capitalistic economic growth model, as advocated by scholars who challenged the message of LTG, such

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as economists Julian Simon and Robert Solow [74,75]. However, it has become increasingly apparent what the limitations are of that growth model, for example with regard to inequality, which can be seen as a feature of capitalism rather than an incidental effect, as recently put forward by, most notably, Thomas Piketty [74]. This relates to asymmetries in the supply and demand of natural resources. Even if human ingenuity can always find solutions for resource scarcity, as Simon proposes, it has found few incentives to secure safe supply for all [74,76].

2.2.3 Sustainable Development

Realisations concerning inequalities in the distribution of resources, as well as the sheer scarcity of some resources and the associated environmental and social impacts of increasingly inefficient mining activities, resonate louder and louder in today's governmental policies and society at large. The term 'Sustainable Development' (SD) derives from such realisations [77]. SD came up as a term in the 1980s, arguably with a highlight in the report 'Our Common Future' (also known as The Brundtland Report) of the United Nations World Commission on Environment and Development [78]. Brundtland et al. defined SD as follows: Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

In its call for action, at the end of the report, Brundtland et al. describe the current *condition humaine* in a way that concisely sums up the concerns and solution pathways. They state that: "Over the course of this century, the relationship between the human world and the planet that sustains it has undergone a profound change. When the century began, neither human numbers nor technology had the power to radically alter planetary systems. As the century closes, not only do vastly increased human numbers and their activities have that power, but major, unintended changes are occurring in the atmosphere, in soils, in waters, among plants and animals, and in the relationships among all of these. The rate of change is outstripping the ability of scientific disciplines and our current capabilities to assess and advise. It is frustrating the attempts of political and economic institutions, which evolved in a different, more fragmented world, to adapt and cope. It deeply worries many people who are seeking ways to place those concerns on the political agendas." [78, page 36-37]

This paragraph underscores the complexity of the challenge, whilst integrating environmental, social, and economic aspects. The Brundtland report laid the groundwork for a major global earth summit (Rio de Janeiro, 1992) and action

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agenda (Agenda 21). Based on this, the Commission on Sustainable Development was initiated, and replaced in 2013 by the High-Level Political Forum on Sustainable Development. Since 2015, a set of seventeen Sustainable Development Goals (SDG) has been adopted by the United Nations, with the aim to implement them around the world. The time horizon is 2030. The Sustainable Development Goals are shown in Figure 2.7 [79].

FIG. 2.7 Sustainable Development Goals [Source: UN]

2.2.4 Systems Thinking

As described above, sustainability is inherently a systemic phenomenon. Thinking in systems implies adhering to complexity. Ladyman et al. (2011) define a complex system as: “an ensemble of many elements which are interacting in a disordered way, resulting in robust organisation and memory” [80]. Interaction implies there is the exchange of energy, matter or information, which makes the elements dependent of one another. As such, Ladyman et al. state that “interaction is the basis for any correlations to build up and hence for order to arise from disorder” [80]. Furthermore, the potential of forming patterns and structures is decisive in making systems complex. The robust organisation of a given order – in patterns and structures – is related to a specific scale, even if elements within it continue to interact in a disordered way. Lastly, the persistence of internal structures gives the system the capacity to “remember”, that is, memory [81]. This definition underscores the deep worries articulated by Brundtland et al. within their call for action:

complex natural planetary systems are jeopardised by man-made interventions that have not taken into account such complexity. As we have learned from, amongst others, changes in climatic behaviour, local interventions can thus have global effects.

Although sustainability is a systemic, integrated term by its very nature, it is interpreted by man in many varieties. Gibbs et al. (1998) state that “interpretations tend towards the ‘weak’ end of a sustainability spectrum, whilst hindering integrative activity and the potential for introducing ‘strong’ sustainability measures” [82]. Weak sustainability is characterised by allowing trade-offs between the social, environmental, and economic aspects [83]. Strong sustainability, on the contrast, does not allow such trade-offs. Many representatives of strong sustainability dismiss the assumption that the economy – as we know it – is superior, whilst alluding to a fundamentally different economic model [83,84,85].

2.2.5 Circular Economy

The Circular Economy (CE) has been introduced as a fundamentally different economic model, opposing the current largely linear economic model based on taking resources from the earth, manufacturing these resources into goods, using those goods, and eventually discarding them. Whereas the linear model gradually destroys the value captured in goods, the circular counterpart proposes a model in which value is retained [86,87,88,89]. In essence, this circular model is not new, as it has been applied by mankind for centuries, throughout pre-industrial societies. Moreover, in parts of the world, and relating to specific goods, a circular model is maintained. Industrialisation, however, has reorganised the economy for the purpose of manufacturing [90]. As of the 1970s, CE has been described as a model to save resources and grow jobs. In a report to the European Commission, Stahel and Reday-Mulvey brought forward the principles and potential of substituting manpower for energy [91]. Stahel, being an architect, started from the notion that “it took more labour and fewer resources to refurbish buildings than to erect new ones, and that this principle is true for any stock or capital” [91].

Since 1987, the Environmental Protection Encouragement Agency (EPEA), founded by chemist Michael Braungart, has been working on the identification of closed-loop principles. In 1995, Braungart and William McDonough founded McDonough Braungart Design Chemistry (MBDC) to turn their work in chemical research, architecture, urban design, and product and process design to the project of transforming industry itself [92]. Braungart and McDonough particularly contested the eco-efficiency concept, which was prevailing in Sustainable Development (SD) frameworks. According to them, eco-efficiency is a fatally limited approach, restricting industry, curtailing growth, and limiting the creativity and productivity of humankind [93]. Although they acknowledged the integrated social, environmental, and economic stance of SD, MBDC proposed an explicit emphasis on the upfront design-integration of those pillars, rather than a focus on accountability afterwards. In doing so, they stressed the potential for making a positive impact rather than minimising negative impact [92]. The associated design-model, coined Cradle to Cradle® (C2C®), is based on three basic principles: waste equals food, use current solar income, and celebrate diversity. C2C® distinguishes biological (natural) and technical (synthetic) flows, whilst eradicating hybrid composite products that cannot be taken apart.

In 2012, the concept of Circular Economy got a boost with the publication 'Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition' [86]. This CE concept is rooted in the principles of C2C®, but also refers back to Stahel's work, as well as to related systems approaches, such as Regenerative Design, Industrial Ecology, Urban Metabolism, and Blue Economy [91,92,94,95,96,97]. CE distinguishes between the consumption and use of materials, putting forward a 'functional service model' in which manufacturers or retailers act as service providers: selling the use of products, not their one-way consumption. This shift in business or value model anticipates efficient and effective take-back systems and design practices that generate more durable products, facilitate disassembly and refurbishment, and consider product/service shifts, where appropriate [86].

The diagrams of Figure 2.8 display the linear economy model next to the circular counterpart. In Figure 2.9, shorter and longer cycles of technical and biological resources are indicated.

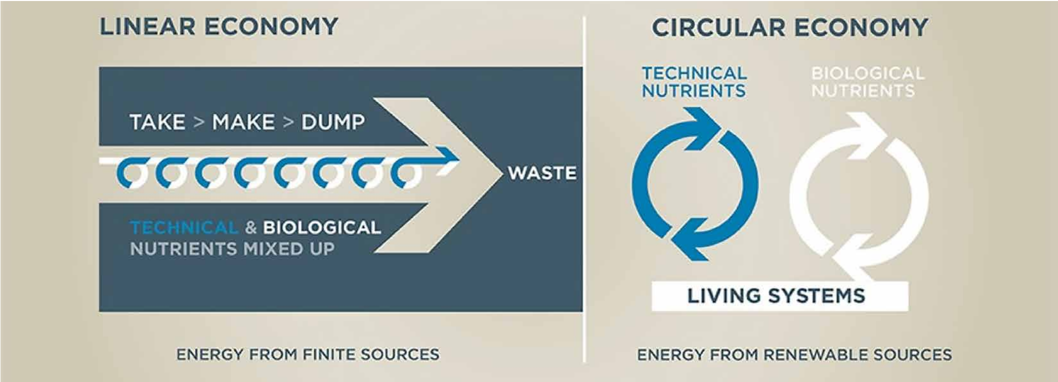

FIG. 2.8 Linear economy & Circular economy [Source: Ellen MacArthur Foundation, based on McDonough & Braungart)

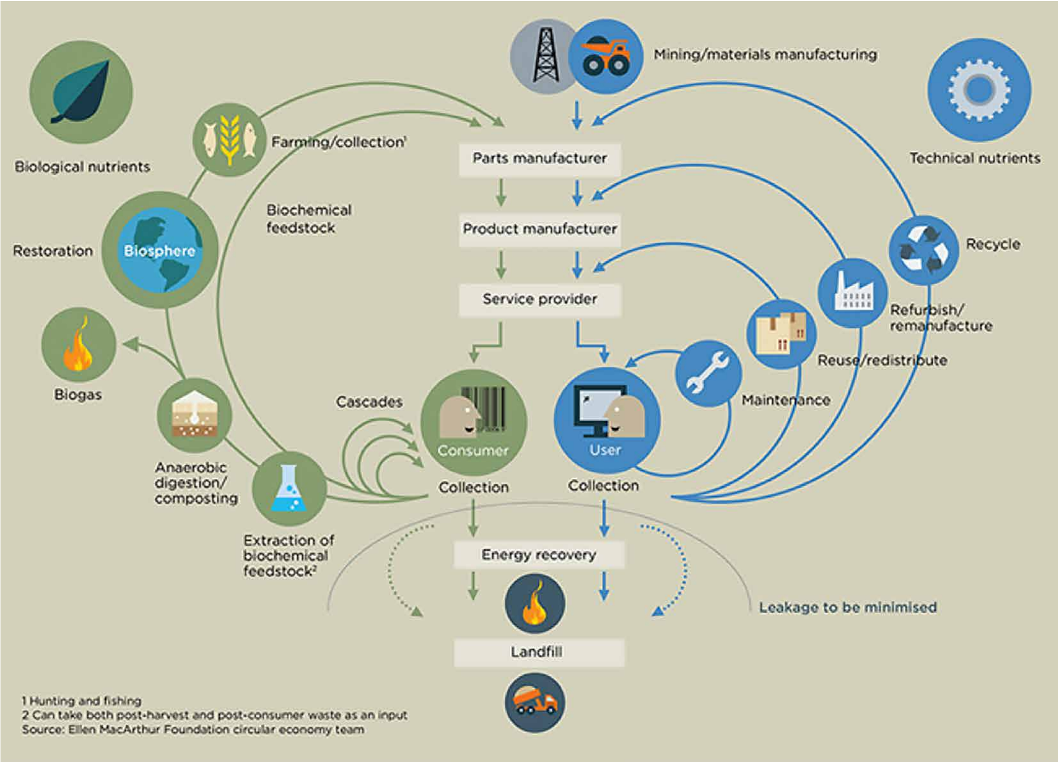

FIG. 2.9 Circular Economy with shorter and longer cycles of technical or biological resources [Source: Ellen MacArthur Foundation, based on McDonough & Braungart]

2.2.6 Between pragmatism and radicalism

Although it could be stated that CE and sustainability are two sides of the same coin, they are not synonymous, particularly with regard to 'weak sustainability' interpretations. Reflecting on CE's current state of development in relation to the European Commission's ambitions, shows that CE is operating on a bandwidth between two points of departure [98,99]. The European Commission's viewpoint leans heavily on established waste and resource management strategies, such as optimisation of (re-) processing-steps and business models *at the end* of a product's functional cycle, at best slowing down the decrease in value of products and resources. The viewpoint of the Ellen MacArthur Foundation (EMF) strongly adheres to *upfront* anticipation of future functional cycles, aiming to retain or increase value, much in line with C2C® principles. The latter viewpoint is generally more disruptive in regard of existing value models.

Ideally these two perspectives reinforce each other in a shared ambition regarding sustainable resource management [100]. In that case, the developmental transition allows for multiple strategies, which are essentially compatible. However, diverging patterns, structures, networks, and sectoral interests could easily make the two perspectives contradictory, based on path dependency and associated resistance to change [101].

As an example: in the Netherlands, finding 'useful applications' for secondary materials has been on public and private agendas for several decades. By consequence, recycling rates of residual materials are high: of the total construction and demolition waste, for example, roughly 93% finds a secondary function [102]. The know-how and infrastructure present in the Netherlands forms a competitive advantage in this respect. It is thus logical and convenient to start by exploring enhanced end-of-life processes. Indeed, applying the waste management hierarchy could contribute greatly to preventing waste or keeping materials in the loop, when done in a sound and smart manner. However, this strategy has not tackled the fact that only very few materials stored in our products can be reused over and over again in their "highest utility and value" [86]. The term 'useful application' is open to interpretation and current recycling is predominantly downcycling. It is thus fair to question the extent to which the status quo can be challenged when adhering to a more pragmatic point of departure. In that respect, Bina (2013) identified a "persisting weak interpretation of sustainable development, and a tension between the fixing or shifting of dominant socio-economic paradigms, which compromises ambitions on a European and global scale" [103].

TABLE 2.1 Constituents of an envisioned Circular Economy, from more pragmatic to more radical, based on the European Commission, Ellen MacArthur Foundation and Cradle to Cradle [Source: Bob Geldermans]

Pragmatic	Radical
Maintain value	Keep products, components and materials at their highest utility and value
Minimise waste	Eradicate waste
Minimise resource use	Maximise resource yields
Keep resources in economy	Restorative systems: Biological nutrients for natural capital building (consumption) – Technical nutrients circulate in 'techno-sphere' (use)
Provide human & environmental protection	Minimise, track & eliminate toxic chemicals
Provide durable & innovative consumer products	Establish product-service systems based on 'use', rather than providing one-way consumption
Achieve monetary savings	Business & value chain benefits
Promote innovation	Implement knowledge feedback loops
More systemic - material-specific lifecycle - approach to integrate design, use, reuse, and recycling (starting with plastics as a pilot case).	Whole systems effectiveness, including "reducing damage to human utility, such as food, mobility, shelter, education, health, and entertainment, and managing externalities, such as land use, air, water and noise pollution, release of toxic substances, and climate change" [86].
Increase share of renewable energy, including 'weak sustainability' technologies, such as energy from biomass	Total reliance on renewable energy, based on 'strong sustainability' technologies

Table 2.1 lists constituents of a CE, as articulated in Circular Economy Package documents of the European Commission (ambitious yet pragmatic, with 'space for play'), alongside those found in literature relating, most prominently, EMF and C2C® (radical, idealised) [98]. The more radical approach emphasises complete rethinking and redesign of systems, including interrelations between (sub-)systems, amongst others with regard to the use of renewable energy to drive resource systems [86,91].

2.2.7 Circular Economy and Sustainable Development Goals

According to Schroeder et al. (2018) CE practices can contribute to achieving a great number of Sustainable Development Goals [104]. The strongest (direct) links were detected with: SDG7 (Affordable and clean energy); SDG8 (Decent work and economic growth); SDG12 (Responsible consumption and production); SDG6 (Water and sanitation); and SDG15 (Life on land) [104]. Concrete related benefits are: job creation; innovation; productivity; resource efficiency; and cost savings [104]. Figure 2.10 displays multiple relationships between SDG in the context of CE practices, as identified by Schroeder et al., whilst integrating social, environmental, and economic pillars [104].

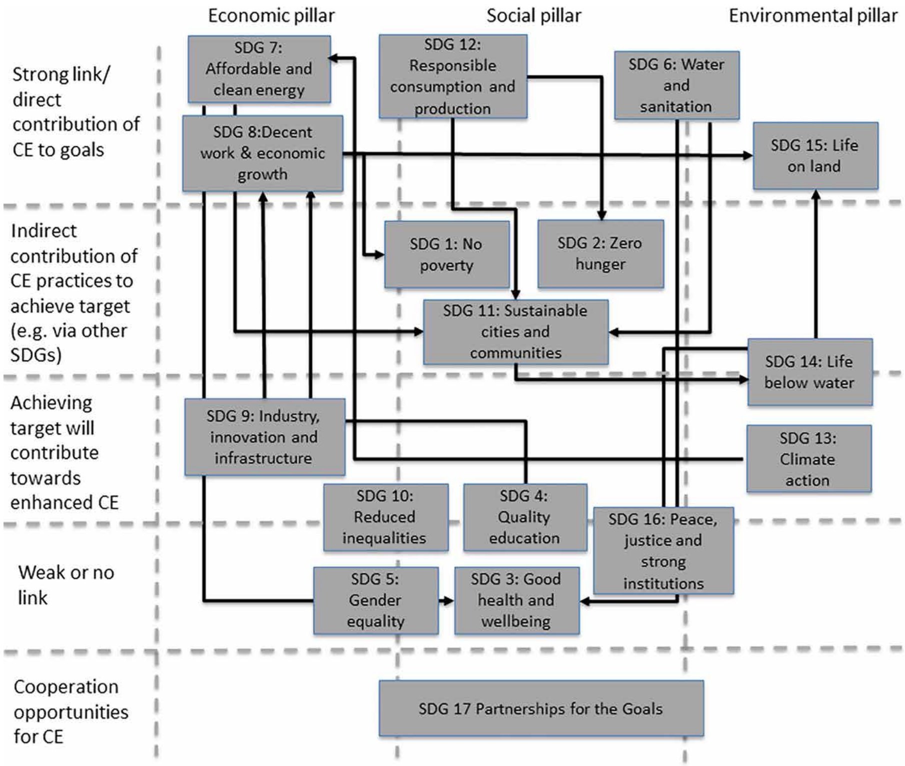

FIG. 2.10 Relationships between Sustainable Development Goals in the context of circular economy practices [Source: Schroeder et al., 2019]

To what extent CE can contribute to meeting the SDGs is yet to be seen. Although multiple potential benefits of a CE are put forward, the concept has not yet matured enough to justify any claim without reservation. A recent study found significant gaps between circular economy aspirations, as communicated by several pilot cities, and applied indicator frameworks: categories, such as education; gender; health; urban planning; people; and safety, appeared to be often overlooked [105]. The overall impact of CE thus requires more study [106].

2.2.8 Circular Cities

Cities are responsible for approximately 75% of all natural resource use, whilst producing roughly 50% of global waste and 60-80% of greenhouse gas emissions [107]. The linear economic model thus prevails in cities as we know them.

At the same time, cities and city regions, being hubs of concentrated stocks, flows and activities, provide an appropriate scale for closing and coupling loops. This is not to say that cities and city regions should be approached as isolated sets of sub-systems, because resilient systemic performance does not always care for such administrative boundaries. However, for exploring local, circular synergies within the enormous diversity of activities and flows, cities are high-potential areas.

In circular cities, resources that drive human activities are by definition *re*generative rather than linear or *de*generative: be they materials, energy, water, nutrients or clean air [108]. This implies that the focus shifts from gradual destruction of resource-value to value-creation through models based on cascades and cycles, as addressed in former subsections. In order to establish such regenerative resource flows there is dire need for new concepts as well as rigorous and critical testing of the existing ones. Efforts in this direction (should) take place at both an academic and a practical level, bringing together many actors, sectors and disciplines [109]. Among key themes are: (1) the alignment, connection, and continuation of flows, and (2) the deployment of shared value models.

Aligning, connecting, and continuing flows requires the meticulous differentiation between physical as well as temporal manifestations. Circulation-pathways will depend strongly on quality and quantity of the given flow. Think for example of building components that become obsolete in one building but can be applied in another, either directly or after one or more interventions. Temporal gradients need to be taken into account in this respect, relating to the time when materials are needed and when they become available. Furthermore, the differentiation of material origins and destinations needs to be taken into account, given its decisive impact on the sustainability of production and consumption systems. This relates to infrastructural and transport issues, as well as economic and demographic activities. In circular city configurations, it is likely that the relationship between resource management and urban quality becomes more apparent and tangible in everyday life. A more reciprocal relationship can be expected between, on the one hand, urban (and peri-urban) layout and design, and on the other, the way resources and products move most optimally for citizens [107]. This necessitates more emphasis on *shared value*. Products, materials, and services will circulate among networked stakeholders and functions in faster and slower loops: some on the demand side and some on the supply side of the value chain. Associated value models need to be based on whole lifecycle performances, eliminating mechanisms that favour linear and one-sided thinking. As such, circular cities also mean healthy, inclusive and democratic cities.

The impact on how cities are conceived, materialised and operationalised in a circular configuration may be substantial, but this does not imply harsh top-down urban planning with futuristic outlooks. Some impacts can be imagined, based on current knowledge, but others can at best be anticipated [109]. Accommodating circular processes in all their diversity means that potential pros, cons, and contradictions in the actions we take need careful consideration, integrating the different interests, of all current and future city dwellers.

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3 Design For Change And Circularity

Accommodating circular material & product flows in construction

This chapter is adapted from a paper under the same name, published in: Energy Procedia. 2016;96:301-311. https://doi.org/10.1016/j.egypro.2016.09.153. The chapter originates in a study for the Municipality of Rotterdam: Geldermans, B., Rosen-Jacobson, L., Zuidema, R., Doepel, D., Welink, J.H.. Circular material & product flows in buildings. Delft: Delft University of Technology, 2015.

3.1 Introduction

3.1.1 Circular Material Flows

In the light of large global and local challenges relating to resource scarcity and supply security, the European Union shows a shift in focus from linear to circular systems, whilst regarding waste as a resource [1]. Not only does a circular approach offer 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, because of large changes in the way actors are interconnected, be it related to water, materials, topsoil for food production or energy systems, e.g. regarding decentralised decision-making, extended producer responsibility, and reverse logistics [4]. So far, many technological innovations and designs for circular material flow systems have fallen short because of their relatively one-sided nature [5,6]. According to Vernay (2013), this is due to an approach which is "too technocratic and too static, taking insufficient account of how environmental, social, technical, economic and temporal factors are integrated in practice" [6].

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), *Design for Reuse*, and *Design for Recycling* (DfR) are such methods that have gained ground in the building sector [7,8]. DfD and DfR focus on de-constructability, reuseability, and recyclability from a technical design point of view, aiming to reduce the negative environmental impacts of construction. Whether components and materials are actually applied, maintained, reused and recycled in the intended way falls beyond the scope of these methods [9]. However, those operational aspects are crucial indicators for the success of envisioned material loops. In essence, concepts such as DfD and DfR 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® [2,10], Regenerative Design [11,12], the Blue Economy [13], and the Circular Economy [3]. These concepts open up new ways of thinking related to the 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. The implications for the supply and value chain, however, are significant, and research in this direction has only recently really taken off. Figure 3.1 displays a Cradle-to-Cradle® value-chain, comprising design, materialisation, manufacturing, distribution, use, collection, and multiple reutilisation pathways. The latter are divided in technical and biological systems. The technical system (above in blue) revolves around service-loops, in which the products and materials follow shorter (inner) or longer (outer) cycles of reutilisation. Distinguished in the figure are: maintenance, redistribution, refurbishment, remanufacturing, and recycling. With regard to the biological system (below in green), use is referred to as 'consumption', referring to the actual uptake and transformation of materials and products [10]. Biological matter coming out of this system can be applied as nutrients for materials or energy, in cascades that optimally capitalise on the value comprised in the material. Furthermore, know-how feedback loops are explicitly represented in Figure 3.1, underscoring the importance of continuous learning. Figure 3.1 is directly related to the C2C® concept, as proposed by Braungart and McDonough, which was also a key precursor and inspiration for the EMF model, displayed in Figure 2.9 of Chapter 2 [14].

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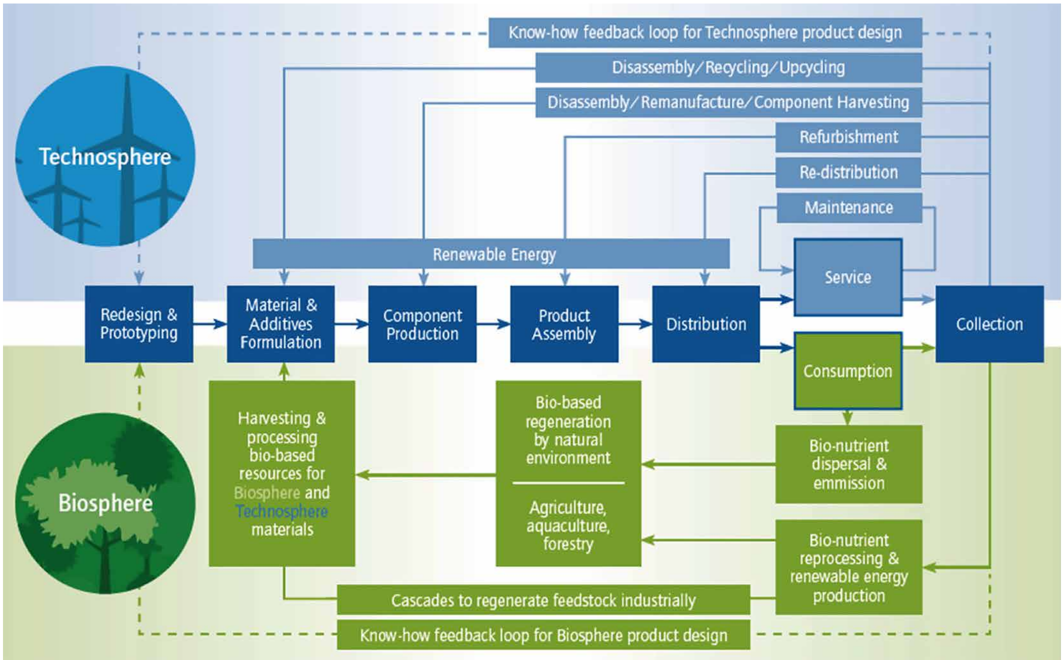

FIG. 3.1 Material flows in a circular economy [Source: Epea & Returnity Partners]

3.1.2 Flexible Buildings

In the last decades, the notion of urban planning has gradually been enriched with the realisation that bottom-up, evolutionary growth can lead to “the most lively and successful parts of our cities” [15, page 7]. The notion of self-organisation as a quality indicator in the formation of urban space is increasingly acknowledged within urban development theory [16,17,18]. Self-organisation can be understood as the opposite of top-down planning: where self-organisation is virtually limitless in its outcomes, top-down planning has inherent limiting effects on diversity [19,20]. These can be linked to both aesthetics and function of urban form.

Meeting the needs of their inhabitants is one of the main tasks to sustain vibrant, liveable cities. Housing quality is one of the main factors here [21]. In the Netherlands, as in many other countries, housing estates developed rapidly after WWII to meet the large demand for housing. The uniformity of such housing estates was met with criticism by, amongst others, John Habraken, as expressed in his book ‘The supports and the people – the end of mass housing’[22]. Habraken’s main point was that architecture failed to do justice to the heterogeneous nature of society, by internalising 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 Table 3.1. 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 [23]. To anticipate occupancy changes and avoid the building becoming 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 are not implemented on a large scale in the Netherlands.

TABLE 3.1 Distinction between Support and Infill [Source: Bob Geldermans]

Support	Infill
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	
Owner/Investor	User
Circularity relation	
Retained or increased value	Adapts to change
Long lifespan	Less waste
	Facilitates reuse cycles

3.1.3 Research questions

This chapter explores 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 and flexible buildings has significant advantages for investors (by adding long-term value to investments), as well as to users (by adding value through extensive customisation possibilities). It could radically alter the way buildings – and the neighbourhoods they occupy – evolve with regard to vacancy rates, deterioration, aesthetics, social cohesion and sustainability. Moreover, the circulation of building products and materials at user tailored moments is enabled by both adaptable capacity and autonomy over infill configurations. In order to assess this synergetic potential from a technical and design point of view, preconditions and guidelines need to be defined. This leads to the following research questions:

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

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

In this chapter, the focus is specifically on building components, products, and materials. Other themes, such as embodied impacts in product and processes, will not be covered. The terms *raw materials, materials*, *products*, and *components* are not synonymous, but represent a hierarchical order, usually increasing in size and complexity (see Terms, Definitions & Abbreviations). With circularity in mind, each level requires different choices. Homogeneity can, for example, be an important condition for a material in order to maintain quality in the next cycle, but may not necessarily be a preferred characteristic for a raw material and its re-application in a new product.

The definitions for Circular Building (CB) and Flexible Building (FB), as applied in this article, are as follows. CB (as a verb) is the dynamic total of processes, materials, and stakeholder-interactions that accommodate regenerative (renewable, circular) flows of building (raw) materials, products, and components at optimal rates and utility. FB (as a verb) is a (set of) building activity(ies) designed to allow easy rearrangements of infill components, whilst accommodating the potentially changing needs of users.

3.2 Methodology

The research presented in this chapter is structured around a series of four workshops, which I developed and coordinated within a timespan of three months. In the workshops, knowledge and experiences were shared, discussed, tested, and redefined with a focus group, in order to derive preconditions for circular building. The interdisciplinary core group, present at each workshop, comprised researchers, architects and consultants from Delft University of Technology (Chairs of Climate Design & Sustainability and Design & Construction Management), Doepel Strijkers Architects, Rotterdam University of Applied Sciences (Chair of Sustainable Architecture & Urban Re/Design), BRIQS Foundation (consultancy firm aimed at sustainable societal systems), and the Knowledge Platform for Sustainable Resource Management (a collaboration between knowledge institutes, the Dutch government, and the industry). This core group defined the content of the four sessions. For each session, experts were added to the core group. The focus-group /workshop structure is chosen as a tool to collect qualitative data in a relatively quick way. Multiple scholars have stated that focus groups provide helpful, flexible, and efficient environments for participants to discuss perceptions, ideas, opinions, and thoughts [24,25,26]. This method was esteemed an appropriate way for deriving basic preconditions from an exchange of diverse perspectives and perceptions from experts. Although the approach was inherently interdisciplinary, the common ground in this initial stage related to the field of Architecture and the Built Environment. All experts shared an interest in and experience of the concept of circular building.

The workshop sessions were moderated by me, and minutes were made by two assistants during each of the four sessions. These minutes were cross-referenced and shared within the core group before being finalised. Each session started with one or two presentations to lay out the specific topic and to feed the discussion. In total, 30 people were involved: 8 graduate students and 22 professionals, with backgrounds in product design, building design, architectural engineering, industrial ecology, real estate management, procurement, policy-making, urban mining, and business development. The organisations involved are listed in Figure 3.2. Figure 3.3 provides an image of one of the workshop sessions (workshop #2).

The lessons learned during the workshops resulted in a set of preconditions, as well as a matrix, integrating material and product cycles, and building design. Subsequently, the findings informed a stepwise design approach, based on an existing method, known as the New Stepped Strategy (NSS) [27]. This was taken as a starting-point because of its straightforward nature, and its track record with regard to sustainable building design and development concepts since its introduction in 2008. The NSS revolves around three steps:

1. Reduce resource demand (through passive, smart & bioclimatic design);
2. Reuse resources (valorising waste heat, waste water, and waste materials);
3. Apply renewable solutions with regard to the remaining resource demand.

Lastly, throughout the workshop trajectory, strong links were maintained with pilot projects, in which preconditions and guidelines could be tested. Most prominently relating to the Dutch Green Deal Circular Buildings, and to the Active ReUse House (Doepel Strijkers Architects, as part of the Concept House Village in Rotterdam [28,29]). However, interaction with, and implementation in, those projects is beyond this article's scope.

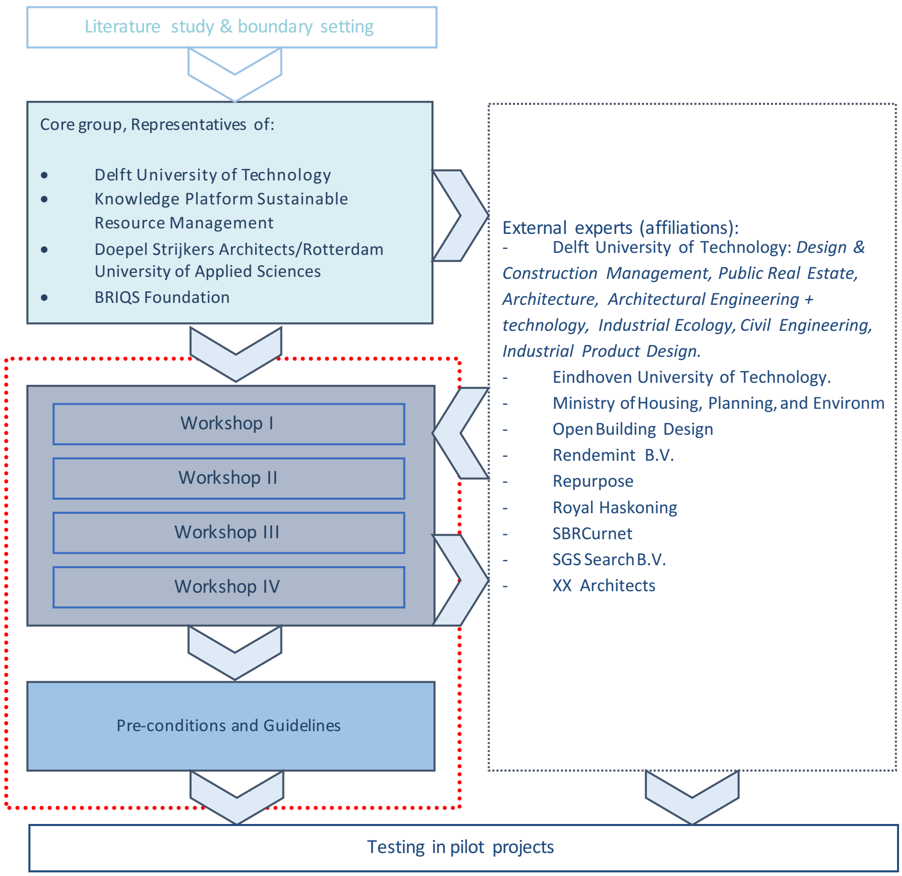

FIG. 3.2 Overall project structure, methods, and involved organisations and companies [Source: Bob Geldermans]

FIG. 3.3 Impression of workshop #2 on adaptability and flexibility in relation to circular building, starting from the FLEX 2.0 Framework of Rob Geraedts, Delft University of Technology [Image: T. Steigenga]

3.2.1 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 a grip on the concept of Circular Building. What is the role of resources, materials and products? 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 [30], 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. These latter aspects are – thus far – not integrated in Adaptable building and Open Building approaches.

III: Materials, Products & Standardisation. 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 the standardisation 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 included: business models, procurement policies, laws & regulations, and social added value.

3.3 Results

The research results are presented in the subsections below, addressing: 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* or *reutilisation flows*, and a stepwise design approach for circular building.[6]

[6] The terms ‘regeneration’ and ‘reutilisation’ have different meanings, but are applied here as two sides of the same coin, linked to the retention, recovery, or increase of value associated with the materials, products, and components.

3.3.1 Key findings from the workshop sessions

TABLE 3.2 Key findings from the workshop sessions [Source: Bob Geldermans]

1	**Session I: Circular building basics**
1a	Regenerative capacity implies no loss of quality or value.
1b	If we manage to substitute all resources, a circular economy comprises few incentives.
1c	Clear definitions are required of which components belong to which 'shearing layer', with specific attention for intersection-zones.
1d	Legal frameworks need to be adjusted to optimally facilitate circular building practices. For example, distinguish between legal & economic ownership, in relation to who has the decision power to make changes to/in the building (investor or user).
2	**Session II: Adaptability & Flexibility**
2a	*Dimensions* and *connections* are the two main 'Design for Adaptability' themes strongly related to circular building.
2b	Adaptability and flexibility are not the goal but means to an end, and instrumental in generating quality and adding value (or saving costs).
2c	FLEX 2.0 scores are arbitrary and as yet not useful for comparative analyses, not least due to the fact that potential interrelations between indicators have not yet been included into the framework.
2d	User awareness is key in order to appreciate and apply adaptable, extendable or demountable design solutions.
3	**Session III: Materials, Products & Standardisation**
3a	By standardising materials, you define conditions for recycling. By standardising products, you define conditions for connections.
3b	Standardisation is not always an effective option, e.g. in the case of digital production techniques can regulate demand for customised elements in a material-efficient way.
3c	If the connections between elements are standardised, the (dimensions of the) elements do not necessarily need to be.
3d	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 optimal.
4	**Session IV: Context & System Conditions**
4a	High-quality data (availability) on materials and related supply chains has advantages in every stage, for all stakeholders.
4b	The transition from a linear to a circular economy takes place in two directions: bottom-up and top-down.
4c	Laws & regulations need adjustment, regarding intrinsic material qualities (e.g. toxicity, purity, etc.), and tendering procedures (e.g. contract methods, procurement, etc.).
4d	Regeneration technologies and processes need to be improved and diversified in order to make significant, not only incremental, next steps.

Table 3.2 lists the key discussion points and findings that emerged from the workshop sessions. In the first session, the discussion gravitated towards two points of attention in particular, which underscored the necessity to differentiate between material, product, and building levels. The shearing layers (or pace layers) of change, as described in Section 1.3.1, was a recurring theme, as well as the Open Building concept, see Section 2.1.4. The second session zoomed into details of adaptability and flexibility in buildings. Based on the FLEX-Framework (developed by Rob Geraedts, Delft University of Technology), the participants classified FLEX-indicators according to the level of relevance for circular building. The third session helped to pinpoint specific points of interest for standardisation that could positively affect both flexibility and circularity. Here, the participants put an emphasis on the connections between parts, and the anticipation of specific service lives of building parts. In the fourth session, the main findings that came to the surface concerned an advanced stance to data sourcing, in accordance with the integrated value chains that accompany circular building propositions.

3.3.2 Intrinsic properties

Materials and products need to fulfill certain criteria in order to 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 the 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 intended use and reuse paths. Although simple, straightforward material use may help streamlining the (distributed) control, homogeneous recyclable products with a high purity and concentration are not necessarily better or worse than more complex products with multiple short maintenance or redistribution cycles. It all depends on the product's application, service-life, and operational processes. Furthermore, the administration required to register all these properties is a learning process rather than a one-off; interventions to the material or product all need to be registered.

3.3.3 Relational properties

Beside their intrinsic qualities, a material or product should relate to the design and use of buildings. These relational properties concern the 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).

Relational properties define the technical boundaries on-site for retaining the intrinsic value of the product or material in question. As above, all relevant interventions – e.g. changing partitioning walls or new piping for service installations – need to be registered.

3.3.4 Preconditions for Circular Building

From a circular design point of view, the value of a product manifests itself at the intersection of intrinsic and relational properties. This value, defined by multiple parameters, is not absolute. A few examples of different values include: 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 dismantled? Can it be easily restored?), Circular Economy value (to which extent can the product function within the designated Circular Economy iterations of Figure 3.1), market value, and cultural value. In separation, neither intrinsic nor relational properties have a decisive significance with regard to circularity; fulfilment is created on the overlap. 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*:

- Defined 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

3.3.5 Circular Building Matrix

This section focuses on the links between material and product cycles on the one hand, and building design on the other. Figure 3.4 visualises a basic inventory matrix linking building layers to biological or technical regeneration or reutilisation routes, proposed within the Circular Economy and Cradle-to-Cradle frameworks (see Sections 2.2.5 and 3.1.1). Six pathways are distinguished in Figure 3.4.[7]

- **Maintenance –** an upgrading intervention on-site, without relocation of the part in question;
- **Redistribution –** utilisation of the part ‘as is’ after relocation to another site, possibly including a period of storage;
- **Remanufacturing –** the rebuilding of a product to original specifications, potentially using a combination of reused, repaired and new parts;
- **Recycling –** breaking a product down to separate raw materials that can be used again in product iterations of a similar quality, that is, retaining value rather than destructing value (this thus excludes ‘downcycling’);
- **biocascades –** applying biological materials in one or more product(ion) iterations, representing gradually decreasing grades, until they are ultimately used up and can safely return to the biosphere in the form of nutrients;
- **bio-feedstock –** direct application of materials as biological feedstock for the production of materials that can be used in high-grade and renewable iterations. This can be referred to as a form of ‘upcycling’.

Two primary infill layers – service system and setting – are highlighted. The distinction in building layers follows the so-called shearing layers of change [31], in the adapted version of McDonough & Partners [14]. In brackets, on the left, the estimated associated material turnover velocity in one performance cycle are indicated. These turnover velocities signify, for example, that partitioning wall settings tend to change on average 3 times relative to the building structure, assuming a lifetime of 75 years. The layers can be further unravelled into sub-categories, up to the smallest units of change relevant for the applicable reutilisation route(s).

7 This is not meant as an exhaustive list. Other (sub-)steps are imaginable, and multiple sets and interpretations exist. For the scope of this dissertation, these pathways are deemed representative.

GROUP (+ turnover rate)	*LAYER*	PART	Bio-cascades	Bio-feedstock	Maintenance	Redistribution	Remanufacturing	Recycling
STUFF (8x)		COMPONENT PRODUCT MATERIAL						
SERVICE SYSTEM (4x)	*Piping & wiring*	COMPONENT						
	HVAC units	PRODUCT						
	Sanitary equipment ...	MATERIAL						
SPACE-PLAN or 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. 3.4 Example inventory matrix of building layers (vertical columns), material turnover rates (left in brackets), and reutilisation routes (horizontal rows), with two groups highlighted: Service system and Space-plan/Setting [Source: Bob Geldermans]

3.3.6 Stepwise approach of Circular Building

Preconditions for circularity can be integrated into the New Stepped Strategy, albeit with important adjustments. To begin with, a differentiation is required between planning and building design on the one hand, and materials and products on the other. 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 3.5). Furthermore, there are multiple routes imaginable, which makes the hierarchical order more complex. The stepwise approach for circular building projects is further explained below.

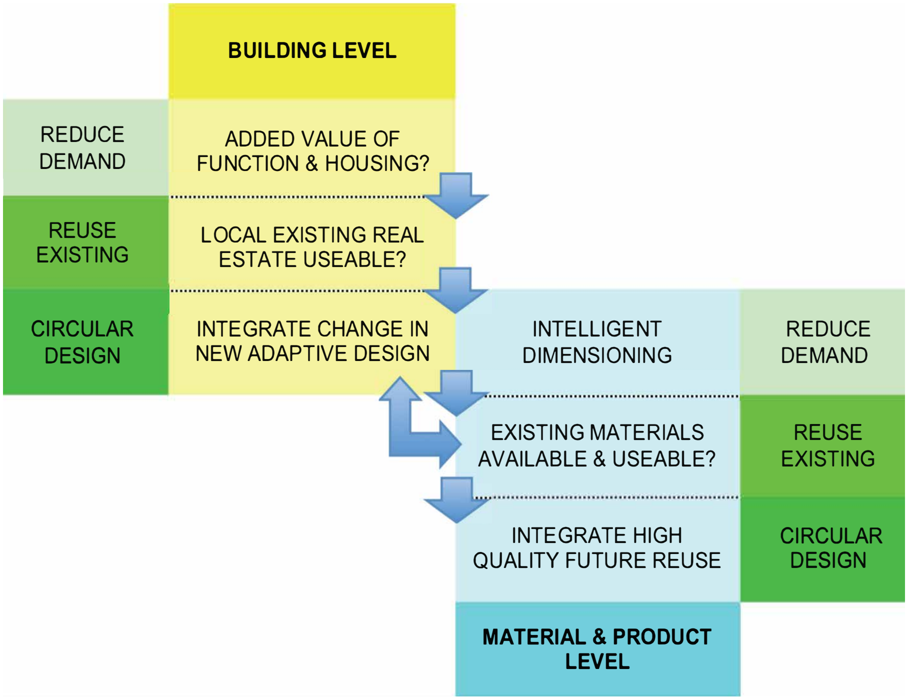

FIG. 3.5 Stepwise approach of Circular Building, on the building level and on the material & product level [Source: Bob Geldermans]

Step 1: Evaluate the added value of the intended functions and their materialisation 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 useability. 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. NB: 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 useability 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. NB: 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.

3.4 Discussion

The workshop sessions with the focus group led to a broad range of key findings, underscoring the fact that, when incorporating notions of change and circularity, organisational, cultural, behavioural, financial, and legal aspects may be as important as technology and design. The emphasis in the research trajectory, however, has been on technical and design aspects. As can be seen in the derived preconditions and stepwise approach. Nevertheless, several other topics, estimated to be particularly relevant in this respect, are briefly discussed below.

Date exchange

For a material to be reused effectively, the intended lifespan and use of a building needs to be anticipated. 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 and linear assemblages of components. This inherently opens up multiple areas of tension with regard to keeping the initial intentions intact and advancing over time, for example relating to the transfer and exchange of information between partners on the supply and demand side of the value-chain. This links to the question: how are data, processes and resources managed over time?

In a circular model, it is essential to assemble high-quality data on the applied materials and products, going beyond basic Environmental Product Declarations (EPD), for example concerning their composition up to the raw material level and their supply and reverse supply chains. The systematic quality-control of these data, including a registration method, is equally important in order to keep up to date with the developments regarding operational feedback. There are no readily available instruments on the market to facilitate this. Building Information Modeling (BIM) is often 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 common in the field. Moreover, the possibilities it offers for material ‘track & trace’ needs further exploration from the perspective of circularity, for example regarding the level of detail and transparency of product data.

Ownership

Bottom-up initiatives can mean a lot in the transition from linear to circular economic models. However, as put forward during the focus group sessions, a large shift has to come from top-down regulations. Legal changes are indispensable for facilitating and sustaining circular economic models, and regulations for procurement and contract methods need to be revised. Legal and economic demarcation is required regarding ownership of the support, on the one hand, and the infill, on the other. Demarcations have to be determined and communicated unambiguously, as 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.

Design freedom

A certain level of standardisation is inevitable in a circular building industry. It ensures that materials and products can be reused in multiple buildings or systems without significant adjustments. The standardisation of connections is key, 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 standardisation on a big scale. When the architect’s primary concern is the design of support structures, optimal infill-freedom may be facilitated. However, subsequently, infill components need to be implemented in anticipation of future change. The opportunities that come with standardised products and components will be accompanied by restrictions regarding appropriate and affordable products on the market. In that respect, it will take ample time and research and development efforts before a mature infill market is in place. Opinions differ concerning the question of whether or not this is a threat for the profession of the architect. With regard to the typologies where the separation of support and infill domains makes sense, such as multi-family buildings, the architect’s work might become more interesting, as those buildings are no longer based on the multiplication of floorplans [32]. Moreover, occupants may well commission architects to guide the infill design process.

3.5 Conclusion

This study underlines that the implementation of circular principles for product- and material use in buildings demands a 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. The relative 'circularity value' resides at the intersection of intrinsic and relational aspects. 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, product level, and material level are illustrated. Successful implementation, however, depends greatly on contextual factors, comprising critical changes in 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 whom.

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4 Circular & Flexible Infill Concepts

Integration of the Residential User Perspective

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4.1 Introduction

The Netherlands has tested the grounds for circular building practices for several years now, leading to state-of-the-art examples, such as the Town hall in Brummen (Architect: RAU, completed 2013), Patch22 in Amsterdam (Architect: Frantzen, completed 2014), the Venlo City Hall (Architect: Kraaijvanger, completed 2016), De Ceuvel (Architects: Space and Matter and DELVA, started 2012), and Circl (Architect: Architecten CIE, completed 2017). To a greater or lesser extent, all these examples adhere to principles of Circular Economy or Cradle to Cradle® (see Figures 2.9 and 3.1). An important aspect that these projects have in common is the distinction between structural and non-structural parts. This distinction facilitates circular flows of materials and products, whilst complying with the basic principles of flexible building. Flexible building accommodates changing spatial configurations in anticipation of changing occupant behaviour, adding different users, functions, and potential upgrades to the equation. As such, a clear connection can be detected between flexible building (FB) and circular building (CB). Additionally, structural and non-structural parts may represent different decision domains, for example: an investor regarding the structural base-building versus a user regarding the non-structural infill. Definitions for FB and CB adhered to in this chapter are:

- Flexible building is a building (noun) or building activity (verb) designed to allow easy rearrangement of infill components, whilst accommodating the potentially changing needs of occupants.
- Circular building (verb) is the dynamic total of associated processes, materials and stakeholders that accommodate circular flows of building materials and products at optimal rates and utility. A circular building (noun) is the manifestation of this in a temporary configuration.

Dutch CB initiatives have not yet ushered in a large-scale implementation of CB concepts in the Dutch construction practice. The call for bringing CB up to scale, however, is resonating on Dutch political agendas [1,2,3,4,5]. In order to comply with those ambitions, the CB focus needs to shift from singular pilot projects for frontrunners to larger scale, replicable implementation strategies for the majority. This is only possible through a close collaboration of key stakeholders. The Dutch building sector at large, however, insufficiently includes a primary stakeholder: the end-user of buildings [6,7]. When aiming at measurable added value, more comprehensive user-centric approaches are required. I advocate that the identification, application, and evaluation of criteria to measure user-benefits of CB are essential next steps in this development. Among major target groups are the inhabitants of multi-family residential buildings: a main typology in the denser urban areas of the Netherlands, only expected to increase in importance due to the growing need for housing in the coming decades [8,9].

Although social aspects, such as health, well-being, and social inclusiveness are generally part of circular building principles, specific benefits for end-users are less so. This chapter explores the synergetic potential of flexible and circular design principles from the perspective of user benefits, in terms of enhanced control and convenience for residents. The hypothesis behind this study is that without integrating the user domain, the replicability of circular building concepts on the larger residential scale cannot be done in a truly sustainable manner. The chapter is structured around two objectives: (1) further identifying the relationship between flexible and circular building; and (2) exploring the impact of circular, flexible building concepts and practices for the users of multi-family housing regarding interior partitioning. In this chapter, I combine multiple methods to gain more insight into the current gaps in research and design, and to provide a tool for deploying a more user-inclusive approach to the circular building development, see Section 4.2.

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4.2 Methods

The research comprises literature study, expert consultations and a quick-scan assessment. The methodology adheres to design research approaches as addressed, amongst others, by Mahmoodi (2001), Blessing and Chakrabarti (2009), and Attia (2018), focusing on the complexity of design, be it in general sense or specifically in relation to architecture and/or sustainability [10,11,12]. The aforementioned complexity is inherent to the dynamic and non-linear relationship between research, on the one hand, and design, on the other. Design not only requires knowledge of the stakeholder goals and the product, but also about the product's life cycle, i.e. how it is to be produced, transported, installed, used, maintained, and repurposed [10]. Improving design processes is thus not a matter of straightforward research activities. To implement improvements effectively, it is deemed vital to apply knowledge from various sources. This is not least applicable to the new field of circular and user-inclusive building. I explore precedent research in multiple domains and combine it with lessons from four cases and input from experts, not as a comprehensive overview, but as a means to integrate perspectives.

In Section 4.3, a literature study is reported regarding housing quality, as perceived by the user, as well as specifications of and connections between flexible and circular building. Key search terms applied are: ‘Housing Quality’, ‘Open Building’, ‘Adaptable Building’, ‘Flexible Building’, ‘Circular Built Environments’, and ‘Building Performance Evaluation’, particularly in the context of Dutch multi-family housing. These terms were applied separately and in combinations.

The research gap regarding circular and flexible building performance in relation to the buildings' occupants necessitates additional study (Section 4.4). Four cases are selected to explore change and flexibility of the interior floor plan from a user perspective: Molenvliet, The Netherlands; Kodan Experimental-housing Project and the Century Housing System, Japan; and Bostadsrättsförening, Sweden. Furthermore, I consulted experts in order to further investigate linkages between circularity, flexibility, and user benefits. The experts were associated with the National Renovation Platform (NRP); the Amsterdam Institute for Advanced Metropolitan Solutions (AMS), more particularly relating the projects Smart Urban Retrofitting (SUR) and Circular Components in the Built Environment (CCBE); and Open Building Design (OBD), all based in The Netherlands. First, the experts' input is sourced during face-to-face meetings of 45–60 min on average. Next, aspects that required additional attention were discussed during separate follow-up sessions between me and the experts, either face-to-face, via email or via telephone. These expert consultations were intentionally semi-structured in order to allow for new, unforeseen aspects to come into view. The combination of those experts safeguarded a level of intersubjectivity.

Based on the literature and expert consultations, I selected a basic set of criteria (Section 4.5) for conducting a comparative quick scan of two indoor partitioning variants: a traditional one and its circular and flexible (*Circ-Flex*) counterpart. In this quick scan, circularity, flexibility, and user perspectives are integrated. Finally, in Section 4.6, the results and methodology are discussed from various vantage points, in particular the institutional context, legal framework, culture, and demography.

The diagram of Figure 4.1 displays the research structure and methods.

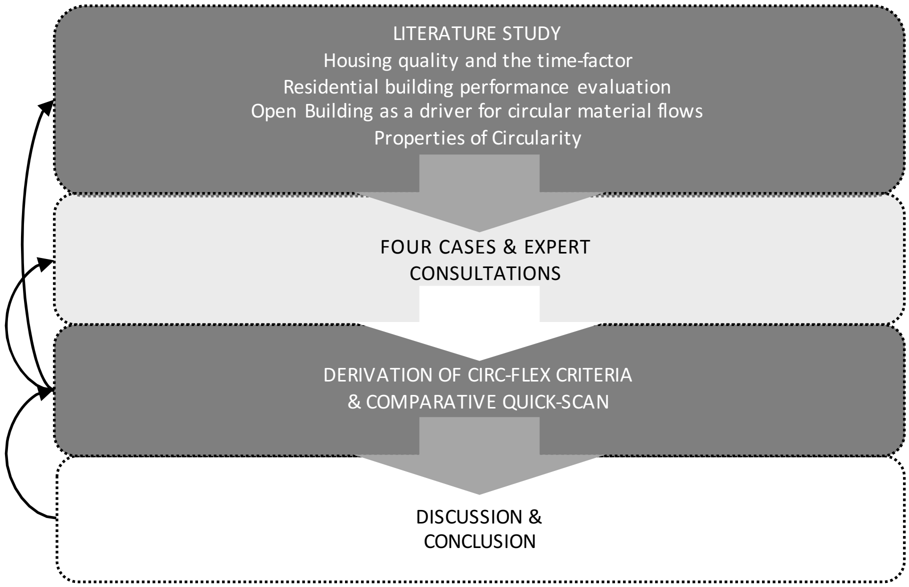

FIG. 4.1 Research structure and methods Chapter 4: Circular & Flexible Infill Concepts [Source: Bob Geldermans]

Delineation

The Dutch context is of primary concern in this research, whilst exploring examples and lessons learned in other countries as well. Furthermore, the focus is on multi-family housing, being a primary typology in densely populated areas such as the

Randstad, see Figure 4.2. Social housing plays an important role in this respect. In the Netherlands, social housing corporations own 30% of the housing stock (of which the majority is multi-family). In the Randstad, this number is higher, peaking at 40–45% in Amsterdam and Rotterdam [13].

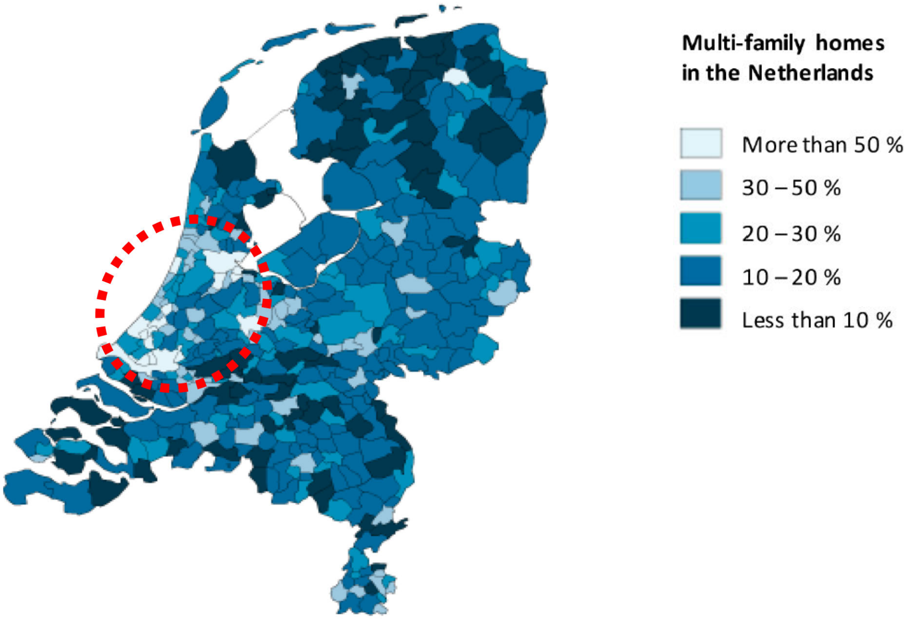

FIG. 4.2 Share of multi-family homes in the Netherlands with Randstad encircled in red [Source: CBS]

4.3 Literature Study

This chapter is allocated to a concise literature study. The starting-point (addressed in Section 4.3.1) is the notion of housing quality over time, whilst anticipating as yet unknown users and use patterns. Subsequently, the focus is on Building performance evaluation (Section 4.3.2); Open Building as a driver for circular material flows (Section 4.3.3); and properties of circularity (Section 4.3.3).

4.3.1 Housing Quality and the Time-Factor

When articulating the importance of buildings in general, and our homes in particular, one could take multiple approaches. From a predominantly objective and technical viewpoint: homes provide us with shelter and protect us from the external environment, and as a result we spend the majority of our time in them [14]. Related, but more subjective and complex, would be a description of the extent to which we feel 'at ease' in our home. This touches upon the experience of safety, comfort, and joy, for example. A more philosophical pondering could lead to the description of De Botton (2006) that "we depend on our surroundings obliquely to embody the moods and ideas we respect and then to remind us of them" [15, page 107].

The importance of individual identities, within the potentially overwhelming collectiveness of a city, becomes most tangible inside of people's homes. This is where diversity thrives. However, developers, authorities, designers and builders have experienced difficulties in internalising that notion of diversity [16,17,18]. John Habraken based many of his publications on this 'system failure' of blending collective (the base-building or support) and individual domains (the fit-out or infill), specifically regarding the realisation of mass housing [17,19,20,21]. He observes that: "zoning laws, building codes, enforceable design guidelines, or covenants […] increasingly replace direct negotiation in the creation of contemporary built environment. Nonetheless, controls, boundaries, and guidelines issued by governing authorities from the top down are a poor substitute for actual conversation between peers" [20, page 9]. Van der Werf points at the lack of acceptance of the distinction between the collective and the individual by fellow architects and developers in the Netherlands, especially when it concerns façade elements [22]. This statement was made in 1993, but is to a major extent still valid: even if the 'Open Building' discourse has evolved among peers in the architectural realm, key parties (developers, corporations, authorities, designers, engineers) in the Netherlands still find it hard to adjust their way of working, not least with regard to risks associated with personalised use and physical changes in the real estate [e.g. 22–25]. Regardless of the nature of those risks, it implies a deeply ingrained inability to internalise 'dynamic user-behaviour' in the design, development and management of real estate. Observing the trends and history of building practice in the Netherlands, and following the associated literature [18,21,27–39], at least three conclusions can be drawn regarding the extent to which multi-family housing in the Dutch context accommodates change over time:

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1. Requirements of housing quality differ per person or target group as well as per time-period; the existing stock will always ask for adaptations.
2. Housing inflexibility is still the norm; the large majority of multi-family housing is designed with no or one single (type of) occupant/occupancy in mind.
3. Paradigm shifts, rooted in a desire for more flexibility, have been hinted at more than once in the last decades.

Straub and Vijverberg [2004], for example, define housing quality as: “the physical characteristics of a dwelling, which are relevant to the use of that dwelling, including the plan features and facilities provided” [33, page 2–3], whilst observing that the existing (social) housing stock does not sufficiently fulfill the changed and changing demand for more space, different space-plans, more quality, and freedom of choice in qualities [ibid.]. Boelhouwer et al. [2014] state that, on an individual level, there is hardly any freedom of choice for tenants of social housing, apart from a restricted right to “zelf aangebrachte voorzieningen’ (self-added facilities), without any guarantee on the value of those interventions at the end of the contract for owner or renter [36]. They conclude that freedom of choice is not going ‘beyond exit’, provided the housing market allows this [ibid]. Tummers [2016] highlights specific changing social conditions that are as unforeseen as they are decisive for new ways of living, hence new design perspectives, by focusing particularly on self-organisation and co-housing in relation to the energy transition [39]. Even though the focus here is on a specific lifestyle and target group, it is indicative for the increasing resilience that is asked of the housing sector, disrupting outdated traditions in favour of new, more sustainable models.

4.3.2 Residential Building Performance Evaluation

If end-users of buildings are insufficiently engaged with the physical and functional development of their direct living environment, these environments are prone to lose contact with their occupants to some degree, and subsequently fail to resonate their identities or a sense of community coherence. Here, I refer back to aforementioned insights of De Botton, Sanoff and Habraken [15,17,18], but this also connects with more practical perspectives and studies from researchers and housing associations aim at understanding and serving basic housing behaviour and the fulfillment of people. For example, with regard to the Dutch housing market, Dogge and Smeets (2004) mentioned the complex relationship between tenants’ satisfaction and commitment [40].

Furthermore, Post-Occupancy Evaluation (POE) has gained ample recognition as an important tool in both academic and applied settings [41,42], addressing the often-occurring gap between the designed and actual performance of buildings [43,43,45]. However, Hay et al. state: "there is little evidence that this body of research has transferred to the practice environment to close learning loops and ensure future projects are informed by a joined-up evidence base rather than the isolated experience of individual professionals" [42, page 2]. Göçer et al. come to a similar conclusion stating that, although POE can help drive the building design and procurement process forward, "the findings do not seem to match the rhetoric; in other words, POE is not used effectively in practice." [46, page 15].

Related to the fact that POE has not yet been effectively integrated in the design and construction practice, it is also still rather limited in its scope, with a large accent on quantitative energy performance and "narrow" surveys of satisfaction [42]. More fundamental questions about the sustainability of the built environment, dealing with e.g. robustness to secure future use and user behaviour, are rarely addressed. Lessons could be learned from studies into consumer behaviour, for example: concerning mental and behavioural response that precedes or follows user activities [47].

4.3.3 Open Building as a Driver for Circular Material Flows

An important commonality among the circular building examples mentioned in the introduction is the distinction between support and infill. This Open Building (OB) approach accommodates changing spatial configurations, in anticipation of dynamic, ever-changing user-behaviour [14,48,49]. The time factor is thus included more prominently. By consequence, the chance increases that different, unpredictable functions and users are becoming part of the equation. At this point, there is a clear liaison between flexible building principles and circular building principles.

The distinction between support and infill is inextricably linked to the notion of diverging and changing interests at stake: between investors and users on the one hand, and between current and future stakeholders (new investors, new users) on the other. Although base-buildings could, and sometimes should, be adaptable as well, the use(r)-flexibility predominantly manifests itself on the infill side, following social dynamics, as explained earlier. This leads to multiple infill material and product cycles during the existence of a building, which accommodates a more effective, bespoke, and up-to-date indoor materialisation, opening up to new supply and service models that serve a circular economy. Such new models match with the ongoing "democratisation" of building services, most prominently tangible in energy supply systems [50].

4.3.4 Properties of Circularity

This study focuses on decision-making power regarding the individual interior domain. The social benefit of this decision power is accompanied by a potential material benefit, provided that key preconditions, concerning overlapping intrinsic and relational properties, are respected, as addressed in Sections 3.3.2 and 3.3.3. [38]. Figure 4.3 visualises this, whilst positioning Circularity Potential at the overlap of material and product characteristics (intrinsic) and building design and use characteristics (relational).

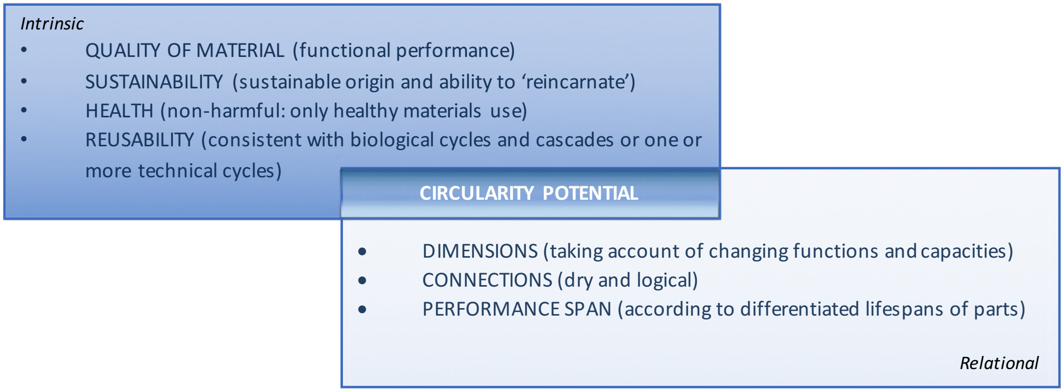

FIG. 4.3 Relational and intrinsic properties of materials and products in circular building configurations [Source: Geldermans et al. 2015].

If non-structural components can be modified to optimally match with the new requirements, it becomes easier to anticipate renewability routes for the redundant products and materials at the highest value and utility. Renewability refers to the use of resources that can be replenished, at least at similar quality levels, and within appropriate time-scales [51,52,53]. The aim for circular resource systems, as articulated in Dutch and European policy documents could thus provide leverage for scaling-up user centred *Circ-Flex* interventions [54,55]. Figure 4.4 revisits the matrix of Figure 3.4, displaying differentiated reutilisation routes for components, products and materials associated with partitioning walls in a circular configuration.

LAYER	*category*	PART	Bio-cascades	Bio-feedstock	Maintenance	Redistribution	Remanufacturing	Recycling
SPACE-PLAN	*Partitioning walls*	COMPONENT						
		PRODUCT						
		MATERIAL						

FIG. 4.4 Differentiated reutilisation routes for components, products and materials in a circular economy (CE) model, relating to partitioning walls in the space-plan [Source: Bob Geldermans]

4.4 Lessons from Four Cases and Expert Consultations

In order to include user benefits into the equation, more grip is required on what those benefits are. As stated in Section 4.3, thus far little research has been conducted to evaluate the performance of residential interior lay-outs as perceived by inhabitants. Several projects and associated studies, however, have provided valuable insights. Four projects in particular are interesting in this respect, because of: (1) their strong focus on flexibility as a value aspect for the user; and (2) their performance-monitoring schemes. To further elaborate on the user benefits, and on the links with flexibility and circularity, I have conducted expert consultations with: the chairman of the National Renovation Platform (NRP); the project managers of the Smart Urban Retrofitting (SUR) and Circular Components in the Built Environment (CCBE) projects, both affiliated with the Amsterdam Institute for Advanced Metropolitan Solutions; and the founder of Open Building Design (OBD). Below, the four cases and the expert consultations are laid out.

4.4.1 Lessons from Four Cases

Molenvliet, Papendrecht, The Netherlands

In the 1970s, architect Frans van der Werf introduced a new typology of high-density housing in a low-rise fabric. The typology consisted of an infillable base-building structure of parallel piers, floors, and roofs around courtyards, combining so-called longitudinal and transversal support structures, and allowing free dwelling fit-outs for each user [23]. The Ministry of Housing nominated this typology 'Experimental', in order to understand how the regulatory framework limits the evolution of housing in the Netherlands. The housing association Papendrecht ordered this 'Experimental' design for 80 dwellings for rent. Van der Werf scheduled two private infill consultations of one hour with each of the users, following the routing of the building blocks on site. During the first meeting, spaces and functions were discussed, related to the ages, hobbies and preferences of each family member. After two weeks, a second meeting was held on confirmation or small changes and on details in kitchen and bathrooms [56]. In 2014, Shanshan Li performed a study on the interior lay-out changes in the Molenvliet project over time, interviewing fifteen households who had lived there between 1–38 years [57]. Eight out of fifteen had carried out renovations, six of which concerned modifications in the partitioning configuration.

Key lessons:

1. The unique life experience of each of the users had to be valued, necessitating an unprejudiced design flow, without the personal preferences of the architect,
2. The hobbies of the users were as important as basic activities.
3. From the renovations that were carried out by eight of fifteen households, six concerned modifications in the partitioning configuration.

The Kodan Experimental-housing Project (KEP) and Century Housing System (CHS), Tokyo, Japan

In the 1970s, the number of dwellings in Japan began to exceed the number of households, changing the aim of research and development from supplying a large number of homes to improving their quality and meeting diverse residential needs [58]. The Tsurumaki-3 housing estate of Tama New Town, Tokyo, was the first undertaking of the Kodan Experimental-housing Project (KEP, Japanese Housing Corporation). KEP started in 1973 to research and develop flexibility and adaptability for housing. Following this first initiative, the Ministry of Construction started the Century Housing System (CHS) as a government-led research initiative formed primarily by academic members in the early 1980s. According to Schmidt et al. (2010), the objective was to "extend the longevity of housing by developing

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a systems approach to the housing sector that focused on the changeability of components throughout the building life, reducing premature functional obsolescence by increasing the building's adaptability" [59, page 1]. This objective led to a system that distinguished five building component layers according to lifespan and economic rationality [59]:

- light bulbs, packing: lifespan 3-6 years
- hot water heater, home appliances, piping, wiring: lifespan 6-12 years;
- partitions, built-in furniture: lifespan 12-25 years;
- exterior doors and windows, roof: lifespan 25-50 years;
- foundation, columns and beams: lifespan 50-100 years.

Wakiyama et al. [2000] studied how residents and managers recognised the CHS system and how it worked for them [60]. The study was conducted sixteen years after the initial occupancy. Minami (2010, 2016) investigated for both KEP- and CHS-related housing projects how residents adopted design concepts according to their individual needs, as well as the way in which they "adapted their living environments to changes in their lifestyles over time by remodelling rooms and changing the position of partitions" [61, page 2].

Key lessons:

1. In Japan, a main driver for moving to open, flexible buildings derived from an expected labour shortage in the construction sector, making it more important to design and construct buildings which require less skilled labour, for example, by residents and users themselves.
2. Respectively 51% (unit design Type A) and 59% (unit design Type B) of the surveyed residents with a KEP movable partitioning system changed the layout at least once (in 15–30 years), due to changes in lifestyle or family composition. Whereas this was 8% of the surveyed residents of a unit design Type C (non-movable partitioning).
3. Out of a set of twenty characteristics that could influence a resident's decision to inhabit a particular housing unit of the CHS project, "easy to change layout" was chosen by 23% of the surveyed residents.
4. The CHS system was perceived as too complex, which made residents shy away from exploring the potential in many cases. This led to a simplification that has been recognised by almost all in the Japanese industry, namely a simple division in a base-building domain and an infill domain.

Bostadsrättsförening (BRF), Stockholm and Göteborg, Sweden

Between 2001–2008, Bostadsrättsförening (BRF) Tenant-Owner association, built several multi-residential housing estates in Stockholm (BRF 1) and Göteborg (BRF 2–5), Sweden. All co-owned properties are situated at waterfront locations, where most of the local housing production was carried out during that period. An extensive report by Femenias et al. [2016] focused on these housing projects, in order to study internal renovations and home-makeover over time. The study aimed to provide insights into what residents appreciate (or not) in their apartments, what changes they made, and the motivations behind them [62]. In 2015, a questionnaire was sent to all 462 households that reside in the five estates, with a response rate of 68% (n=315). The questionnaire revealed that not only did the owners engage in renovation and redecoration of the apartments, which was presumed when initiating the study, they also rebuilt and reconstructed the apartments, which was not anticipated. The questionnaire gave insights into the amount and nature of renovations that the present owner-occupier had carried out in their apartment as well as of alterations they knew that former owners had done [62,63,64].

Key lessons:

1. Residents are dissatisfied with, among others, a lack of storage facilities and work space, a lack of soundproofing between different rooms, the layout of the kitchen and bathroom, poor quality of materials, unused surface, and narrow, dark hallways
2. Many renovations were (also) due to the fact that “the apartment has material and performance of low technical and aesthetic quality, and is therefore replaced earlier than normal maintenance” [62, page 42].
3. Overall, over 30% of the respondents in this study made changes to the floor plan layout.
4. The findings did not indicate that the desire to achieve a higher sales value was a direct motive for action. Instead, “increased value appears as a supporting argument to increase the standard or personalise” [62, page 26].

4.4.2 Expert Consultations

National Renovation Platform

The National Renovation Platform (NRP), is an independent foundation striving for sustainable use of the building stock through renovation and transformation strategies. The notions of co-design, adaptable buildings and flexibility strongly resonate in these strategies. Ongoing projects on circular transformation of real estate in Amsterdam defined the expert-input, alongside the long track record and practical experience of the chairman of NRP, F. Bijdendijk. In his position as the director of a housing corporation, Bijdendijk pursued the integration of Open Building principles, amongst others leading to the 'Solids' (open building shells without fixed zoning plans) in Amsterdam, see also Section 7.1.5.

Key lessons:

- The reasons behind alterations in the lay-out of dwellings may range from longer-lasting arguments, such as increase or decrease in family size, to quicker passing ones, such as lifestyle changes. But there are many more arguments imaginable that could drive modification of the space-plan. Key is the user's control to modify the interior layout by changing partitioning configurations, in any way he or she wants. This social aspect of the Open Building concept has always been at the heart of the National Renovation Platform (NRP). NRP keeps a close eye on social and demographic phenomena and how that relates to the quality and quantity of existing real estate. NRP underscores the importance of new collaborations between stakeholders when collective and individual domains are separated. Moreover, this separation also requires new ways of financing, linked to the material and technical divisions. New ownership configurations will emerge, in which the user has full control over the infill. This represents a value, provided that the next user of the space has the same level of control [67]. This does not mean that the user should necessarily own the infill components: ownership can also be outsourced to suppliers or other external parties. The aforementioned considerations are closely connected to the extent to which the circularity of products and materials can be established and managed.

Amsterdam Institute for Advanced Metropolitan Solutions

The Amsterdam Institute for Advanced Metropolitan Solutions (AMS), is a knowledge institute founded by Delft University of Technology (TUD), Massachusetts Institute of Technology (MIT) and Wageningen University and Research (WUR), with the aim to implement and test innovations in real urban settings. Two AMS projects in particular were relevant in the context of this chapter: Smart Urban Retrofitting (SUR, project lead: WUR, Department of Social Sciences) and Circular Components in the Built Environment (CCBE, project lead: TUD, department of Management in the Built Environment). The former refers to the restructuring of existing housing stock in Amsterdam, involving informational flows, and actor relations. The latter concerns the development of a circular kitchen model, in co-creation between housing corporations, suppliers and knowledge institutes. The consultations took place with the project managers of aforementioned projects.

Key lessons:

- The Smart Urban Retrofitting project (AMS/WUR) underscored the fact that changing circumstances are rarely accommodated in housing design and development, specifically with regard to the interaction and mutual understanding between key stakeholders in the Amsterdam housing sector: housing corporations and social housing residents. A wide communication gap made it hard for housing corporations to implement upgrades to the housing stock. Although this project concerned energetic behaviour and interventions, rather than layout alterations, the lack of appropriate communication is indicative of the sector's culture, forming a barrier for residents-engagement. Communication was predominantly 'one-way', that is: the housing corporation sending information to the tenant, rather than 'two-way', for example through conducting appropriate surveys. Moreover, differences in understanding and interpreting the provided information increased the gap between housing corporation and residents. It was found that bottom-up strategies, such as co-creation and community participation, are crucial institutional aspects of urban retrofitting, even if they could potentially slow-down the decision-making process [24].
- The Circular Components in the Built Environment project (AMS/TUD) focused primarily on the shorter cycles of component-renewability: maintenance, reuse/redistribution, and remanufacturing, in order to keep components fit-for-purpose for as long as possible [25]. However, longer cycles, i.e. recycling trajectories, are anticipated through the choice of materials and Design for Disassembly. The project looked at circular service installations (boilers) and kitchens. In particular the circular kitchen was elaborated with key stakeholders, who together explored the feasibility to market, whilst developing technical, industrial, and business models. Although the end-user was not directly involved in the project, apart from minor testing with a tenant focus group, the lessons learned did reflect their needs. Most prominently relating the fact that the concept would increase the tenants' freedom of choice, including associated flexibility throughout the use period, since parts of the modular kitchen would come in a range of options. Moreover, the emphasis on market-uptake, rather than on user reflections, was based on the fact that the logistics of product and material circulation should remain the responsibility of the market. The rationale is that this model leads to increased control over the material flows, whilst liberating the resident from any potential burden. This way, more engagement from the user is facilitated, but without stringent obligations.

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Open Building Design

Open Building Design (OBD), initiated by architect Frans van der Werf, is based on the vision that in housing, residents should decide the lay-out of their own dwelling. Van der Werf has applied Open Building principles in his own work as of the 1970s, some of which gained renewed attention in recent years (such as Molenvliet, see 4.4.1), also in relation to circular building ambitions.

Key lessons:

- Van der Werf of OBD endorses the statement that among the most important changes to the interior lay-out are addition and/or removal of indoor partitioning walls. In accordance with Christopher Alexander's *Pattern Language* [1977], this importance can be understood via three perspectives: effective use, social experience, and sense-making [65,66]. First, partitioning divides spaces according to functional differentiation. Second, partitioning provides a base for distinct interior design. And thirdly, partitioning supports dynamic processes of change in the activity of living [66]. Virtually countless reconfiguration schemes in the interior lay-out are possible, without compromising fixed elements, such as mechanical, electrical, plumbing utilities and infrastructure. Van der Werf designed housing structures with flexible lay-out capacity in multiple projects, such as the Pelgromhof project in Zevenaar for example (1999–2001), see Figure 4.5. Figure 4.5 shows (on the left) the open plan, with only a fixed shaft for technical services, and (on the right) user consultation in a real-size model, where infill components could be positioned on a modular 30 cm grid. Van der Werf indicates that the interaction with the residents, as of the initial stage, is labour-intensive but rewarding. It does justice to the fact that all households are different, and personalisation needs to be respected in the design and materialisation of individual housing units.

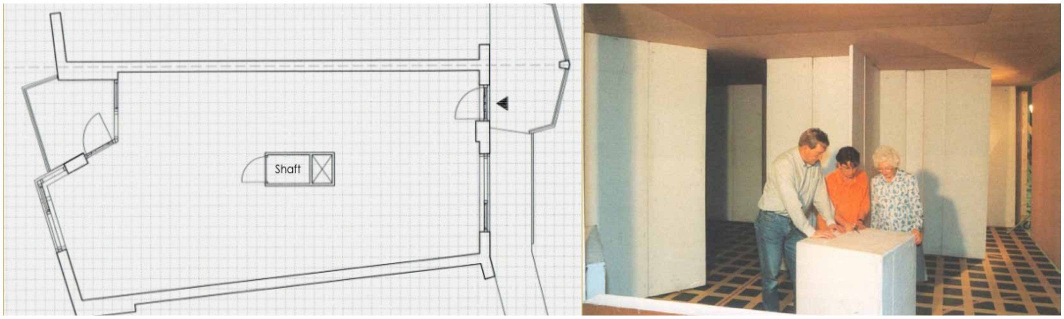

FIG. 4.5 (left) Open plan design and (right) user consultation concerning Pelgromhof project, Zevenaar, the Netherlands, Frans van der Werf 1999–2001 [Source: Frans van der Werf]

INFILL PRACTICE WORKSHOP

On 30 April 2018, I coordinated a workshop 'Infill Practice' at the Faculty of Architecture & The Built Environment, Delft University of Technology. The goal of the workshop was for Architecture and Building Technology students to get acquainted with the infill domain of a given empty dwelling, whilst understanding diversity within wholeness. Workshop leader was architect Frans van der Werf, who presented many different examples of infill in his introduction. He highlighted possible processes with future inhabitants, as well as the organisation of private consultations. Next, Frans explained several practical tools, such as furniture cards (to be used in paper floor-plans) and the true scale model, based on a 30 cm modular grid. Furthermore, the role and attitude of the consultant and questions of ownership were addressed. The participants learned about different types of households, types of dwellings, parcelling of a support structure, and the organisation of infill procedure. Most importantly, the participants learned to let the occupant lead the infill-design process. The 16 participants formed duos of designer/client in two sessions: one concerning a small empty dwelling and one concerning a larger one. The designer fulfilled a consulting role, letting the client talk about his/her (spatial) requirements, lifestyle, hobbies, etc. Each round of consults was followed by a plenary reflection. In the end, 16 completely different floor-plans emerged, and the participants gained a better understanding of the subjectivity and diversity of residential infill plans. Figure 4.6 displays various examples of the resulting floor-plans for both small and larger types of dwelling.

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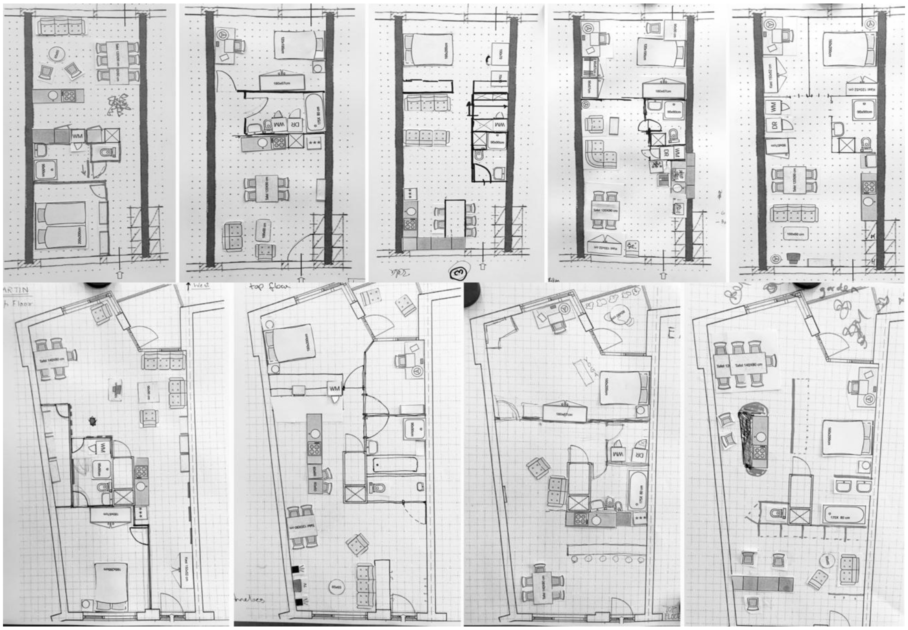

FIG. 4.6 Results from the workshop. Above, five floor-plans of dwelling type 1 (50 m^2). Below, four floor-plans of the dwelling type 2 (70 m^2) [Source: Bob Geldermans and Frans van der Werf]

4.5 Derivation of Circ-Flex Criteria

Based on literature study and expert consultations in this research, and in correspondence with the findings from Chapter 3, I derived three interrelated categories with sub-criteria. This leads to a list of eleven basic *Circ-Flex* criteria. Categories and criteria are formulated below and in Table 4.1.

1 Flexibility: the extent to which a partition wall, or a part of it, can easily and safely be disassembled, reassembled, repurposed, or disposed of. Specific attention goes to dimensions and especially connections, i.e., how elements are fixed
2 Circularity: the extent to which walls and wall elements can easily, safely and purely follow high-grade renewability cycles, such as maintenance, redistribution, remanufacturing and recycling, and bio-cascades for biological materials. The main focus is on technical and design anticipation of such cycles, i.e. the capacities of stakeholders in the supply chain are left out of the equation

3 User benefits: concerning the mental and behavioural engagement and response that precedes or follows activities by the user. This user response always has an element of subjectivity, implying that aspects may come to the forefront that overrule solutions chosen by designers and engineers. Multiple drivers can be decisive forces in this respect, leading to purchasing behaviour that is either in favour of or at the expense of *Circ-Flex*. For this exercise, two criteria were highlighted in the expert consultations: a) willingness to engage or invest (in time and money), and b) freedom of choice, concerning a range of options for materialisation, either DIY or outsourced.

Comparative Quick Scan of Two Variants

My area of interest is the difference between the performance of a typical partitioning wall and its *Circ-Flex* counterpart. Of primary concern is the capacity to accommodate change as a quality aspect for the user. This assessment is meant as a first step towards a user-centred method for assessing circular building benefits. I compare two non-bearing partitioning schemes following the criteria listed in Table 4.1. Additionally, this quick-scan evaluation integrates practical literature on home remodelling and material flows, more specifically: Guy and McLendon (2003), Guy and Ciarimboli (2008), Wallender (2018), Gibson (2018), Ghyoot et al. (2017), and Rotor Deconstruction (2018) [68–73].

TABLE 4.1 Circ-Flex criteria at the crossroads of flexibility, circularity, and user capacity [Source: Bob Geldermans].

Circ-Flex Criteria	
Unlocking Flexibility Capacity	Ease of Disassembly
	Ease of Re-assembly
	Ease of Repurposing or Disposing
Unlocking User Capacity	User willingness to invest in time and money
	User perceived freedom of choice
Unlocking Circularity Capacity	Ease of Maintenance
	Ease of Redistribution
	Ease of Remanufacturing
	Ease of Recycling
	Ease of facilitating Bio-cascades
	Ease of facilitating Bio-feedstock

For a fair analysis, schemes of a similar typology are selected, rooted in the residential renovation tradition of the Netherlands. Only the innovative wall scheme introduces clear notions of flexibility and circularity. For the sake of simplicity, I assume that the innovative scheme fits seamlessly and completely into circular models, even if such products may not yet be available on the market. Key here is to compare two wall configurations that at first sight do not differ significantly in aesthetics, functional purpose, and technical specifications for residential settings. The quick-scan thus follows the basic requirements for a semi-finished partitioning wall.

- Variant 1, the reference, is a common timber-frame wall with plasterboard panels and mineral wool insulation. Wires, pipes and insulation can sit within the cavity between the drywall sheets, which cover both sides of the frame. In a finalisation step, the wall is plastered. Although, technically, such a wall is relatively easy to dismantle, future reuse is usually not anticipated. Nor is it designed, built, and used in a way that tolerates easy replacement without damaging other parts of the housing unit, such as piping, wiring, ceiling, floor, or other walls. This variant is comprised of: a timber frame (European pinewood), fixed with metal connections and screws onto floor and ceiling; glass wool insulation; plasterboard drywall; wooden skirting boards. Pre-treatment and finishing usually done with traditional products.
- Variant 2 is a partitioning wall built out of products that are fully designed for circular material and product flow purposes, anticipating existing, proven constructing techniques (not much different from variant 1). It comprises existing elements, as listed in so-called Material Passports, such as developed within the Buildings as Material Banks project (BAMB) for example, and/or C2C®certified products registry [74,75]. This way the wall comes as close to a circular wall scheme as possible, knowing that not only flexibility is anticipated, but also the circularity potential, relating material health and data embeddedness, which in turn accommodates supply and demand cycles at the most optimal rate and utility. The wall scheme comprises a timber frame (European pinewood), fixed with metal connections and screws in framework, using a mounting profile against ceiling and floor; organic fibre insulation; organic board for panelling and plinths. Pre-treatment and finishing done with pure loam- or lime-based products, for example.

In square metres, there is no difference between the two variants. Furthermore, other specifications are left out of the equation, such as cable and wire content, as they have no relevance for this exploration of criteria for user value. Starting position: post primary installation, i.e. the wall is already in place, and layout modifications are considered. Moreover, costs are only obliquely addressed. Table 4.2 brings together the findings of the quick scan assessment. For the traditional variant, 'down-cycling' ("recycling" into lower grade materials) and 'Incineration and Landfill' are added as possible treatment routes, that are not considered in the *Circ-Flex* variant.

TABLE 4.2 Quick Scan comparison between traditional and Circ-Flex variant [Source: Bob Geldermans].

	Variant 1 Traditional Partitioning Wall	Variant 2 Circ-Flex Partitioning Wall
Unlocking Flexibility Capacity		
Ease of disassembly (Easy, Moderate, Hard/Strong)	– Easy–Moderate. – Moderate–Strong impact on direct physical context	– Easy. – Moderate impact on direct physical context
Ease of re-assembly (Easy, Moderate, Hard/Strong)	– Easy-Moderate. – Even if dimensions remain the same, constructive adjustments are required	– Easy, if dimensions remain the same. – Easy–Moderate if material adjustments are required
Ease of repurposing or disposing (Easy, Moderate, Hard/Strong)	– Easy, if traditional (linear) routes are sustained. Moderate–Hard if 'regenerative' trajectories are sought.	– Easy–Moderate. Depending on status of (reverse) supply chain. Easy from the perspective of material purity
Unlocking User Capacity		
User investment (Time and Expenses)	– Time-commitment low with regard to all stages. Initial financial investment relatively low. Expected return on investment low or negative (i.e., discarding costs rather than residual value).	– Time-commitment low with regard to (dis-) assembly stages. Initial financial investment low–moderate (purchasing costs often higher). Expected return on investment low–moderate. New financial models may emerge.
Freedom of choice (Availability and Variation)	– Abundant and readily available materials and products in a diverse range.	– Partly readily available materials and products, partly limited to a few eligible products. The latter products are, in most cases, not readily available via common channels (such as DIY shops).
Unlocking Circularity Capacity		
Maintenance	– Surface layer accessible for maintenance. Other parts dependent on wall-finishing	– Surface layer accessible for maintenance. Other parts dependent on wall-finishing
Redistribution	– Timber, metal, plasterboard, insulation	– Timber, metal parts, board, mounting profile, insulation
Remanufacturing	– Metal, possibly timber	– Metal, mounting profile, – possibly timber
Recycling (equal or higher grades)	– Metal, insulation	– Timber, board, insulation
Down-cycling (lower grades)	– Timber, plasterboard, insulation	–
Incineration or Landfill	– Timber, plasterboard, insulation	–
Bio-cascades	– (uncontaminated) Timber	– Timber, insulation, board
Bio-feedstock (e.g., soil improver)	–	– Insulation

Additional sources: Flexibility Capacity [68,69,71]; User Capacity [68,70,71]; Circularity Capacity [72,73]

4.6 Discussion

Multiple considerations emerge with regard to the research structure and results, these are addressed below. First, a reflection is provided on the methodological framework. Next, potential constraints are addressed in relation to the results, from institutional, legal, cultural, and demographic perspectives.

4.6.1 Reflection on Methodology

The goal of this chapter was to introduce user benefits to the circular building discourse and practice in the Netherlands, whilst exploring the relationship with circular and flexible concepts. A literature study revealed a research-gap with regard to the integration of the user, both in building design and building performance evaluation. A study of four cases and expert consultations provided more insight into the perceived quality of flexible layout configurations and into linkages between user benefits, flexibility, and circularity. However, the four cases were of a very different nature and period. Moreover, three of those cases were not located in the Netherlands. Conclusions drawn from these insights thus need to be handled with care. Despite those constraints, the findings were valuable enough to extract basic notions on what drives (or obstructs) residents to modify the layout of their homes. These notions were paired with the findings from expert consultations and literature study, and, in correspondence with results from Chapter 3, led to to a basic set of criteria. The expert consultations took place in a semi-structured way throughout the research trajectory, making it hard to cross-check statements and learning-points. Such a heuristic evaluation method has the advantage that it can be executed relatively fast and can allow for unforeseen aspects to come into the picture, deploying a certain experience-based logic. The disadvantage, however, is that in reducing the complexity, some facets may be overlooked. Still, such an approach inherently leads to intersubjective results and a certain level of agreement, provided that the variables are minimised. The expert consultations provided valuable insights, despite diverging accents in their reflections, which caused a certain bias. These insights either provided decisive conclusions regarding e.g. user engagement and the need for personalisation, or they confirmed findings from the literature study. This may not provide a sound basis for a comprehensive analysis, but was sufficient for a rudimentary set of criteria and a quick scan assessment.

An important choice was to keep the two variants as comparable as possible. Current circular building innovation demonstrates a bias towards engineered, modular partitioning concepts, whilst emphasising design and engineering considerations rather than addressing the users of common residential typologies. My target, however, is much closer to the latter group. I deemed it justified to assume that those residents are more likely to follow known routes and patterns rather than radically alter their behaviour in this respect, at least within the foreseeable future. This assumption was supported by what the experts had experienced, particularly relating to the Smart Urban Retrofitting (SUR) and Open Building Design (OBD) projects. This led to questions of accessibility to and familiarity with materials and products, as well as the associated costs. Currently, there is not a large range of products to substitute the traditional ones, whilst facilitating renewability routes, as indicated in Table 4.2. However, there are certainly several products that apply: regarding additive-free, recyclable boards or insulation, for example, as well as decorative paint and other coating products. Examples include: ECOR® board (Noble Environmental Technologies), Everuse® insulation (EverUse B.V.), and Graphenstone® paints and mortars (IEdiSA). Some of these return in the next section concerning institutional, legal and cultural constraints.

Lastly, partitioning flexibility, as an added quality for the user, relates primarily to the relational properties of Figure 4.3, concerning: performance span of the partitioning, dimensional freedom, and connections that allow easy disassembly. However, it goes without saying that adaptations in partitioning components should never occur at the expense of the quality of intrinsic properties, as indicated in Figure 4.3 as well. Rather the opposite: the flexibility of components accommodates timely upgrades in that respect, think of innovations regarding thermal comfort control, air purification, volatile organic compounds reduction, and mould control.

4.6.2 Institutional, Legal, Cultural, and Demographic Context

The results presented in this chapter need further reflection regarding constraints, in particular regarding the comparison of two variants. Building paradigms, on the one hand, and lifestyles, on the other, are both culturally and historically determined. As mentioned above, this has an effect on intervention-options and purchasing behaviour of the residents. With regard to the housing paradigm in the Netherlands, and the institutional system behind it, one could observe that notions of flexibility have been introduced several times over the last decades, but have not become the norm in this sector. Influenced by “circular ambitions” of decision-makers, resonating in local, national and regional policy documents, new opportunities are emerging.

Not least when those ambitions are coupled with demographic trends that impact the housing market, for example relating co-housing and self-organisation. However, as yet, the effects are not yet noticeable, let alone measurable. A main challenge in this respect is the acknowledgement of diverging decision-making domains, i.e. regarding structural and collective parts of housing and individual interior parts. This comprises multiple interrelated cultural, institutional, and legal aspects. As long as residents feel insufficiently incentivised to demand more decision power, the building sector does not feel inclined to contest traditional methods, and authorities refrain from implementing legally binding measurements. And vice versa. That said, a change is tangible with regard to purchasing strategies of governments, for example. Whether and when this reaches the housing sector remains a question. At this moment, the housing sector faces other challenges that are overruling, sometimes even excluding, notions of circularity and individual user requirements. Such challenges are, for example, the transition towards better energetic performances, and sufficient housing supply, of a sufficient quality, for an increasing demand. The latter is valid for many parts of the Netherlands, not least in the Randstad. Authorities and housing corporations, as well as other investors in the housing stock, have key roles in this respect. This comes with the responsibility not to approach challenges in an isolated way, but explore synergies. In that respect, lessons learned in the circular kitchen pilot can be meaningful for other modular concepts for the interior domain as well. This relates to technical, industrial, business, and legal aspects of energy service installations as well as to bathrooms and partitioning walls.

In other countries, one could experience forces of a different nature. In Japan, for example, the adaptability and flexibility of the housing sector increased massively over the last years, informed by challenges of a decrease in skilled construction workers. As yet, Japan primarily focuses on flexibility and adaptability, and not so much on the link with circular material flows. Moreover, Japan has a completely different housing culture from the Netherlands. It is expected that the comparative results are more valid with regards to other countries where affordable multi-family (social) housing is common, and where there is a certain familiarity with (and growing awareness of) both the resilience of the housing stock over time and sustainability challenges of construction materials. One could think of Sweden, Denmark, and the UK, for example. That said, I estimate that the results provide valuable insights for formal and informal building industries around the world that are exploring the benefits of CB.

Concerning the applicability of products and innovations that facilitate circularity, there are other related challenges at stake. Related, because it is linked to questions of legal ownership: in the Netherlands, in principle, what is added immovably ("nagelvast") to a dwelling becomes part of the real estate, ownership of which is usually not in the hands of the tenants. That leads to a brief reflection on the implementation of circular partitioning walls. Many innovative products, including those that claim or are proven/certified to be applicable for circular applications, lack the safety standardisation of more established products. This is either because standardisation lags behind, or simply because the products do not comply with the regulations (yet). Looking at a fibre board product that fits within the variant 2 scheme, for example, shows that fire safety is a main concern. Such products avoid the use of impurities, such as flame retardants, in order to comply with the circularity capacity. That same quality, however, is an obstacle for use in common partitioning configurations, as described in Section 4.6.1. As soon as the board is fixed, even if that is done in a simple-to-reverse way, it is illegal. This reveals a clear conflict in the development potential of partitioning wall products with a strong circular capacity. A freestanding variant, however, could be a solution here, provided it scores sufficiently on other parameters important for the user in question, be it with regard to flexibility capacity, circularity capacity or user capacity. This relates to the observation that, although many criteria of Tables 4.1 are relatively well understood, the combination and integration of those criteria are not. This resonates clearly in the category of 'Unlocking user capacities'. For example, time-commitment may increase when high-quality repurposing routes are sought but not facilitated through product design or logistics. This blocks the circularity potential. Closely related are financial aspects: innovative financial models, required to facilitate circular value chains, are still underdeveloped [76].

4.7 Conclusions

The underlying hypothesis of this chapter was that without tapping into the user domain, circular building cannot reach economies of scale in a sustainable way. The chapter was structured around two objectives: (1) further identifying the relationship between flexible and circular building; and (2) exploring the impact of circular, flexible building concepts and practices for the users of multi-family housing regarding interior partitioning. Particular emphasis has been on multi-family housing and the large group of residents that do not have the privilege to act as commissioner or co-developer of their own homes, i.e. lacking the means to create decision power. From the viewpoint of sustainability, this is problematic. In the first place because it disregards users' unique sense of engagement with their living environments. Moreover, it hinders a smooth transfer to a different use of the space

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due to unforeseen changes. Eleven *Circ-Flex* criteria, grouped in three categories, were identified as essential for facilitating circular material flows through buildings, in relation to the benefits for residents. The three categories concerned: flexibility capacity, circularity capacity, and user capacity. Together, these criteria extend the circular building discourse to the domain of the user. In a quick-scan assessment, a first grasp was given concerning the differences between a traditional and a *Circ-Flex* partitioning wall, revealing both opportunities and challenges. The opportunities are associated with the current momentum around CB in the Netherlands, leading to innovations that potentially support user-integration. This concerns product or building design as well as participatory processes. The challenges, on the other hand, are associated with the lack of preconditions for the large scale implementation of such innovations. These concern, for example, reverse logistics and institutional alignment.

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TOC

5 Human Health & Well-Being In Relation To Circular And Flexible Infill Design

Assessment Criteria On The Operational Level

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5.1 Introduction

In Western societies, we usually spend 80–90% of our daily lives indoors, as outlined in Chapter 1. This necessitates an appropriate management of the indoor environment "so that we feel comfortable and healthy" [1, page 18]. Although the comfort, health and well-being of residents has been addressed in postwar mass housing, in terms of minimum size standards and functional basics, occupant-diversity and changing requirements have not been taken into consideration [2–7]. Still today, changing user requirements are seldom factored into the design and management of residential buildings [8,9]. Diversity and change, however, are drivers of indoor modifications and define the sustainability of the housing stock, both from a social and from a real estate perspective, as addressed in Chapters 1 and 2. This touches upon a myriad of aspects, such as design, asset management, stakeholder integration, user behaviour, legal framework, procurement and reverse logistics.

This chapter addresses research gaps between resident health and well-being on the one hand and circular and flexible (*Circ-Flex*) product performance on the other. *Circ-Flex* can be understood as a systems approach rooted in the synergistic liaison between circular and flexible characteristics, as outlined in Chapter 4. Circular characteristics concern the dynamic total of associated processes, materials and stakeholders that accommodate renewable flows of building materials and products at optimal rates and utility. Flexible characteristics concern those aspects that provide 'accommodative capacity', allowing the easy rearrangement of building components, whilst facilitating the changing needs of occupants. In order to extend the CB discourse to the domain of the end-user, I integrated three aspects in Chapter 4: circularity capacity, flexibility capacity and user capacity. This approach was tested on the design and operation of non-bearing indoor partitioning, likely to change over time due to new functions or different user requirements. That same product is at the heart of this chapter.

The objective of this chapter is to determine assessment criteria for the performance of indoor partitioning products in a *Circ-Flex* model, including residential health & well-being as well as operational processes. The overarching aim is to establish a more integrated and inclusive approach to the transition from linear to circular built environments. This ties in with recent calls for a more comprehensive evidence-base to better inform the policy debate, in the light of interrelated Sustainable Development Goals, as communicated by the World Health Organisation Regional Office for Europe, see Chapter 2 [10]. Results from this analysis lead to specific areas of intervention concerning the partitioning product in the test-case, and, more importantly, generic lessons about integrated performance indicators of infill components in *Circ-Flex* applications. Next to partition walls one can think of e.g. kitchens, bathrooms side-sheeting and insulation of interior walls and ceilings in enrgy renovations.

The chapter is structured as follows. In Section 5.2, the research methods are explained. These include a literature review regarding indoor environmental quality and indoor air quality in general and the relation with circular and flexible building (products) in particular (Section 5.3); an analysis and synthesis of three assessment schemes aiming at the operational level (Section 5.4); and the validation of synthesised criteria on a test-case (Section 5.5). Finally, in Section 5.6, the results are discussed from various vantage points, incorporating notions of: validity, data availability, stakeholder engagement, contextual conditions, supply and demand patterns and regulatory framework.

5.2 Methods

First, in Section 5.3, a brief literature review is reported regarding indoor environmental quality (IEQ) and indoor air quality (IAQ) in general and the connection with *Circ-Flex* in particular. The emphasis is on residents' health & well-being in relation to circular building assessments. Multiple search terms were used in various combinations, in English as well as in the Dutch translation, using multiple academic and general search engines. The variation in search engines was deemed important, not least given the significance of circular building developments outside of the academic realm [11]. The consulted literature during the first iteration contributed to additional key terms, subsequently leading to a set of 26 terms, see Table 5.1. Although there are certainly other terms that represent thematic overlaps, it was estimated that the aforementioned approach established a comprehensive and workable framework. Given that CB is still in its initial stage, particularly with regard to a sound scientific and practical evidence-base, other terms (such as 'sustainable' and 'green') were applied instead of 'circular' in a secondary query.

TABLE 5.1 Search terms applied in various combinations, in English and Dutch translation [Source: Bob Geldermans].

Resident Health related	Circular Building related	Assessment related
– 'indoor environmental quality' (and 'IEQ') – 'indoor air quality' (and 'IAQ') – 'health' – 'well-being/comfort' – 'occupant health' – 'residents' – 'user benefits'	– 'circular building' – 'circularity' – 'Circular Economy' – 'Cradle to Cradle' – 'circular design' – 'regenerative design' – 'sustainable building' – 'green building' – 'built environment' – 'buildings' – 'building products'	– 'impact' – 'assessment' – 'analysis' – 'evaluation' – 'criteria' – 'indicators' – 'measuring' – 'measurement'

Subsequently, in Section 5.4, the link between IAQ and circularity is further explored with regard to assessment tools and guidelines that focus on the product and operational level. As tools and guidelines with that specific aim are rare, several instruments with an overlapping scope are explored, either concerning material circularity or concerning IAQ within sustainable building frameworks. Three schemes are scrutinised in more detail: Cradle to Cradle Certified™ (version 3.1), the Pre-Returnable Procurement® tool (version 3.1) and the WELL Building Standard™ (version 2). The former two show overlaps in their focus on human health and circularity, albeit with different objectives and approaches. The latter does not focus on circularity but puts an accent on human health in the overall performance of a building during its service life, including the building products. Based on these schemes, criteria are synthesised. Several embodied impacts are included to underscore systemic relevance and interrelations between factors. The aim is thus not to compare existing tools but to analyse, prioritise and synthesise criteria matching this study's specific objective.

Next, in Section 5.5, the synthesised criteria are applied to an indoor partitioning product, comprising of a solid, modular prefab wall panel. The aim of this step is twofold: (1) to validate the criteria and test their workability, shedding light on the level of detail required to assess the product and operational level, including the entire process from harvesting and/or extraction of resources and all people involved in that process, up to use and reuse; and (2) to detect specific points of intervention regarding the product and operation under scrutiny. Several industry partners contributed to this assessment stage, providing data on product properties, production processes, (reverse) supply chain logistics and waste treatment.

5.3 Literature Review

5.3.1 Assessing Indoor Environmental Quality

Indoor Environmental quality (IEQ) can be described by a variety of aspects (or stressors), such as: odour, air pollution, fresh air supply, air velocity, moisture, temperature, noise, vibrations, illuminance levels, luminance ratios, reflection, tactility and appearance [1,12,13]. From those aspects, a range of categories can be derived: from indoor air quality, thermal comfort, acoustics and visual or lighting quality, to aesthetic quality, spatial quality, tactile quality and ergonomic quality. All relate to the human senses. Potential stress factors concern all three systems of the human body (nervous, immune, and endocrine system) and can result in both mental and physical effects [1]. It is estimated that one in six Europeans live in unhealthy buildings [14]. Bluyssen (2013) states that major health effects seem to be associated with more than one stressor, whilst taking account of previous and future exposures, as well as the duration and combination of exposures [15]. Figure 5.1 lists associated stressors, stress mechanisms diseases & disorders.

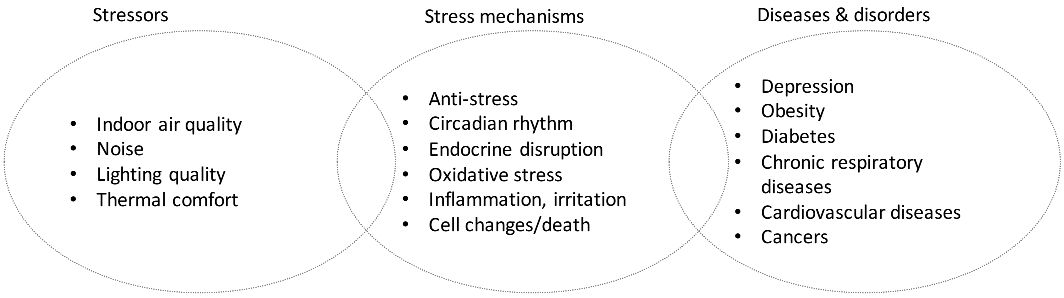

FIG. 5.1 Stressors, stress mechanisms, diseases & disorders associated with indoor environmental quality [Source: Bluyssen, 2013]

Internal partitioning can have an impact on all subsets of IEQ. Most of the subsets are also addressed in the European standards, albeit on a basic level. The complexity that resonates in Figure 5.1 has not yet found its way to standardisation schemes in line with end-user needs [15,16,17]. There is ongoing debate about control measures, assessment methods, indicators and interactions between factors. With regard to indoor air quality (IAQ), the Scientific Committee on Health and Environmental Risks (SCHER) states that over 900 chemicals, particles and biological materials are associated with health effects and yet the database for indoor air risk assessment is limited [18]. Multiple factors determine the IAQ, such as quality of the surrounding outdoor air, ventilation and indoor sources of pollution. For this study, the focus is on indoor sources, specifically building products and finishing materials associated with partitioning. Products and materials used in indoor partitioning may release physical, chemical or biological emissions that can have adverse health effects. Primary emissions are those substances released directly, as an inherent characteristic of the material or product in question, whereas secondary emissions are those substances that are released through actions on the materials [19]. Emissions can take place during or shortly after construction as well as in the long-term use stage and during deconstruction at the end of a material or product service life. Adverse effects for the residents are dependent on exposure, dose and response over time.

McDonough and Braungart (2003) state that none of the materials used in contemporary buildings are specifically designed to be healthy to people [20]. This statement underscores the fact that materials, products and buildings have become more and more heterogeneous, introducing multiple substances and synthetics that pose potential threats to human health. Building standards regarding health and safety have difficulties to keep up with this development [21]. In their article, McDonough and Braungart mention, amongst others, plasticisers in Poly Vinyl Chloride (PVC) that may disrupt human endocrine systems [20]. Furthermore, they refer to the use of heavy metals such as lead (that have neurotoxic properties), cadmium (classified as carcinogenic), and volatile organic compounds (VOC, suspected carcinogens and immune system disruptors) released from, for example, particle boards, paints and adhesives [20]. The list of harmful substances is long and risk assessments are up for debate but the statement of McDonough and Braungart remains valid. Even if some potentially harmful chemicals are being phased out, others emerge, in response to ever changing market and regulatory dynamics. Think of additives to enhance fire safety, for example. What is more, the heavy accent on energy efficiency measures in buildings (like airtightness), as a consequence of climate and resource policies, may make matters worse, because such measures inherently imply an increased need for ventilation to avoid the accumulation of air-contaminants [15].

A study by Steinemann et al. (2017) on the focus on the IAQ of green buildings and associated certifications points out that IAQ is not yet fully integrated in the assessment methodologies [22]. They observe that “green” certification schemes may provide inadequate incentives for improving IAQ and that green practices and products could actually impair IAQ. An important factor in this respect is the large focus on ventilation for IAQ control, rather than on source control and exposure reduction [22]. Multiple other studies and policy documents in this or related fields indicate that there is or should be an increased attention for IAQ in the current (European) building practice, beyond energy performance and global climate concerns alone [15,21,23–32]. An important step in securing such attention on the operational side is the recently revised Energy Performance of Buildings Directive (EU) 2018/844 of The European Commission (EC) which puts more emphasis on human health and well-being [33]. With regard to the regulatory framework, a brief study of the literature reveals significant differences between scope, threshold levels, methods and EU member states [15,17,34]. The debate is ongoing between academia, industry and authorities regarding objectives and legally binding restrictions, not only due to varying interests and interpretations of available data but also linked to the fact that assessments are difficult because indoor air can contain a mixture of many different pollutants [18]. The complex interrelations between various factors are important, that can have a significant effect on the IAQ.

An example is the relation between formaldehyde emissions, room temperature, relative humidity and air circulation rates [35–38]. EU regulations in this respect tend to aim at single products rather than accumulated exposure. Moreover, regarding the Netherlands, the mechanisms of monitoring and law-enforcement are missing [17].

5.3.2 The Operational Level

This section aims to establish a more integrated approach to indoor environmental quality by coupling user benefits to circularity and flexibility. Specific attention thus goes to the relation between the three aspects: user health aspects associated with partition materials; flexibility of partitioning schemes; and circularity of applied materials and products. The objective is to rate the potential impact on residents' health, well-being and comfort concerning both the intrinsic material properties of the wall-components (are there reasons for concern regarding the applied materials on the shorter or longer term?) and the related construction & deconstruction properties (can the components be placed and reutilised easily?). Simultaneously, the circularity factor dictates that the whole supply (and reverse supply) chain needs to be taken into account, in order to facilitate material cycles beyond the housing unit. Combined, those points increase the complexity of an assessment, not least regarding the availability of specific data.

This complexity is one of the reasons why assessment tools that aim to measure circularity are often sub-optimal [39–46]. Such tools simplify the complexity that is inherently part of circular product and material systems, failing to take account of specific or detailed levels "to further focus on the very core and essence of circular economy, which is the circulation and recirculation of products and materials in loops" [40, page 5]. Saidani et al. (2017) introduce an operational and product level, which they refer to as 'nano-level,' next to the macro (city, region or country), meso (sector or inter-firm) and micro (single company) levels that are the commonly applied scale-levels in approaches to measure circularity [40,47,48]. The argument for a shift of focus to the nano-level is that this operational level essentially binds the various scale levels, whilst looking more closely at the actual, effective performance of circular economy implementation [40].

The reality of extracting detailed data from, for example, suppliers and manufacturers, however, is more often than not disproportionately complicated or labour-intensive, if the data are available at all. In its elaboration on barriers for the CE, Nguyen et al. (2014) identify three barriers that stop companies from shifting from linear to circular resource use with regard to their products [49]:

- First, the extensive supply and manufacturing footprint that companies have created, leading to geographic dispersion of parts, even for simple products;
- Second, the sheer complexity and proliferation of modern product formulations, rarely labelled or made public, hence difficult to identify, even for manufacturers themselves;
- And third, the difficulty of ingrained habits, linked to decisions made a long time ago.

It is thus unsurprising that, to date, there is no recognised, evidence-based way to assess how effective a building product or service truly is in making the transition from a linear to a circular mode of operation [50,51,52]. The World Business Council for Sustainable Development states that companies are shaping and framing the concept of CE based on how it is most material to their core business, which leads to a lack of consensus regarding how to measure circularity [52].

Saidani et al. identified three tools that particularly focus on product and operational circularity: Material Circularity Indicator (MCI, Ellen MacArthur Foundation, 2015), Circular Economy Toolkit (CET, University of Cambridge, 2013) and Circular Economy Indicator Prototype (CEIP, Cayzer et al., 2017) [40]. An assessment of these tools revealed substantial room for improvement with regard to, most notably, operational value. Each tool shows a lack of data-construction support and practical guidance. As described above, such operational aspects are crucial in the context of this chapter. Moreover, those tools do not distinguish different renewability routes, nor do they connect substantially with social factors that are intertwined within the sustainable development goals (SDG), put forward by the United Nations [53]. For example, with regard to clean water (SDG6), clean energy (SDG7), decent work (SDG8), reduced inequalities (SDG10) and so forth.

Furthermore, the Circular Building Assessment scheme (CBA) deserves mentioning, which is currently being developed within the framework of the European Horizon 2020 project Buildings as Material Banks (BAMB). CBA brings together four years of study and practical experience regarding, most prominently, reversible building design and material passports. However, at the time of writing, this instrument is still in the development stage. Moreover, although CBA is designed as a modular tool and thus allows for extensions in the future, its scope does not (yet) include health data in relation to the end-users of buildings [54,55].

From the viewpoint of building-occupants' health related to material use, there are few assessment schemes on the market that prioritise this domain [22]. However, the WELL Building Standard, launched in 2014, has been identified as a meaningful framework in this context, as it focuses explicitly on health & well-being of building occupants. Moreover, the Cradle to Cradle® Product Standardisation scheme (C2C

Certified™) offers a matching approach, revolving around material health and material reutilisation. Lastly, Dutch firm Rendemint developed the Pre-Returnable Procurement® circular purchasing tool (PRP®), which is gradually gaining ground in The Netherlands. PRP® aims at whole value chains, tracking and tracing resource use and preservation, as well as social fairness.

5.4 Analysis and Synthesis of Three Assessment Schemes

Together, WELL Certified™, C2C Certified™ and PRP® provide the basis for a set of criteria and assessment guidelines. In this section, the three schemes are further introduced (5.4.1 - 5.4.5) and synthesised (5.4.6).

5.4.1 Cradle to Cradle Certified™

With regard to the relation of IAQ and circular building principles, the Cradle to Cradle concept (C2C®), both as a philosophy and certification system, deserves recognition. As of the 1990s, C2C® has been dedicated to removing potentially dangerous chemicals from current life cycles, with particular attention for human exposure in the built environment. The C2C Certified™ program was launched in 2005 by McDonough Braungart Design Chemistry (MBDC). It focuses predominantly on the product level [56]. In 2010, a scale-up of C2C Certified™ took place, executed by the newly founded Cradle to Cradle Products Innovation Institute. The C2C Certified™ scheme includes five assessment categories: Material Health, Material Reutilisation, Renewable Energy, Water Stewardship and Social Fairness. Thirty-nine standard requirements are distributed over these five categories. Furthermore, C2C Certified™ has five certification levels: Basic, Bronze, Silver, Gold, Platinum, which reflect the level of accomplishment. The standard requirements relate to one or more of the certification levels. C2C Certified™ guides and controls the assessment trajectory of products and processes, accentuating the necessity to submit evidence-based documents and to gradually improve.

5.4.2 WELL Certified™

The WELL Building Standard was launched by the International WELL Building Institute in 2014, seeking to implement, validate and measure features that support and advance human health and the well-being of building occupants [57]. WELL approaches human health as a state of being free of disease and "the enjoyment of productive lives from which we derive happiness and satisfaction" [58]. The Standard's performance metrics are based on a review of the existing research on the effects of indoor spaces on individuals and has been advanced through a peer reviewed process. The certification procedure includes submission of evidence-based documents as well as a performance evaluation. The focus is on the following categories: Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind and Community. Within these categories, WELL distinguishes twenty-three preconditions and ninety-four optimisations [58]. For each certification level (Silver, Gold and Platinum), 100% of the preconditions must be met. Furthermore, between 20% and 80% of the optimisations must be met, 20% for Silver and 80% for Platinum [59].

5.4.3 Pre-Returnable Procurement®

The Pre-Returnable Procurement® tool was first described by Rendemint in 2009 and is available as a software tool since 2011. PRP® is designed to analyse, measure and compare a reported end-result (project, process, product), based on 'circularity potential.' This circularity potential is defined as the provable preserved resources throughout the whole value chain, from resource to resource, realised in accordance with international human rights and relative to 'absolute circularity' [60]. 'Absolute circularity,' in the definition of Rendemint, means: zero resource loss and zero human rights violation. PRP® measures and compares the preservation in quality, quantity, non-toxicity and human rights of initial and end-weight (in kg) to: (1) achieve an end-result, (2) maintain and reuse that end-result and (3) break the end-result down again to the resource level. PRP® provides an integrated assessment method, intentionally avoiding a scoring system based on selected criteria. To structure and manage the data-collection and registration process, PRP® applies a division in three entry levels: Items, Materials and Resources. Each level distinguishes the categories Product, Extraction, Social fairness, Toxicity and Reutilisation. Data need to be based on verifiable evidence regarding the whole chain of custody.

5.4.4 Complementary and Overlapping Aspects

The three aforementioned schemes enter the realm of material use, as well as performance over time, whilst addressing the health and engagement of stakeholders. Given their differentiated objectives, the schemes cannot be compared but they comprise overlapping and complementary attributes. Table 5.2 lists several characteristics per scheme and indicates the connection with the core focus of this chapter, that is, the relation between (1) user health, (2) circularity and (3) flexibility.

From C2C Certified™, the categories Material Health and Material reutilisation have principal relevance for this study, representing the ultimate goals for all products to be manufactured using only those materials that have been optimised and do not contain any materials/chemicals from the banned list [56]; and for the industry to "eliminate the concept of 'waste' by designing products with materials that may be perpetually cycled to retain their value" [56, page 49].

From WELL Certified™, the aspects Materials, Air and Community are especially relevant in this context, due to their direct relationship with material performance and stakeholder engagement. The first aims to reduce human exposure to hazardous building material ingredients through the restriction or elimination of compounds or products known to be toxic and the promotion of safer replacements [56]. The second aims to ensure high levels of indoor air quality across a building's lifetime through diverse strategies. Only the aspect 'source elimination' is considered in this study. The third is selected given its adherence to participatory design approaches that address the physical determinants of health and well-being. It is within the concept of 'Community' where aspects of user-feedback loops reside [56].

The PRP® approach opposes a straightforward division and selection of criteria, as all levels (Items, Materials, Resources) and categories (Product, Extraction, Social fairness, Toxicity, and Reutilisation) contribute equally to one unambiguous result. These aspects overlap with many of the C2C Certified™ and WELL Certified™ features, whilst adding a certain rigour with respect to completeness: all resources need to be accounted for throughout the whole project's duration. In such a system, every modification will come to the foreground and the circularity potential can be measured in real-time, relative to the initial, baseline assessment.

TABLE 5.2 Characteristics of three schemes: Cradle to Cradle (C2C) Certified™, WELL Certified™ and PRP® [Source: Bob Geldermans].

	C2C Certified™	WELL Certified™	PRP®
Since	2010 (scale-up)	2014 (in pilot)	2011 (software tool)
Main scope	Product design, development and reutilisation	Building performance in use	Procurement, analysis and development of products, projects, processes
Key target group	Designers and Manufacturers	Building owners, Developers, Managers, Employers	Government, Semi-government, Companies
Data type	Quantitative and Qualitative	Quantitative and Qualitative	Quantitative and Qualitative
Assessment method	Standardisation: Basic, Bronze, Silver, Gold, Platinum levels	Standardisation: Silver, Gold, Platinum levels	Circularity potential (kg)
Relation with study focus	User health; Circularity; Flexibility	User health	User health; Circularity; Flexibility

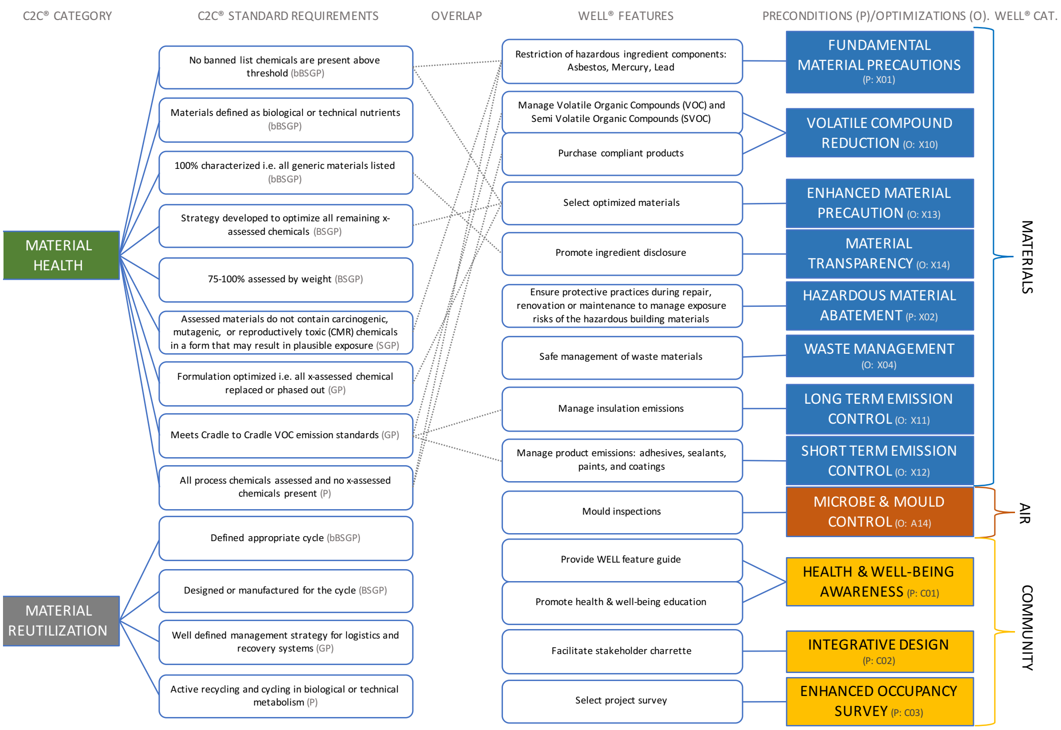

FIG. 5.2 Selected aspects from C2C Certified™ (left) and WELL Certified™ (right), with interlinks [Source: Bob Geldermans].

Figure 5.2 displays the selected aspects from C2C Certified™ and WELL Certified™ standardisation, as a step up to a synthesis. C2C Certified™ aspects are on the left of Figure 5.2, with 2 main categories and 13 selected standard requirements. WELL Certified™ aspects are on the right, following 3 categories, 12 preconditions/optimisations and 14 features. In brackets, references to the WELL Certified™ arrangement are added to the preconditions and optimisations. For C2C Certified™, references are added in brackets concerning the standard requirements' validity for one or more certification levels, following the hierarchy: Basic (b), Bronze (B), Silver (S), Gold (G), Platinum (P). The overlap with PRP® is further addressed in subsequent sections.

5.4.5 Additional Features: Embodied Impacts of the Value Chain

Thus far, the focus has been on residents' direct health and well-being in conjunction with material use and reutilisation associated with indoor partitioning. However, there are impacts elsewhere in the system as well. Although those impacts are not at the core of this chapter, I prefer to integrate some of them to illustrate the necessity of a systemic perspective. For this, I adhere to two aspects in the C2C Certified™ and PRP® schemes: social fairness and energy management. Concerning the former: in shifting the attention of circular building concepts to the health and well-being of residents, the social aspect of circular building is highlighted. This can never be done in any meaningful way if the health and well-being of workers in the supply chain is not also addressed. Concerning the latter: currently there is growing attention in the Netherlands, as well as on EU level, about the relation between circularity, energy and climate, whilst acknowledging the significance of an integrated scope [61–65]. This necessitates a link between materials and energy, looking at resource use, including energy carriers and other materials.

In Figure 5.3, I provide an illustration of the expanded system boundary for indoor partitioning, taking account of the whole value chain, including 'reverse supply.' I distinguish various spatial scale levels associated with the flow and temporary storage of resources, and display various supply-chain stages. The figure reflects the assumption that in a circular economy reverse supply chain logistics will increase, whilst limiting the dispersion of resources on a global market. At least, this can be assumed for the (re/de)-materialisation of interior partitioning.

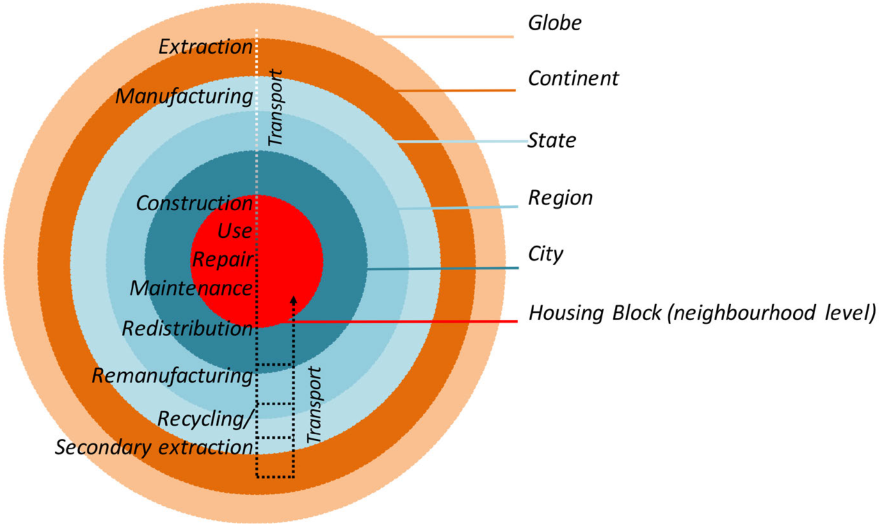

FIG. 5.3 Systemic impact building components through spatial scales [Source: Bob Geldermans].

Within the C2C Certified™ framework, the focus is on a "future in which industry and commerce positively impact the energy supply, ecosystem balance and community" [56, page 54]. Hence, their focus is on renewable energy and carbon management, ultimately phasing out any use of fossil fuels, whilst managing emissions that do occur as biological nutrients. The requirements for organisations striving for certification of a product become more stringent with every hierarchical step (from basic to bronze, silver, gold and platinum). The platinum scheme includes energy use and greenhouse gas (GHG) emissions associated with the product from Cradle to *Gate*. This means, from a circular or continuous flow perspective, that a significant part of potential embodied energy and carbon impact is not accounted for, namely from Gate all the way to the next Cradle. It is easy to understand why these cutoffs are applied when practicality and allocation issues are taken into account. However, for this study, I adhere to the whole value chain from one iteration to the next, as anticipated by the PRP® method. Embodied energy is defined as: the total primary energy demand for extraction, processing, manufacturing, construction, use, deconstruction and reprocessing to secondary materials associated with the partitioning components, including transport (see Figure 5.3). Embodied carbon signifies the related CO_2 emissions. With regard to social fairness, C2C Certified™ and PRP® bring up human rights for all stakeholders in the value chain. Both schemes refer to acknowledged social responsibility programs as a benchmark, dependent on the organisation, product or project in question.

5.4.6 Synthesis of Criteria

Several key categories can be distinguished that in unison cover the pillars at the heart of this study: user health; flexibility; and circularity. C2C Certified™ and PRP® specifically address (1) material health & material transparency (due to the interlinks, sub-categories are combined into one category); and (2) material reutilisation. WELL Certified™ also focuses on material health & transparency but has no focus on the reutilisation aspect. Furthermore, WELL Certified™ adds a specific criterion concerning (3) microbe & mould control to the equation. This category has particular relevance for this study, concerning inherent material selection and handling properties in relation to moisture conditions and mould growth. Moreover, WELL Certified™ introduces notions of (4) health & well-being awareness; (5) integrative design; and (6) perceived performance, all of which are relevant in relation to product performance, notably concerning valuable feedback loops throughout supply, use and reuse chain. Finally, 'embodied impact' is represented by (7) embodied energy; and (8) social fairness, which are included in C2C Certified™ as well as PRP®.

Table 5.3 displays a synthesised set of criteria and assessment guidelines. It concerns a total of eighteen criteria, divided over the eight aforementioned categories, derived from the assessment schemes analysed in Section 5.4. The term 'Criteria' is applied in order to relate to the *requirements* of C2C Certified™ as well as *features*, *preconditions* and *optimisations* of WELL Certified™ and integrated aspects of PRP®. The criteria are either directly transferred from their original framework or slightly adapted. The latter is the case when aspects from one source are merged, multiple sources overlap or when aspects are applied to the specific perspective of this study. This is indicated in brackets behind the criteria. Each criterion is accompanied by potential assessment guidelines. Where applicable, references are made to current European performance requirements for internal partitioning, as part of the European Technical Approval Guideline, ETAG 003 [66].

TABLE 5.3 Synthesised set of criteria and assessment guidelines for Circ-Flex performance, based on C2C Certified™, WELL Certified™, and PRP®, including European Technical Approval Guidance (ETAG) reference [Source: Bob Geldermans].

Criteria	Assessment Guidelines	ETAG Reference
1 MATERIAL HEALTH & MATERIAL TRANSPARENCY		
1.1 X-LIST PRODUCT		
X-rated chemicals in product. (C2C, in overlap with WELL and PRP). *NB1: C2C differentiates between biological nutrient (BN) materials and technical nutrient (TN) materials. Thresholds relating exposure risks may be different for BN and TN*	**Appropriate certification**, if applicable. If not: **Banned List declaration** And the following, depending on level of completeness: **Supplier Declarations** **Manufacturer Declarations** Section in **Bill of Materials** (see 1.4)	(EC) No. 1272/2008 (Classification, Labelling and Packaging of substances) EN 13501-2 (classification of construction products and building elements using data from fire resistance and smoke leakage tests)
1.2 X-LIST PROCESSES		
X-rated chemicals in processes. (C2C, in overlap with WELL and PRP). *NB: See 1.1 above*	Identical to 1.1 above	(EC) No. 1272/2008 (Classification, Labelling and Packaging of substances)
1.3 X-LIST OPTIMISATION		
Formulation optimised: all x-assessed chemicals replaced or phased out. (C2C, in overlap with WELL and PRP).	**Strategy Declarations**, referring to the documents of 1.1 and 1.4, including time-plan and budget	–
1.4 LIST OF MATERIALS		
100% characterised. All products/ materials/resources listed, that is, full ingredient disclosure. (relates to C2C, PRP and WELL).	**Bill of Materials** (BoM) and **documents listed in 1.1**, depending on the level of completeness. BoM should include, for example: part description, parts per unit of product, materials, part weight, total weight and percentage of total weight. WELL explicitly links this to a "**digital or physical library**" open to the residents, in connection with category 4: Health & Well-being awareness.	–
1.5 BIO/TECHNO DEFINITION		
Materials defined as biological or technological ingredients (C2C)	**Identification in BoM** whether technical or biological cycle applies	-
1.6 EMISSION CONTROL (long term)		
Long term emission control (WELL, in overlap with C2C)	**Test results** of Volatile Organic Compounds (VOC) emissions from partitioning wall (components), using real-time data or environmental chambers. For threshold levels, both WELL and C2C refer to the California Department of Public Health (Latest standard method: v1.2) [68]	EN 16516 (VOC, SVOC and Very Volatile Aldehydes, including Formaldehyde)
1.7 EMISSION CONTROL (short term)		
Short term emission control regarding adhesives, sealants, paints, coatings (WELL, in overlap with C2C)	See 1.6	EN 16516 (VOC, SVOC and Very Volatile Aldehydes, including Formaldehyde)

TABLE 5.3 Synthesised set of criteria and assessment guidelines for Circ-Flex performance, based on C2C Certified™, WELL Certified™, and PRP®, including European Technical Approval Guidance (ETAG) reference [Source: Bob Geldermans].

Criteria	Assessment Guidelines	ETAG Reference
1.8 PROTECTIVE PRACTICES		
Ensure protective practices during repair, renovation, maintenance and disposal, linked to hazardous materials. (Adapted from WELL, in overlap with C2C and PRP)	**Test results** of hazardous substance release from partitioning materials during repair, (de)construction, maintenance and disposal activities.	–
2 MATERIAL REUTILISATION		
2.1 CYCLE DEFINITION		
Defined appropriate cycle. (C2C, in overlap with PRP)	**Indication of reutilisation route**, as either biological or technical nutrient, after first designated function. For example, added to the BoM. *Similar to 1.5*	–
2.2 CYCLE DESIGN		
Designed or manufactured for the cycle. (C2C, in overlap with PRP)	**Reutilisation score**, expressed in percentages of the homogenous materials concerning a) recycled content (RC) or rapidly renewable content (RRC) (<10 years) + b) recyclable content (R) or biodegradable content (B), in formula: $\frac{[(\%RC \text{ or } RRC)*1]+[(\%R \text{ or } B)*2]}{3} x100$	–
2.3 RECOVERY STRATEGY		
Defined management strategy for logistics and recovery systems. (C2C, in overlap with PRP)	**Nutrient management strategy**, concerning: reutilisation method; contextual conditions (e.g., disassembly); stakeholder communication method; value chain collaboration; timeline; budget; targets	–
2.4 RECOVERY & CYCLING		
Recovery and cycling in technical or biological metabolism. (C2C, in overlap with PRP)	**Collection and reutilisation** program **Actual reutilisation** data **Test results** in the case of uncertainties in biological cycle (e.g., testing how compostable materials are)	–
3 MOULD CONTROL		
3.1 MOISTURE		
(Delayed) moisture related problems (Adapted from WELL)	**Indication of moisture conditions** during implementation, including storage, documented by contractor.	EN 15026:2007-Aspects of Durability and Serviceability
	Mould susceptibility declarations (as part of material documents)	EN 12524-Hygrothermal properties

TABLE 5.3 Synthesised set of criteria and assessment guidelines for Circ-Flex performance, based on C2C Certified™, WELL Certified™, and PRP®, including European Technical Approval Guidance (ETAG) reference [Source: Bob Geldermans].

Criteria	Assessment Guidelines	ETAG Reference
4 HEALTH & WELL-BEING AWARENESS		
4.4 INFO & GUIDELINES		
Provide product information and guidelines and promote education to highlight the relationship between health & well-being and buildings or building components (Adapted from WELL)	**Documentation/professional narrative** concerning the components, including, for example, origin, implementation, use, reuse and disposal specifications. Accessibility to **educational materials/ digital or physical library** regarding health & well-being aspects associated with the components.	–
5 INTEGRATIVE DESIGN		
5.1 CO-DESIGN APPROACHES		
Facilitate co-design towards better buildings through interactions between stakeholders, including, for example, end-users, designers, investors, sub-contractors and suppliers, (Adapted from WELL)	**Apply feedback mechanisms** concerning the way in which product design, application and logistics evolve, following know-how, data loops and experience throughout the value chain.	–
6 PERCEIVED PERFORMANCE		
6.1 PERFORMANCE EVALUATION (post occupancy)		
Short and long-term performance-evaluations relating the component's functioning. Primarily aimed at the use stage but also anticipating construction and disposal. (Adapted from WELL)	Ongoing **data report mechanisms** in place, concerning the perceived performance of functions/components, following appropriate intervals, that is, recurrent surveying (or other instruments to collect end-user experiences). And the **infrastructure in place** to link these data to 5.1 (co-design approaches)	–
7 EMBODIED ENERGY AND CARBON		
7.1 EMBODIED ENERGY		
Quantification and qualification of total energy required for the whole-reverse-supply network in the value chain. (PRP and C2C)	**Energy balance (input/output) in Joules** and **GHG emissions in CO_2-eq.** per functional unit	–
8 SOCIAL FAIRNESS		
8.1 SOCIAL IMPACT SUPPLY CHAIN		
Potential for social issues throughout the (reverse) supply network in the value chain, for example, child labour, forced labour, excessive work time, provision of a living wage, worker health, safety and legal protection. (PRP, in overlap with C2C)	**Social performance declarations** from partners in the (reverse) supply chain, and/or **compliance with certification or standardisation schemes**, depending on level of completeness. *Regarding audits or certification, multiple program's may apply, such as Global Reporting Initiative, Social Accountability International or B Corps.*	–

C2C Certified™ developed an elaborate set of guidelines regarding problematic substances and threshold levels. Concerning Category 1 of Table 5.3, the C2C Certified™ “x-listed” classification is followed, adhering to the most ambitious level (Platinum). This includes, what C2C Certified™ refers to as, ‘banned’ list and ‘grey’ (lack of data) chemicals. Within WELL Certified™, many of those x-listed materials and chemicals are present as well, albeit distributed over multiple requirements (preconditions and optimisations), in function of its focus on in-use building performance. In most cases, WELL Certified™ refers to relevant external sources for specific standards and guidelines. PRP® does not work with precautionary lists but in providing a full account of all resources used, potentially problematic aspects, such as toxicity, will arise. In this respect, PRP® refers to external standards, such as the regulatory framework REACH of the European Chemical Agency [67]. Reutilisation criteria, Category 2 of Table 5.3, are derived from C2C Certified™. These largely overlap with the scope of PRP®. Categories 3, 4, 5 and 6 are adapted from WELL Certified™. Category 3, regarding mould control, inherently relates to PRP® as well, being inextricably linked to the quality of the item/material/resource. Moreover, the potential addition of (treatment) substances or the devaluation of quality due to mould will also need to be reported in the PRP® framework. Category 4 concerns the importance of awareness-creation regarding the relation between buildings and health, particularly aimed at residents. Category 5 addresses the notion of co-design towards better buildings by integrating feedback loops across the value chain. This category overlaps with PRP® in case modifications to the initial materialisation, on the level of item, material or resource, are concerned. Category 6 specifically zooms into the performance as perceived (and fed back) by the occupants. Lastly, in categories 7 and 8, PRP® is guiding, due to its whole-systems scope, integrating associated pre-use, use and post use processes. These two categories overlap with C2C Certified™.

5.5 Application of the Criteria to a Partitioning Product

5.5.1 Introduction

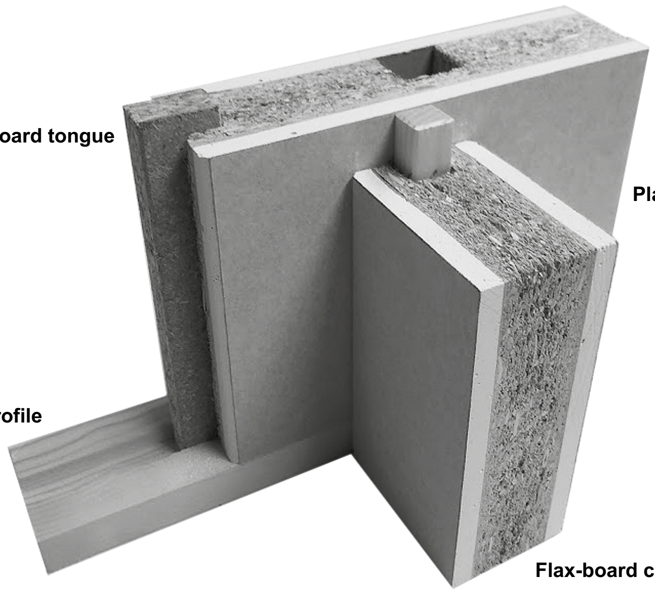

FIG. 5.4 Wall module with main components [Source: Bob Geldermans].

In this section, the criteria of Table 5.3 are applied to a state-of-the art indoor partitioning product by means of a quick-scan assessment. Through site visits and discussions with stakeholders, additional data were acquired on product properties, production processes, product implementation and waste treatment. The product in focus is a solid prefab wall module, used in basic partitioning schemes for commercial and residential purposes. The core of this module is flax-board. Flax is grown for the production of linen yarns. Flax fibres are primarily meant for the textile industry but are also used in insulation materials for the building industry and in the paper industry. The seed of the plant is used for the production of linseed oil. At the end of the chain, the remaining woody materials (stalk parts and roots) are used for the manufacturing of flax-boards. At the manufactory, cable-ducts are cut out and the flax-boards are bonded together with plasterboard, before being cut to standard-size modules. During assembly on site, chipboard elements (“tongues”) are utilised to keep the wall modules in place and timber (pinewood) studs are applied as ceiling and floor profiles (as well as posts). Furthermore, foam is placed in floor and ceiling cavities and MDF or Meranti is applied for skirting. The thickness of the total module is approximately 54 mm: 34 mm for the flax core and 2 × 10 mm plasterboard. Figure 5.4 is a sketch of the wall module and its main components.

5.5.2 Assessment of Product Performance

Virtual starting-point: for the renovation of a multi-family apartment block in the Netherlands, the owner (for example a housing corporation) aims to meet the residents’ desires for a reconfiguration of the spatial layout. For the assessment, only the new materialisation is taken into account, not the removal of any existing components. However, future change/removal is factored into the scope. A standard ‘fitness for use’ is assumed, following the European standard: the product complies with all requirements in that respect. Moreover, the manufacturer has a proactive stance with regard to the sustainability performance of their products. This resonates, amongst others, in the manufacturer's ambition to adhere to circularity and flexibility principles, both concerning material performance and-reverse-logistics. The product has a C2C® certification: Basic. Finishing layers (any type of coating) are not part of the core assessment but are expected to occur at least once during functional iterations.

The set of criteria and assessment guidelines introduced in the former sections (culminating in Table 5.3) form the backbone of this assessment. The product is explored and assessed following eight categories with eighteen features, applying both quantitative and qualitative elements. This concerns an explorative assessment to reveal if – and to what extent – the product complies with the given criteria and which stakeholders are or need to be involved. Where applicable, the functional unit is: 1 m^2 of partitioning wall. Concerning materials, the main focus is on: plasterboard, flax-board, chipboard and adhesives (bonding agent between flax-board and plasterboard). The anticipated cycle is from cradle to cradle: starting from extraction of resources and processing of the parts, to construction, use, dismantling and repurposing routes (in low or high-grade applications) whilst accounting for transport. Functional cycles for residential use are estimated to be on average 15–20 years but the product has a potential service life that is much longer. All stages of the supply-use-reuse iteration are taken into account as the product's operational model for assessment.

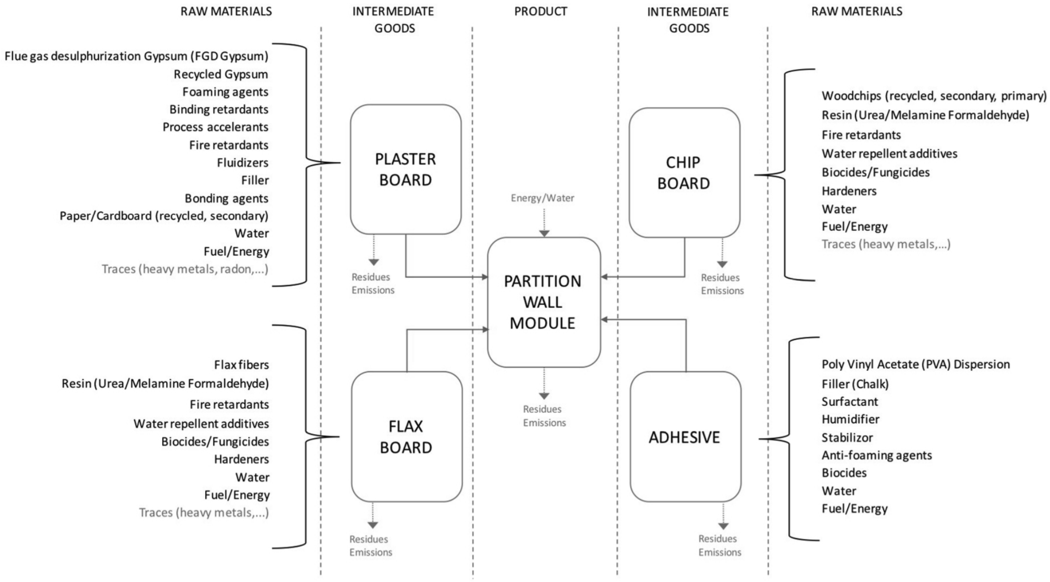

FIG. 5.5 From raw materials via intermediate goods to final product [Source: Bob Geldermans].

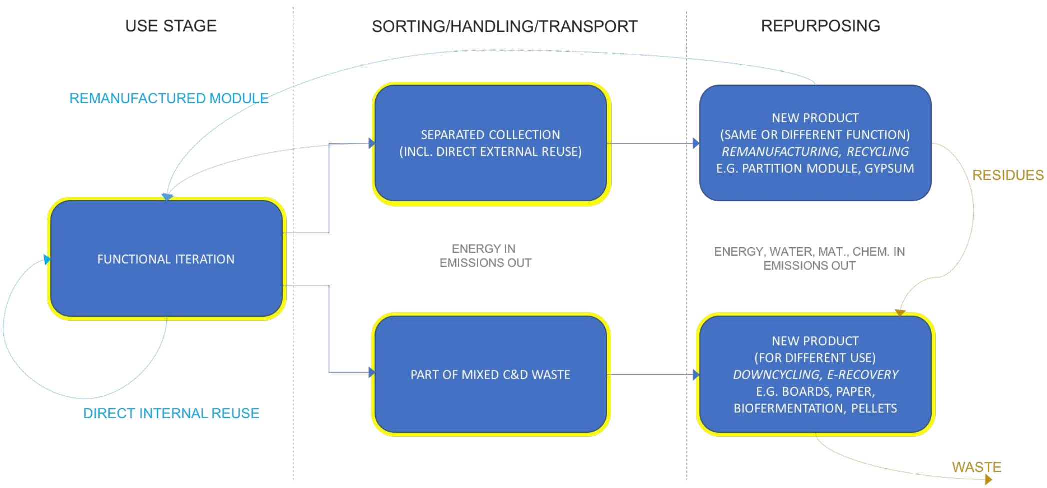

FIG. 5.6 From product in use to repurposing routes and final wasting. Most common processes highlighted yellow [Source Bob Geldermans].

Figure 5.5 visualises supply flows towards the final product. In the far left and right, a (non-exhaustive) list of the most probable raw materials and resources is given. This includes additives, water and energy, as well as trace elements that may be part of the intermediate goods, albeit in small quantities. The 'intermediate goods' domain includes residues that emerge in the manufacturing process. The same goes for the final product, which also requires the input of resources such as energy and water. Figure 5.6 displays end-of-service-life processes, including two scenarios: one towards down-cycling purposes, gradually reducing the value represented by the product and one towards higher-grade repurposing, maintaining or adding value. As yet, the former, low-grade, route is dominant practice in the Netherlands.

Table 5.4 lists observations and notes with regards to each of the 18 features. This is not so much a score card to pinpoint good and bad performance aspects but first and foremost a validation of the synthesised set of criteria. It objectively reflects on the status quo in relation to *Circ-Flex* ambitions focus on mental and physical health of residents during use.

TABLE 5.4 Test-case assessment of partitioning product following synthesised set of criteria [Source: Bob Geldermans].

Criteria	Partitioning Product Test-Case
1.1 X-LIST PRODUCT	The product is C2C Certified on a Basic level, which complies with this feature regarding banned list chemicals and related thresholds.
1.2 X-LIST PROCESSES	The product does not fully anticipate chemicals applied in associated processes. To comply with this feature, more detailed supplier declarations are required. Moreover, from a circularity perspective, it is important to anticipate finishing layers on the product. Such coatings are expected to occur several times during a residential use cycle.
1.3 X-LIST OPTIMISATION	The manufacturer is working on an optimisation strategy (as part of the C2C Certified trajectory) but this is not yet formalised.
1.4 LIST OF MATERIALS	The product is 100% characterised by its generic materials (as part of the Basic C2C certification) but not on a level of detail that is needed for the intended Bill of Materials.
1.5 BIO/TECHNO DEFINITION	The appropriate metabolism is identified for the product and its materials and/or chemicals (as part of the Basic C2C certification).
1.6 EMISSION CONTROL (long term)	This applies to the whole product. Apart from compliance with basic standards for intermediate goods through their suppliers, the manufacturer tests the final product with regard to VOC emissions. The product is labelled EU class E1 [69]. Own tests indicate 50% of that. This is below most standards, including that of the California Department of Public Health. However, details of those tests were not disclosed.
1.7 EMISSION CONTROL (short term)	See 1.6 with regard to adhesives. Sealants, paintings or coatings beyond the scope of this study but are defining factors in the overall performance of the partitioning product.
1.8 PROTECTIVE PRACTICES	Not Applicable
2.1 CYCLE DEFINITION	The product complies through appropriate certification (C2C Certified Basic)
2.2 CYCLE DESIGN	Product can be reused and down-cycled safely (depending on in-use interventions, such as coatings and finishing layers) but insufficient data to assess reutilisation score.

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TOC

TABLE 5.4 Test-case assessment of partitioning product following synthesised set of criteria [Source: Bob Geldermans].

Criteria	Partitioning Product Test-Case
2.3 RECOVERY STRATEGY	Certain aspects of the recovery strategy are met, such as potential reutilisation routes and Design for Disassembly basics. Other aspects are anticipated but at this moment in time not implemented, such as value chain collaboration, budget and targets in this direction.
2.4 RECOVERY & CYCLING	In line with point 2.3 above: an active recovery & cycling program is not in place.
3.1 MOISTURE	In case the manufacturer executes and controls the work (which is most of the time), moisture aspects before and during installation are according to the norm. The manufacturer provides guidelines for transport and storage. Guidelines regarding conditions on the construction site, such as relative humidity, are provided. Inspections during and after construction are beyond the manufacturer's scope. See 1.7 with regard to the comment on coatings.
4.1 INFO & GUIDELINES	The product comes with basic documents and professional narrative regarding the product, installation and use. There is little to no information on reuse and disposal stages that correspond with *Circ-Flex* ambitions. Furthermore, the manufacturer is not actively pursuing a role as educator with regard to the relationship between health, well-being and building components from the occupant's perspective.
5.1 CO-DESIGN APPROACHES	The manufacturer seeks interaction with supply-chain stakeholders, to align their product with demands of the market. This interaction increased, due to the C2C certification process, which required detailed input from suppliers. There is no structured communication strategy in place with regard to the input from, for example, residents and maintenance companies.
6.1 PERFORMANCE EVALUATION	The product's prefab process generally increases assembly and disassembly speed, whilst reducing potential nuisances on site. Beyond that, performance evaluations are not in place, in the sense of formal POE feedback loops.
7.1 EMBODIED ENERGY	In 2016, an LCA study was conducted (as part of the C2C certification process), including an inventory of thermal energy, electricity and transport fuels used for shipment of the intermediate goods and manufacturing of the product. These data can easily be converted to functional units, such as Joules and CO_2-eq. per m^2 of product. However, this LCA was not extended to the embodied energy associated with the intermediate goods (left and right of centre in Figure 5.5), nor does it take account of shipment to site, instalment, use & maintenance and repurposing steps.
8.1 SOCIAL IMPACT SUPPLY CHAIN	A streamlined self-audit has been conducted to assess protection of fundamental human rights, as part of the C2C certification trajectory (Basic). The basic C2C certification also includes the implementation of management procedures in case of any identified issues. Impact associated with the supply-chain is beyond the scope of C2C basic. However, the manufacturer complies with the global code of conduct (IWAY) enforced by one of their clients.

5.6 Discussion

In this section, I reflect on the overall research context (5.6.1), and briefly on each category of the proposed selection criteria (5.6.2), with particular attention for operational impact. Finally, specific results are discussed in relation to the test-case (5.6.3).

5.6.1 Standardisation and Assessment Context

In the Netherlands and the EU, the current regulatory framework does not yet address the circularity performance of products. Occupants health, on the other hand, is part of the scope, albeit with difficulties to keep up with market dynamics as well as societal and scientific developments, as discussed in Section 5.3. Current approval guidelines, such as the European Technical Approval Guideline, with which each EU member state has to comply, have limitations in that respect. The implementation of those guidelines differs greatly per member state and so does associated law-enforcement. Although regulations – and the harmonisation thereof – have improved the overall quality of construction works across Europe in the last decades, this has not led to inherently healthy buildings. Quality issues remain an issue in that respect. Poignant examples of poor indoor air conditions related to, for example, moisture, mould and formaldehyde problems, are still occurring throughout Europe, The Netherlands included [70]. Against this backdrop, an exploration was carried out into applicable assessment schemes with an explicit aim for occupant health and material circularity. It was found that three assessment schemes were particularly eligible with regard to aforementioned task. This is not to say that other schemes completely omit the mentioned aspects. On the contrary, many instruments on the market show thematic overlaps. However, end-user health and/or operational product performance is not commonly addressed, certainly not in an uncompromising manner. This led to the selection of C2C Certified™, WELL Certified™ and PRP®. These schemes provided a comprehensive framework in response to set task and form the basis for criteria and assessment guidelines to determine a product's performance relating to circularity, flexibility and user benefits. Other aspects, such as costs, are beyond the scope of this research.

5.6.2 Reflection on the Synthesised Criteria

The synthesised set of criteria, as outlined above in Table 5.3, comprises eight categories. The first category, ‘Material Health & Transparency,’ represents eight criteria that integrate all aspects deemed essential, starting from a thorough ‘material passport,’ up to the chemical level and with specific mention of problematic substances in product or associated processes. This is, although data-heavy and potentially data-sensitive, crucial in regard to the materialisation complexity we face in our built environment, as mentioned in Section 5.4. In the case of C2C Certified™, this is safeguarded only at the platinum level. The PRP® approach can be complementary in that respect. PRP® does not apply a point-based standardisation hierarchy but aims at one score: the circularity potential. This score has the ability to unambiguously reveal the compliance with (or deviation from) full circularity, as well as *where* in the value chain challenges reside (both relating resources and human rights). Woven into the PRP® approach is the intention to engage all key stakeholders in the value network, in order to effectively source data and create awareness. At this moment in time, one could expect barriers to emerge, relating to the availability and accessibility of data. This touches upon several interrelated issues, concerning, for example, material complexity and ingrained habits relating to decision-making processes, as addressed in Section 5.3.2. Next to that, a point-based scoring system is more familiar to most and the associated certificates are internalised in market mechanisms. However, such a code of conduct does not mean that circularity, as an inherently systemic phenomenon, is always facilitated: on the contrary, one could argue. As long as incentives lack to thoroughly relate individual operations to overarching systems performance, circularity will never take off. In that respect, creating awareness and engagement across the chain of custody is an essential step in the transition from linear to circular systems.

Category 1: Material Health & Transparency

The notions of progress and time are addressed by the inclusion of optimisation strategies and the anticipation of repair and maintenance cycles. Those aspects underscore the necessity to integrate learning loops and operational, short-cyclic, interventions associated with the product. C2C Certified™, with its focus on designers and manufacturers, emphasises learning loops for product optimisation, whereas WELL Certified™ has specific attention for interventions in the use-stage. The hazardous materials asbestos, lead and PCBs part of this WELL Certified™ feature will not be part of new C2C Certified™ products (according to the banned list, in alignment with the Living Building Challenge Red List [71]), and will thus not end up in the materialisation. However, this does not address other aspects that concern product-interventions in the use stage and their impact on health and/or circularity potential (this will be addressed under Category 4). Lastly, the criteria on long-term and short-term emission control, derived from WELL Certified™ in overlap with C2C Certified™, are explicitly distinguished, given their relevance for infill product performance and functional iterations. Such products can emit VOCs, either in the short run or over a longer period. It was stated in Section 5.3 that norms tend to focus on products rather than accumulated exposure. This underscores the urgency for more integrated approaches. The difficulty to address this in single product assessments reveals the necessity for stronger communication between scale levels and during multiple temporal intervals. In that respect, there is currently no attention for the question: how many qualified products can safely accumulate in relation to VOC emissions (and for how long), in a residential space?

Category 2: Material Reutilisation

The reutilisation of materials in cyclic models is addressed through defining and designing products and processes appropriately, as well as by achieving operational strategies and execution management. Especially the latter is thought to be important for bridging the gap between theory and practice. From that viewpoint, PRP® has developed its model for the enforcement of agreements between clients and suppliers, most notably concerning take-back models and reverse logistics. This proposition concerns legally binding contracts that might be challenging now for some organisations but could be instrumental in mobilising the market, and creating new potential for safeguarding material circulation in the future. What happens in the use stage, between supply and reverse supply, is decisive in this respect.

Category 3: Mould Control

Category 3 has been included to anticipate mould issues that can emerge over time as a result of product behaviour, either intrinsically or in relation to contextual conditions. This indicates, again, the overlap between product and building levels. The main concern is the role a product has in the possible creation of mould growth. This is usually related to moisture conditions but has also strong links with applied coatings. It can be expected that products themselves are in line with the required norms, which shifts the attention to the way products are transported, stored and treated. Key aspects include: storage off the floor and away from weather exposure; a dry and ventilated installation area; wicking prevention; and clear communication regarding wall finishing and treatment. Appropriate guidelines and agreements are thus required, as well as multiple inspections, taking account of the fact that it takes several days for mould and mildew to develop [72,73].

Category 4: Health & Well-being Awareness

The health & well-being information of products is a key aspect of extended stewardship, in which the use and reuse stages are internalised effectively. This criterion is specifically aimed at increasing the awareness of and feedback loops from building users regarding the relation between health, buildings and materials. The anticipation of interventions that affect the product quality is important, as it inevitably impacts the performance in terms of health, flexibility, and/or circularity. WELL Certified™ introduces a wider interpretation of health and well-being, from the viewpoint of happiness and sense-making, as addressed in Sections 5.3 and 5.4. Within the current criteria such perspectives are addressed implicitly, needing further elaboration.

Category 5: Integrative Design

Categories 5 and 6 have close ties with aspects of co-design and feedback loops. Category 5 hints at a specific part of the WELL Certified™ precondition termed 'Integrative Design.' Although WELL Certified™ concerns the whole building scale, the integration of stakeholders (such as owners, occupants, architects, engineers and managers) during the establishment of a project, is as relevant with regard to specific infill products. Particular emphasis is put on engaging those stakeholders that are usually kept out of the realisation process or those only concerned with fragments of it. This taps into the notion of interrelated (sub) systems that in unison define the quality of a whole building. This has clear links with factors such as diversity and change, as put forward in Section 5.3 but also with more straightforward aspects of the logical sequences in which construction takes place.

Category 6: Perceived Performance

Category 6 specifically addresses the need for increased monitoring of a product's and building's performance beyond energy efficiency and thermal comfort. This study points at aspects of materialisation, tying into health, well-being and flexibility potential. Post occupancy surveys can be appropriate tools for this task.

Categories 4, 5 and 6 unveil a challenge, relating to the interface between product and building scopes. For example, regarding the question how far a product supplier's responsibility stretches, beyond providing guidelines and professional narratives. What type of monitoring schemes are appropriate? And who coordinates

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alignment between the stakeholders? For the most part, this remains a grey zone. Knowing that Category 2 primarily hints at material recovery and reutilisation *after* not the influencing factors *during* a functional iteration, this question relates mainly to the realm of Categories 4, 5 and 6. Feedback loops and data-sharing between stakeholders could inform maintenance, repair, reuse and upgrade cycles. However, it does not say much about actual operational performance, defining and securing the required mechanisms at the right moment by the right stakeholder. Guidelines, contracts, (dynamic) bills of materials and software could be instrumental here, much in the way PRP® anticipates. In a PRP® trajectory, each intervention or mutation needs to be registered, be it on the entry level of Item, Material or Resource (see Section 5.4.3). The impact on health and circularity potential, relative to a baseline analysis, can thus be assessed in real-time. This requires consistent coordination efforts, most likely conducted by a housing or facility manager, in close conjunction with residents, suppliers and (maintenance) contractors. Although first initiatives in this direction have started, more experience is needed to build on, particularly regarding residential settings. It has to be seen which models and methods would succeed in Dutch housing. The building sector in the Netherlands is different from, for example, the Japanese one, where lifelong contractual relationships between stakeholders (such as housing suppliers, owners and users) are more common [9]. Further research in that field should, amongst others, deepen the link between business models from the supply side and value as perceived by the user. These considerations also touch upon the application of ICT in homes. Attention for smart technology and building-information-modelling is increasing but innovations have a long way to go, certainly concerning stakeholder-integration in the residential sector [74,75,76].

Category 7: Embodied Energy & Carbon, and Category 8: Social Fairness

Finally, embodied aspects resonate in Categories 7 and 8. This was not part of the core scope but I integrated these to address systemic relevance and threats of burden-shifting. Of course, many other embodied aspects would apply here as well. A key challenge is related to whole-systems-quantification regarding embodied energy and carbon: getting the functional unit and system boundaries right, agreeing upon appropriate cut-offs. This will come back briefly in reflection on the test-case.

5.6.3 Lessons from the Test-Case

The test-case was focused on a relatively straightforward infill product. Closer examination, however, paints a more complex picture. Tracing one product back to its intermediate goods and subsequent raw materials shows an exponential increase in applied resources. And that is not the end, nor beginning, of the line, as most of those resources originate elsewhere. Confidentiality issues, unknowns, as well as cultural barriers or ingrained habits emerge in this respect, as addressed in Section 5.3. The C2C certified™ scheme offers a system to deal with this, but it is not applicable to the basic certification level with which the given product complies. That said, a generic characterisation is already valuable, pinpointing potential weak spots with regard to health issues or *Circ-Flex* potential. In this case one can think of formaldehyde content and product composition. Regarding the former, the product complies with all relevant norms, as indicated in Section 5.6.2. In accordance with the regulatory framework, this does not take into consideration potential accumulated exposure. The latter aspect (product composition) relates to the fact that it concerns a composite product, in which the constituent materials together achieve new properties. Those properties reflect the core functional aspects: room dividing, robust, low-weight, cost-effective, modular and such. The product is not designed for circularity but is compatible with product and operational models that aim at longevity and short reuse cycles: the product could be reused multiple times in similar applications. The manufacturer mentions a predicted service life of 75 years but there is no evidence for this available yet. Whether or not reuse actually happens is currently beyond the scope of the manufacturer and depends greatly on what happens within this period. How is the product treated? What finishing layers or jointing products are used? This confirms the remark in Section 5.6.2 on the grey zone between the scopes of product and building performance. Also with regard to mould issues, the application of coatings are decisive factors. This needs to be internalised into a product's value model one way or another, in order to capitalise on it's circularity, flexibility and health potential. Finally, at the very end of its functional life, the product can be downcycled. Being a composite product makes it impossible to do so in a high-grade, renewable manner.

Concerning Categories 3–6, the product does not comply in the way that is intended in this research, or a lack of data inhibits a proper assessment. This is in line with the regulatory framework and organisational culture in the sector. Being engaged in the circular building discourse, however, the supplier explores ways for improvement. This greatly correlates with and depends on shared efforts between value chain partners, willing to play a pioneering role. At present, developments in this direction are in their infancy. Lastly, it could be advocated that the inherent benefits of the product's and the supplier’s agility are related with Categories 5 and 6, particularly in regard to the assembly and disassembly speed and a certain dimensional modularity flexibility.

Taking a brief look into the supply-chain reveals that the companies that provide intermediate goods are generally willing to think along with envisioned changes in the end-product's performance. However, they are bound by their own business models and internal processes. A peek into the world of gypsum, for example, immediately shows the complexity here. Gypsum can be recycled over and over again, only losing a fraction of its initial quality along the way. In the test-case product, recycled gypsum as well as flue gas desulphurisation (FGD) gypsum replace virgin, natural gypsum for 100%. FGD, coming from coal-fired power plants in Germany and the Netherlands, currently takes up 90% of the share. Coal-fired power plants are being gradually phased out between now and 2035. This necessitates the exploration of new sourcing options, unavoidably also leading to virgin gypsum, to be shipped in from locations farther away. This is but one example of interdependencies within a complex system, touching upon (embodied) energy and climate, as well as circularity considerations.

5.7 Conclusion

The current traction of Circular Building (CB) comes at a cost, namely that the market moves faster than science, leading to a lack of evidence-based knowledge and an overflow of interpretations and assessment methods. Understandably, most of those assessment methods narrow down the scope to manageable sizes, inherently simplifying the complexity. Among the aspects that are often under-represented in those methods are: actual performance on the product and operational level and the impact on and role of residents. This chapter took those two vantage points to explore the state of affairs and integrate criteria that better reflect the needs in this respect, specifically aimed at *Circ-Flex* infill products and health. This led to the prioritisation and synthesis of criteria from three different assessment schemes. The purpose of this exercise was not to compare existing tools but to synergise. It was shown that these schemes have overlapping and complementary features that, in unison, provide a solid basis for an integrated assessment of the circularity potential and health impact of infill products. In total, eight categories were defined, comprising eighteen criteria, that were tested on a non-bearing partitioning product. This test helped to validate the set of criteria, pinpointing specific areas of intervention to match the product's performance with *Circ-Flex* requirements.

The partitioning product of the test-case shows potential with regard to a transition from linear to circular practices, indicating ways for the market to advance. However, various aspects came to the foreground that do not comply with the *Circ-Flex* criteria. In fact, some of those aspects are found to substantially reduce the circularity potential of the comprised materials. This is because design and manufacturing are not aimed at circularity, and because operational mechanisms for circularity are not in place. New mind-sets are required in the supply chain to develop and implement appropriate design, manufacturing, and reutilisation strategies. Moreover, those strategies require alignment throughout the supply-chain (or rather: value network). For example, product suppliers need to internalise the use and reutilisation stage or have it outsourced to another party, such as a housing corporation or facility manager. Either way, it must become part of the client-supplier negotiation. This ties into material composition and health aspects much more than is currently the case. Detailed up to date material and product data are pre-conditional to unlock flexibility and circularity capacity. And potentially damaging emissions associated with building products are inextricably linked to this. Design, maintenance and upgrade cycles will thus get a different status in such a model and the role of the buildings' occupants will also change. Safeguarding a healthy interior over time, securing the circularity potential in the future, necessitates the reshuffling of value models and value chains, including the binding agreements and multi-criteria learning loops that feed them.

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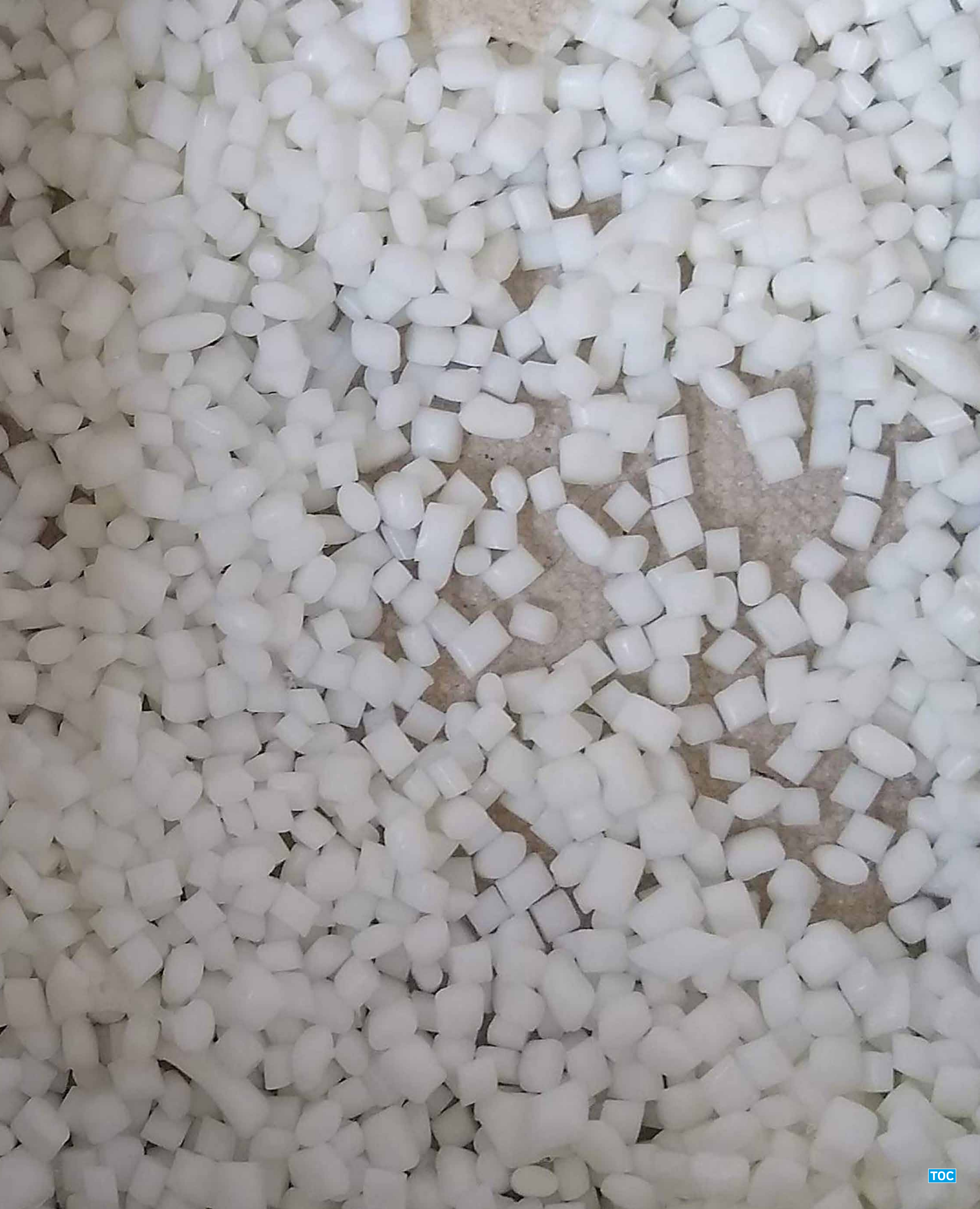

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6 Circular And Flexible Indoor Partitioning

A Design Conceptualisation of Innovative Materialisation and Value Chains

This chapter is adapted from a paper published on 26 August 2019 as: Geldermans, B., Tenpierik, M., Luscuere, P. Circular and Flexible Indoor Partitioning — A Design Conceptualisation of Innovative Materials and Value Chains. Journal Buildings 2019, 9(9), 194; https://doi.org/10.3390/buildings9090194

6.1 Introduction

In the preceding chapters, I argued that accommodative capacity of multi-family residential (or mixed functions) buildings depends on the level of flexibility in the individual home-unit infill. Although this notion has been entertained in architectural design and development, it has not delivered the anticipated large scale results, as outlined in Chapters 1 and 2 [1,2,3,4,5]. Also in the Netherlands, traditional housing design and building paradigms prevail, giving priority to generic, uniform, rather than specific, pluriform, design. The current traction in the Netherlands around the concept of circular building provides leverage for change in this respect. Flexibility of the housing unit, specifically relating the infill, can accommodate a bespoke and up-to-date indoor materialisation in line with user requirements. This, in turn, opens up to new product supply and service models that serve a circular economy,

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integrating design, manufacturing, use, operation, and reutilisation. In practice, however, integration of the latter three steps – use, operation and reutilisation – is insufficiently secured due to engrained technical and organisational patterns, leading to underachieving operational models, as argued in Chapter 5.

This chapter focuses on the materialisation and operation of partitioning wall components in relation to circular and flexible (*Circ-Flex*) performance, see Chapters 4 and 5. The hypothesis is twofold: (1) A stronger integration of materialisation and operation aspects is indispensable in establishing sustainable value-models, and (2) recent innovations concerning the reversibility of material connections will help disrupting the status-quo in this respect. I draw particular attention to natural fibre composites, reversible adhesives, and biodegradable insulation materials, all with inherent renewability potential. Innovations in this direction may lead to a broadening of the product range for partitioning configurations, anticipating healthy, circular, and flexible resource systems. The geographical context is the Netherlands, in particular the Amsterdam metropolitan area, based on its articulated ambitions regarding circular economy implementation, and the associated policies deployed [6].

The structure of this chapter is as follows. First, a background sketch is provided with regard to the notion of time, change, and material circularity in design and planning. Second, the housing challenge in the Amsterdam metropolitan area is described, as well as the way in which the concept of circularity has found its way into the municipal and regional policies. Next, the design conceptualisation stage is explained, including two methods and tools: *Circ-Flex* assessment, and Activity-based Spatial Material Flow analysis. Subsequently, results of the conceptualisation stage are presented regarding materialisation and operation, culminating in a circular–flexible partitioning configuration based on side-panel and insulation innovations. Finally, the results are reflected upon from technical and organisational vantage points. Figure 6.1 visualises the methodological structure.

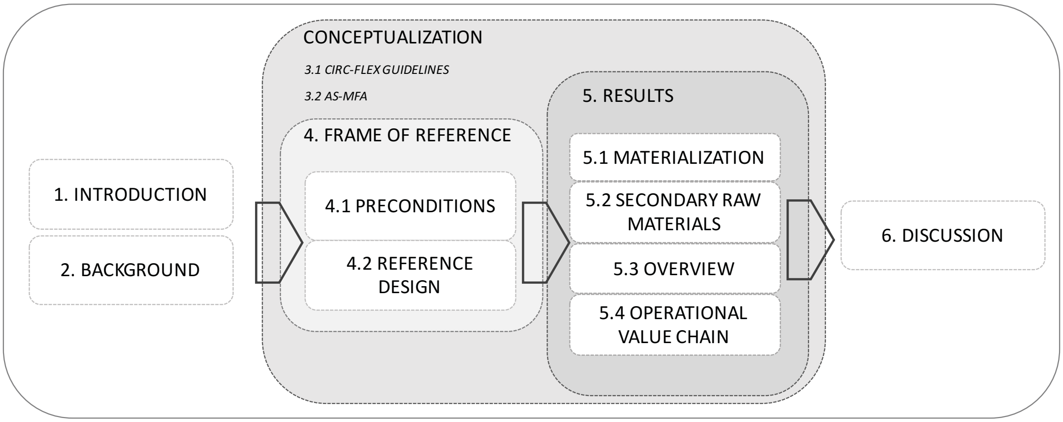

FIG. 6.1 Methodological structure of the research [Source: Bob Geldermans].

6.2 Background

6.2.1 Time, Change, and Circularity

The notion of time in architectural design and planning in relation to quality and change, is captured well by the 'timeless way of building,' put forward by Christopher Alexander in the 1970s [7]. Alexander's 'timeless way' accommodates a quality that is essential to life and living, but can only be described by its surrounding and constituent characteristics. Thus, Alexander describes it as a 'quality without a name' [7]. A similar quality can be detected in the concept of Open Building [8]. As outlined earlier in this dissertation, John Habraken distinguished the structural support of a building from the non-structural infill. The latter is the domain of the end-user, and should be treated accordingly in associated design and decision-making. The crux is that evolving individual patterns of living thrive when optimally supported by the environment in which they take place. People attach meaning to objects and environments through interactions that occur within spaces, and those meanings affect perceptions and subsequent interactions [9–14]. The physical space can thus be seen as a backdrop for changing activities and interrelations.

The concept of buildings being assemblies of dynamic layers with diverging functional and temporal identities has also been elaborated by Stewart Brand, who introduced six shearing layers: Site, structure, skin, services, space plan, and stuff, see Chapter 1 [15]. Alexander, Habraken and Brand all touch upon the awareness that the built environment is inextricably part of larger systems, comprised of countless interrelated processes that operate in complex configurations. One aspect of this complexity, analogous with nature, is that processes and their associated material manifestations have different timescales with little or no exchange (of energy/mass/information) between them [16]. Translated to building design, this implies that 'faster layers' (shorter material turnovers) are not obstructed by slower ones (longer material turnovers). An important theoretical framework supporting this notion is Design for Disassembly (DfD). DfD allows for easy modifications of spatial typologies and disassembly of building parts [17,18]. DfD thus facilitates future change, as well as the recovery of building parts on various levels: whole buildings, sub-systems, building components, and materials [19,20]. DfD is thus a precondition – and accelerator – of a circular economy in relation to construction and planning [21,22,23].

6.2.2 The Amsterdam Context

The Amsterdam metropolitan area (AMA) has high ambitions with regard to shifting from a linear to a circular society [6,24,25]. Simultaneously, there are other challenges with regard to the built environment in the AMA. The housing demand faces a steep increase. Roughly 200,000 new housing units should be built in the AMA by 2040, and at the same time, vacant office spaces will be transformed into spaces for residential or mixed functions. On top of that, a large share of the existing building stock is not up to standard with regard to housing quality and energetic performance. This necessitates huge renovation efforts, not least by the housing associations that own about 40–45% of the stock [26]. The AMA also deals with demographic changes, that resonate in the housing requirements; for example, with regard to an ageing population and increase in single households [27,28]. Such developments underscore the notion that the building stock, new as well as renovated or transformed, needs to accommodate for changing functions and lifestyles. The housing challenge in the AMA is an opportunity to translate ambitions regarding circularity and flexibility into practice.

Within the AMA, multiple initiatives are and have been taking place in anticipation of the shift from linear to circular. For example, the municipality of Amsterdam developed the Circular Innovation Program to accelerate insights in the transition towards a circular economy [29]. Several key value chains were pinpointed as high-potential, with special attention for the construction and the biomass value chains [24,29]. In an evaluation of the Circular Innovation Program, it was observed that the high-value reuse of building materials is hindered by business-as-usual approaches merely aimed at linear optimisation, and that current value chains are thus closed in a low-value manner [30]. Furthermore, the need was identified to deploy a more integrated approach to logistics, land use, spatial planning, financing, and regulations in order to achieve a successful upscaling of value chains [25,30]. As such, Amsterdam and its metropolitan area give shape to its ambition to be a global leader, aiming to prove that the circular economy is a realistic and viable concept [31].

6.3 Conceptualisation, Methods, and Tools

In this section, two methods and tools are introduced that are applied within the conceptualisation stage. First, in Section 6.3.1, *Circ-Flex* assessment guidelines are introduced, which inform the design preconditions. Next, in Section 6.3.2, a method is presented to track waste and secondary raw material flows at a local scale: The Activity-based Spatial Material Flow Analysis. The conceptualisation stage consists of three clusters. First, design preconditions are introduced and the frame of reference is provided. Next, regular materialisation and operation pathways are analysed. This builds up to a specific circular and flexible non-bearing partitioning configuration, which is described in the last step.

6.3.1 Circ-Flex Assessment

Circ-Flex criteria and assessment guidelines were determined by me with the aim to establish a more integrated and inclusive approach to the transition from linear to circular built environments, tying in with recent calls for a more comprehensive evidence-base to better inform policy, in the light of the interrelated Sustainable Development Goals [32]. Circ-Flex can be understood as a systems approach rooted in the synergetic liaison between circular and flexible characteristics, as explained in detail in the previous chapters. In Chapters 4 and 5, I coupled those characteristics to issues of end-user health and well-being, in response to the gaps that exist in research and

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practice concerning this linkage. After an exploration of multiple assessment methods and frameworks, I derived an elaborated set of *Circ-Flex* criteria and assessment guidelines from three schemes in particular: Cradle to Cradle™ Certified, WELL™ Certified, and Pre-Returnable Procurement®. Overlapping and complementary features of those schemes provided the basis for an integrated assessment of *Circ-Flex* potential and residential health impact of infill products. One of the main findings was related to what I referred to as "orphan operational processes" i.e., those processes that are likely to play a decisive role in determining the *Circ-Flex* potential, but which continue independently from any 'parental links' and become blind spots in assessment schemes.

Circ-Flex requires accurate monitoring in order to anticipate changes over time, whilst becoming more than a theoretical possibility. This means that appropriate measures need to be taken at the right moment in time by the right stakeholder, instrumentalising, amongst others, design, contracting, (dynamic) resource passports, and software. Table 6.1 repeats *Circ-Flex* assessment guidelines as synthesised in Chapter 5, excluding the additional embodied-impact categories concerning social fairness, and embodied energy and carbon. In this chapter, the accent is on the first two categories of Table 6.1, albeit in anticipation of the other four.

TABLE 6.1 Summary of Circ-Flex criteria, excluding embodied impacts [Source: Bob Geldermans]

Category	Summary of criteria
Material Health & Transparency	X-listed chemicals in raw materials/product or process, following the Cradle to Cradle® Certification Standard; Complete characterisation of applied (raw) materials; Materials defined as biological or technological ingredients; Short term and long-term emission control regarding potentially damaging offset of chemicals; Protective practices in repair/ maintenance/disposal, linked to hazardous materials.
Material Reutilisation	Defined appropriate cycle/reutilisation route (biological or technological); Designed for the cycle, following a reutilisation score expressed in percentages of recycled content, rapidly renewable content, recyclable content, and/or biodegradable content; Management strategy for logistics and recovery pathways; Collection and reutilisation program.
Mould control	Anticipation of (delayed) moisture related issues, in relation to operational conditions.
Health & Well-being Awareness	Provision of information and guidelines throughout the whole value network, highlighting the relationship between health & well-being and buildings/building components.
Integrative Design	Facilitation of stakeholder co-creation towards continuous improvement.
Perceived Performance	Short and long-term performance-evaluations relating to the component's functioning. Primarily aimed at the use stage but also anticipating construction and disposal.

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6.3.2 Activity-based Spatial Material Flow Analysis

Material flow analysis (MFA), as an analytical tool, is closely linked to the fields of industrial ecology and urban metabolism. Both fields of science depart from the realisation that the ways and rates in which urban territories mobilise, consume, and transform resources, are not sustainable, nor is the resulting waste and pollution [33–36]. Recently, there have been initiatives to enrich the scope of MFA, providing more grip on the inner workings of analysed systems. Those inner workings include the role of key players and processes, as well as the impact on territorial quality [37,38]. This helps decision makers to establish integrated strategies for the shift from linear to circular urban development [37,39]. The Activity-based Spatial MFA (AS-MFA) is a novel approach to help identify site-specific leverage points for eco-innovative solutions [39]. AS-MFA has been developed within the framework of the EU Horizon 2020 research project 'Resource management in Peri-urban Areas' (REPAiR), as part of work package 3 ('Developing and Implementing Territorial Metabolism based Representation and Process Models'), which I coordinated. The aim of AS-MFA is to identify and map specific economic activities relating to material flows and stocks from waste production in cities' sub-systems, as well as the involved actors and their interrelations. In doing so, AS-MFA connects material, spatial, and social analyses, in anticipation of both lifecycle-based sustainability impacts, and circular solution routes, as sought by public and private stakeholders in the six European case-study areas (Amsterdam, Hamburg, Napels, Pécs, Łódź, and Ghent) [39]. The method follows a six-step iteration: (1) Determination of material scope; (2) Definition of the associated supply chain; (3) Selection of geographic and spatial scales; (4) Definition of case-specific value chain; (5) Modelling of the mass flows; (6) Mapping and visualisation of the results. With regard to data, AS-MFA adheres to EU-wide classification systems, as well as national and local sources. For the Amsterdam case-study, the AS-MFA was applied to construction and demolition waste (CDW), and food waste. Building materials currently 'in stock, locked inside the built fabric,' were included in the anticipation of future material-release during renovation or demolition stages. Figure 6.2 is an example of AS-MFA results, generated through a digital tool, developed as part of the REPAiR project. In the background, the contours of the Netherlands can be discerned, with the North Sea coastline on the left. The lines signify various categories of CDW flowing from source (AMA) to destination (AMA and beyond), from where they are further processed.

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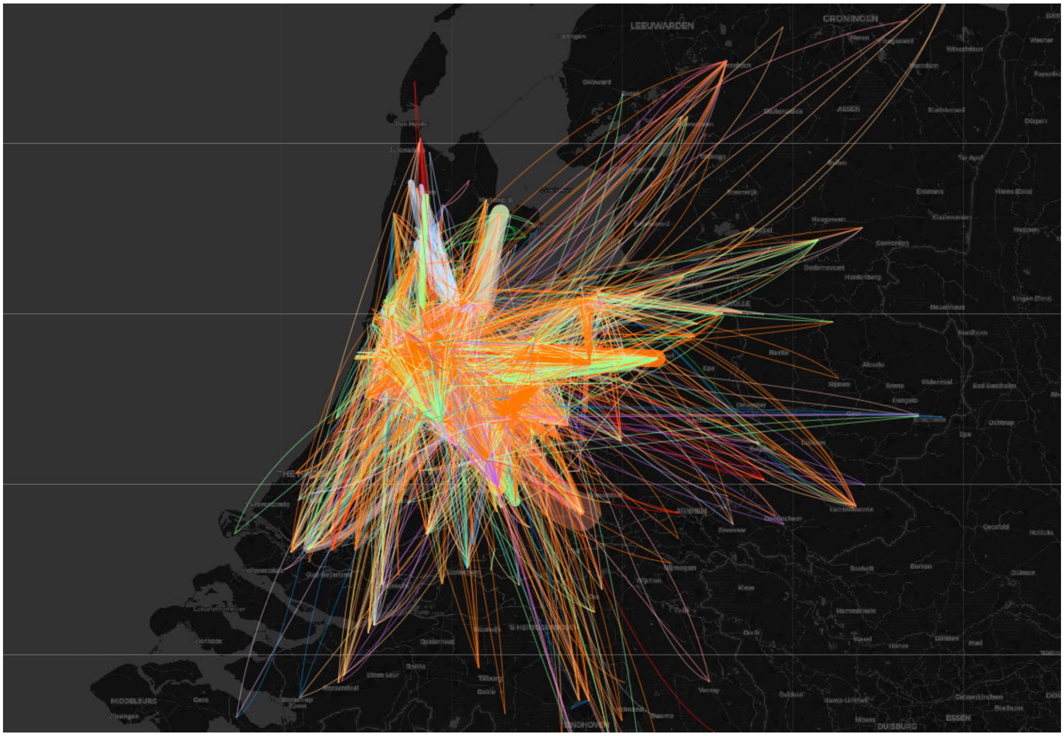

FIG. 6.2 Example of an Activity-based Spatial Material Flow Analysis (AS-MFA) result, concerning construction and demolition waste (CDW) originating from the Amsterdam metropolitan area (AMA), in tons/year, from origin (disposal location) to destination (storage) [Map generated with the GDSE software (REPAiR project)]

The tool is open source and can be accessed via the link: https://gdse.h2020repair.bk.tudelft.nl. The full AS-MFA methodology is described in the publication REPAiR D3.3: Process model for the two pilot cases [39].

6.4 Design Preconditions and Frame of Reference

6.4.1 Design Preconditions

In this section, preconditions are formulated. The starting point is the assumption that a critical level of flexibility is accommodated by the super-structural design of a multi-family property. The residents of each individual housing unit are free to define the whole infill layout, and thus also the type and location of room dividing partition walls. In order to anticipate change, the partition walls should not obstruct any potential future intervention, be it due to infill rearrangements, maintenance, repair, replacement, or upgrades. The circularity of associated parts (building components, materials, and raw materials) needs to be respected at all times. Those parts cannot thus be seen in isolation but always in relation to provenance and destination, underscoring the relevance of whole value chains and the inherent distribution of control. The design brief takes a user-centred approach, adhering to healthy building and renovation concepts that allow for a high level of flexibility regarding the space layout, whilst striving for high circularity potential of the associated materials.
The focus is on a non-bearing partition wall. Below, preconditions are listed that integrate intrinsic properties of the partitioning part and relational properties, with regard to user experience, physical context, and value chain performance:

1. The partitioning wall unlocks flexibility-capacity, through ease of assembly, disassembly, reassembly, and reutilisation;
2. The partitioning wall unlocks circularity capacity, through the ease of maintenance, reuse, redistribution, remanufacturing, recycling, and/or facilitating biological cycles;
3. The partitioning wall unlocks user capacity, by an inclusive approach that takes account of the willingness to engage, freedom of choice, and the health and well-being of end-users;
4. The partitioning wall supports coordination between subsystems, particularly in regard to installations and electric or data provisions;
5. The partitioning wall accommodates multiple duty ratings.

All preconditions originate in *Circ-Flex* criteria and assessment guidelines, although the first three preconditions are more explicitly addressed than the last two. These latter two, however, represent aspects that are no less relevant for the conceptualisation exercise. Precondition 4 highlights the fact that partitions 'communicate' with adjacent parts, such as doors and ceilings, as well as mechanical, electric, plumbing (MEP), and information and communication technology (ICT) infrastructure. Precondition 5 is based on the level of duty the partition should be able to support, in case present or new-users and/or functions require a different performance profile, for example, when compartments change from a domestic duty to office functions. Although the options are virtually limitless, and heavier duties could be imagined with regard to the required performance, a typical 'medium duty' is assumed, compatible with categories A and B of the Eurocode "Action on Structures" [40,41]. This resonates in, amongst others, fire, thermal, and robustness performance. Precondition 5 implies a certain level of product-familiarity: neutral enough to withstand forces of change, both from the perspective of users and building owners.

6.4.2 Frame of Reference

The design conceptualisation departs from familiar examples of residential floor to ceiling wall systems that are easy to assemble, disassemble, and re-assemble, but robust enough to function in a (semi-)fixed setting. In the Dutch context, two primary partitioning variants apply in this respect: (a) a configuration based on homogeneous or heterogeneous solid wall modules, in which framework, insulation and cladding are incorporated, and (b) a hollow variant based on a studwork with separate side-panels and insulation. In the latter configuration, the framework is comprised of either timber or metal studs. Eventual finishing layers are not part of the conceptualisation, even though these may have a strong impact on circularity, flexibility, and health performance. This will be addressed in the discussion section. Figure 6.3 displays, on the left, a solid partitioning wall configuration, and, on the right, its hollow counterpart (in the metal stud variety).

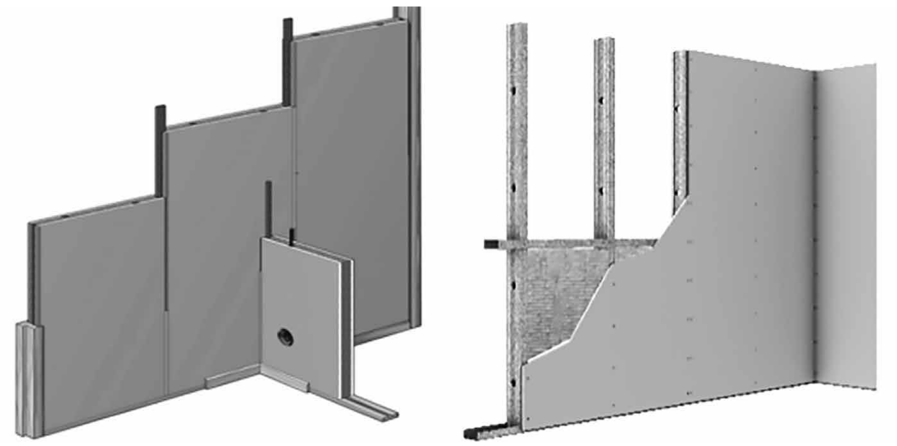

FIG. 6.3 Solid partitioning wall configuration (left) and its hollow-wall counterpart (right) [Source: Faay/Emeralheights]

Considerations concerning changing requirements for cables and wires have been addressed in the past, and solutions have found their way to the market. Infill Systems BV (with a branch in the Netherlands and the United States of America), for example, has patented multiple variations relating to “invisibly arranging cabling in an indoor space defined wholly or partially by non-load-bearing partition walls” [42, page 2]. Those patents are rooted in the notion of Open Building and the flexibility of the space layout, as addressed in Section 6.2.1, with a long history of research and implementation [43–49]. Moreover, several manufacturers of partitioning products have integrated those notions into their products. An example is the ‘Cable Stud,’ by the aforementioned Infill Systems BV, especially developed for hollow metal stud wall configurations that anticipate optimal freedom for positioning of installations and associated infrastructure. Variations on this innovation can be found in, amongst others, the Knauf BoWall system, and the Faay KBL system. The latter is developed for a solid-wall system. In contrast to hollow-wall systems, solid-walls reduce flexibility with regard to the placement of, for example, MEP and ICT provisions.

Regarding the materialisation of hollow-wall partitioning, the main roles are claimed by the boards used for side-panelling and the insulation material within the cavity between two boards. A primary product with regard to side-panelling is gypsum board, which is widely used for partitions [50]. Gypsum boards are an example of materials that can function in circular models, consisting primarily of recyclable calcium sulfate dihydrate ($CaSO4 \cdot 2H2O$). Although recycling rates are still relatively low on a European scale, the Netherlands shows increasingly high scores, induced by more stringent regulations that prevent transboundary landfilling [51]. Yet, an orchestrated effort is still required to fully capitalise on the recycling potential of gypsum-based waste. A recent study into the benefits of deconstruction (and segregated disposal) versus demolition (and disposal in mixed waste) showed that the latter is significantly more expensive [50].

A small percentage of the weight of the gypsum board product (usually 1%–5% for a basic board, but more if specific properties are required) consists of additives, such as binding agents, process accelerants and retardants, fillers, reinforcement fibres, fire retardants, and foaming agents [52]. Those additives are not regenerated to their initial quality, and become an impurity in the gypsum-recycling process. Moreover, other impurities may accumulate in the secondary gypsum flow along the way, adding up to about 10% of impurities in total. Although most substances can safely be integrated in the production processes, a certain level of gypsum-purity is required [53]. This necessitates the addition of purer gypsum. Gypsum recycling is thus essentially downcycling.

Flue gas desulphurisation (FGD) gypsum is currently the main raw material in gypsum boards for the Dutch market [54]. In light of the imminent phase-out of coal-fired power-plants as the primary source of FGD gypsum, other sources need to be explored, apart from increasing the share of recycled gypsum [54]. Most likely, this will lead to natural mines in, for example, Morocco, Spain, or France. Another source would be so-called Phosphogypsum, formed as by-product in fertiliser production. This raw material, however, is controversial due to its (weak) radioactivity, and is currently not broadly accepted as a safe alternative [55].

Concerning insulation materials, mineral wool (or man-made vitreous fibres: MMVFs) is and has been widely applied in Dutch construction. In current demolition flows, rock wool is more common than glass wool, as the latter entered the market later [56]. There are reported health threats associated with mineral wool, in particular in manufacturing, construction, and deconstruction or demolition stages, but exposure may also occur during do-it-yourself home remodelling activities [57]. As yet, there is no substantial evidence regarding the human toxicology of mineral wool. Certain MMVFs have been classified as carcinogenic in the past, by the World Health Organisation. However, this classification was withdrawn after the manufacturing industry altered the composition of their product [58]. Currently, multiple sources report the status: 'Reasonably anticipated to be human carcinogenic' for glass wool [59,60]. In the Netherlands, there are several facilities that recycle mineral wool at a high-grade. This requires appropriate disposal and logistical management, which is not widely applied yet, neither in the Netherlands nor in Europe as a whole [61–63]. Although nowadays not as widely used as their mineral counterpart, cellulose wool has been applied in partitionings' constituents for a long time, whilst becoming increasingly sophisticated [64]. Not many data are available with regard to whole lifecycle performance of contemporary cellulose materials, but LCA-based studies detect advantages and disadvantages regarding the environmental performance for cellulose insulation products, such as paper wool [64–66]. From the viewpoint of flexibility and circularity, uncertainties regarding the end-of-life stage are prominent obstacles, whereas human and environmental health issues are related to dust and additives [64–66]. A Dutch manufacturer of recycled paper insulation products (Everuse®), has tackled the end-of-life issue to some extent, by retaining ownership and taking back the products after an agreed functional life [67]. The issue relating to additives, however, remains unsolved.

6.5 Results: Materialisation and Operation Analysis

In this section, components of hollow non-bearing partitions are presented, in line with the design preconditions set out above. The primary vantage points are related to materialisation and operation. First, the materialisation of side-panels and insulation is described, with an accent on specific – bio-based – innovations. Next, local secondary material flows are addressed, in relation to raw material sourcing. Subsequently, a materialisation overview is provided, focusing on two variants of side-panel and insulation products for hollow-wall partitioning. This overview includes a range of properties, such as material composition, product and material origin, recycling potential, and technical specifications. In the final subsection, the operational value chain aspects of two specific materials and products are described.

6.5.1 Materialisation

Distinguishing multiple material levels (from raw materials to building components) is required for determining circularity and flexibility potential, as well as the distribution of control in the value chain. Several materials and products are explored, aimed at proven technologies and new innovations, and based on the availability of data. The starting points for these explorations are two databases in particular: The Cradle to Cradle® Products Innovation Institute, and the Materials Passport Platform (prototype) [68,69]. These sources are considered to be most reliable with regard to conscientious adherence to the given preconditions and underlying assessment guidelines. Additional data were sourced from product suppliers. Linked to inherent renewability potential, the scope was subsequently narrowed down to focus predominantly – but not exclusively – on bio-based products, both for side-panels and insulation.

Side-panels

Natural fibre composites (NFCs) are engineered products that comprise organic fibres in either a lignin and hemicellulose matrix (intrinsic part of woody materials), or a combination with synthetic or bio-based resins. Engineered fibre boards can provide a cheaper alternative, with more uniform properties than wood [70]. From my angle, products and production techniques that lead to composites with irreversible-thermosetting-bonds between raw materials are problematic. This is valid for most NFCs currently used in interior partitioning functions. Besides the irreversibility, binding substances are often based on volatile organic compounds, such as formaldehyde, potentially leading to harmful emissions over time [71]. Regardless of the enhancements in the last decade, influenced by an increasing awareness of industry and regulatory frameworks regarding potential health effects, those characteristics are not compatible with the *Circ-Flex* ambition of this chapter. Even when theoretically renewable bio-based binding agents are applied successfully, irreversibility remains an issue. What is more, the environmental and social impacts of raw materials for those alternative glues (often wheat or corn-based) are still up for debate [72,73]. Processes related to those innovations are rather opaque. Sustainable land use, natural biosphere protection, and food-competition, amongst others, are issues that require more elaboration [72]. Important progress is made in the industry, with regard to sustainability performance, specifically concerning recycled and recyclable content [74]. When shredded after one or more service lives, fibres can be used in new boards with little loss of quality. This extends the life significantly, but is not circular on a raw material level: Neither binding agents nor fibres are regenerated to a quality-profile that is similar to or higher than their initial states.

An alternative for wood-based panels that recently emerged on the market, and that tackles the aforementioned issues, is based on the conversion of cellulose fibres with pressure and heat. Following this technology, a product was introduced by Noble Environmental Technologies, referred to as ECOR. ECOR (currently holding a Cradle-to-Cradle® Silver certificate) is based on a 'platform technology', allowing for many different types of fibres as raw materials, whilst ‘upcycling’ low/no value residues to a high value product [75]. It is made in single 2.5 mm (FlatCOR) and

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multiply woodpanels, as well as three dimensional assemblies with a honeycomb core, and can be applied for non-bearing indoor partitions, amongst others [76]. As a raw panel, ECOR is free of additives. However, in many building applications some form of treatment is required, e.g. for resistance against fire, moisture, or biological decay. Although ecologically sound alternatives for potentially damaging chemicals are often available, implementation takes time, due to the heavy engagement that is required from material manufacturers and the chemical industry [77]. An example is the Molecular Heat Eater® (MHE) technology, which concerns a non-toxic, biodegradable flame retardant technology based on food-grade chemicals, that functions in multiple ways to slow or extinguish a fire [78]. Raw materials can be sourced from organic residues, local to the production facility, such as agricultural, horticultural, and food waste [79]. ECOR has recently teamed up with the company DSM-Niaga, focusing on a reversible adhesive technology. ECOR and DSM-Niaga developed a laminated panel that can be brought back to its separate parts by "un-clicking" the polyester adhesive. Subsequently, the adhesive can be recycled, as can the individual ECOR panels. This innovation, referred to as NEP (Niaga ECOR Panel), is currently aimed at the furniture domain, but indoor building applications are explored. Being at a Technology Readiness Level of 6–7, the innovation still needs to be demonstrated in an operational environment. In concept, however, the technology could work well for indoor partitioning. Given that adhesives and binders are primary concerns for *Circ-Flex* applications, the disruptive potential of NEP is significant [80,81].

Figure 6.4 shows a graphic representation of the NEP innovation, and examples of NEP products.

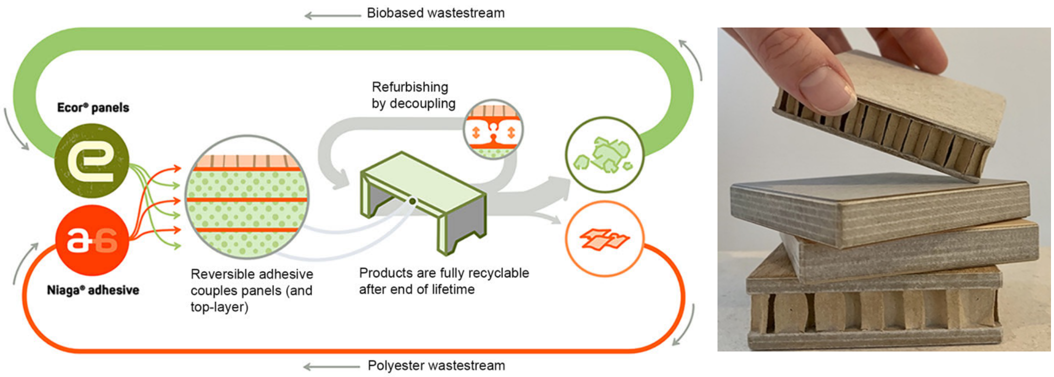

FIG. 6.4 Niaga ECOR Panel innovation [Source: DSM-Niaga and ECOR]

Insulation

Acoustic and thermal performance are important requirements for the partition, enhanced by an insulating part of the wall system. When focusing on insulation materials for a hollow-wall system, and taking account of flexibility, circularity and health, two main categories can be distinguished: synthetic and organic core materials. An example of the former is Calostat®, a thermal insulation board based on silicon dioxide, that renders it incombustible. Although not many data are readily available regarding this product, it performs very well on the Cradle to Cradle® product scorecard, with 'Gold' scores for four out of five categories, and 'Platinum' (the highest score) for Material Health [82]. As such, it outperforms other mineral insulation products. Flax, hemp, cellulose, and seaweed based insulation products are examples of the organic variety [83,84]. Enhancing specific properties, such as fireproofing, necessitates the use of additives, which impacts the associated barriers in reutilisation pathways. In that respect, the ecological fire-retardant mentioned in the preceding paragraph is no less applicable to these insulation materials. An innovation that has received increasing attention over the last decade concerns a type of bio-composite that is self-growing, renewable, and can be locally produced [85]. This bio-composite comprises a substrate that is inoculated and bound together by fungal mycelium; i.e. the filamentous "root" structure of fungi. The substrate can consist of organic fibres; for example, agricultural by-products, such as switchgrass, flax shives, or hemp [86]. Mycelium is said to have superior intrinsic fire-retardant characteristics compared to many other insulation products [87,88]. Studies into its functional performance as insulation materials are limited, and the results vary, depending on fungal species and fibre substrate. Therefore, more tests, and consistent testing methods, are required before solid claims can be made [89,90]. However, the outlook is promising regarding intrinsic fire retarding, thermal, and acoustic properties, and excellent life-cycle performance: multiple locally sourced feedstocks can be applied, energy requirements are low, and at the end of its service-life, mycelium-based material is fully biodegradable [89]. It is estimated that, in light of the steady progress, the material will soon be cost competitive as well [87,91]. Figure 6.5 shows a detail of a mycelium-fibre insulation panel.

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FIG. 6.5 Mycelium-fibre insulation panel [Source: Bob Geldermans]

6.5.2 Secondary Raw Materials and Waste

The renewability of (raw) materials is an essential aspect of *Circ-Flex* performance. In this section, waste and potential secondary raw materials associated with the AMA are addressed, following the AS-MFA method. This links to both biological and technical cycles, whilst necessitating a more advanced stance towards the secondary material market, in order to avoid waste flows (by adhering to renewable models) or apply them as feedstock for new materials. The AS-MFA tool helps to identify secondary flows, as a precursor for both those aspects. Figure 6.6 shows, as an example, the wood waste stream in the AMA, associated with the year 2016. In this figure, the actors (represented by circles and numbers) are linked to activity groups, following the level-1 categorisation of the Nomenclature des Activités économiques dans la Communauté Européenne (NACE) [92]. The lines, with widths relative to volume, represent wood that is disposed of as a waste stream per activity group, clustered by geographical location, as well as its treatment location. This concerns a flow of roughly 15 kton in the year 2016. Secondary wood with a high enough level of purity (excluding, for example, wood in mixed waste) that currently ends up in low-grade linear pathways, such as incineration, might be an appropriate source of fibres for *Circ-Flex* partitioning configurations. About half of the flows in Figure 6.6, approximately 7.5 kton, is currently incinerated [93]. AS-MFA also provides a grasp of materials currently locked inside the built stock. For wood, this is estimated to be approximately 9,000 kton. AS-MFA can be paired with other territorial ‘layers’ to identify local/regional areas that can play a role in the value chain. For example, by exploiting degraded land, under-used fields, or urban territories in transition [94]. Such territories can be applied as temporary or permanent production areas, locations for processing facilities, and/or the storage of building materials, in order to establish local synergies between supply and demand. Finally, other materials can be integrated into the flow model as well [39].

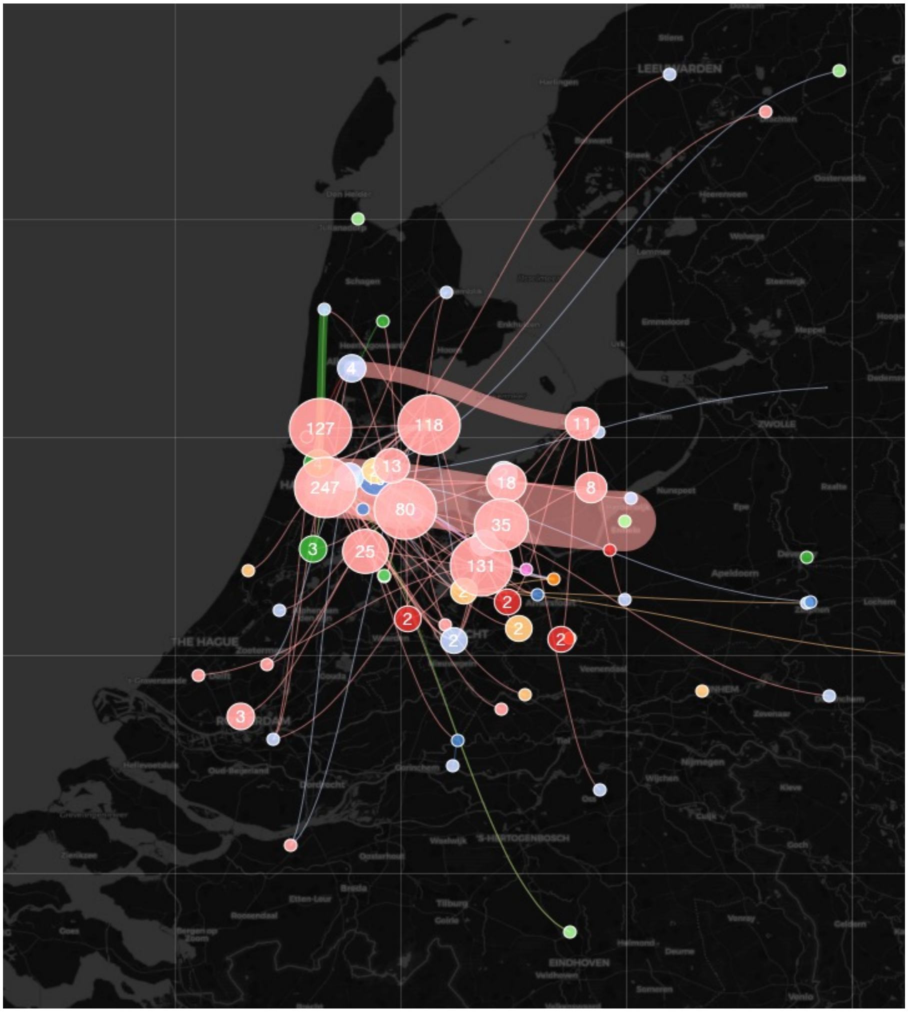

FIG. 6.6 Wood materials as part of the CDW flow in the Amsterdam metropolitan area (2016) [Map generated with the GDSE software (REPAiR project)]

6.5.3 Materialisation Overview

Figure 6.7 displays rudimentary sketches of a partition wall design, consisting of a stud framework (timber in this example), two side-panels, and insulation within the cavity. The cavity allows for cables and wires in order to position electrical and data provisions wherever desired. To facilitate that, a cable-duct is foreseen at the bottom (depicted on the right in Figure 6.7), adapted from the aforementioned groundwork by Infill Systems BV [42]. These devices are fitted into the vertical member. The vertical members slot into timber or metal mounting profiles on ceiling and floor. The skirting board can be taken off in order to reach cables and wires. The materialisation facilitates personalised (re)configurations, allowing for many variations. Materials can either be pre-cut in various standard sizes or customised on-site. Lastly, for this exercise I assume the use of common fasteners for dry, direct connections, even though this restricts reuse and recycling to some extent [18].

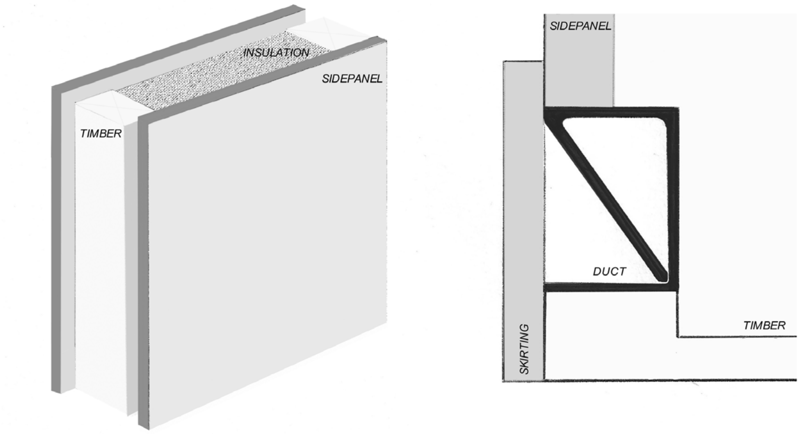

FIG. 6.7 Basic partition wall configuration (left) and detail of the cable-duct behind skirting board (right) [Source: Bob Geldermans].

Table 6.2 brings together data for two variants of the components, side panels and insulation, focusing on materialisation, origin, and reutilisation. Table 6.3 assembles technical specifications and a price indication. Tables 6.2 and 6.3 do not aim to provide a complete set of parameters to assess *Circ-Flex* performance, but rather first insights from the analysis into the material and operational performance of the products and their functions in the intended scope. Table 6.2 particularly refers back to the categories 'Material Health and Transparency' and 'Material Reutilisation' of Table 6.1, whilst anticipating AS-MFA aspects concerning secondary materials and geo-referencing.

TABLE 6.2 Side-panels and insulation: Materialisation, origin, and reutilisation [Source: Bob Geldermans].

Component	Material	Production Location	Raw Material	Raw Material Origin	Geogr. Scale	Material/m²	Reutilisation Potential
Side-panel	Gypsum board	The Netherlands	Flue Gas Desulfurization Gypsum	Coal-fired power plants	State; Continent	Roughly 25 kg/m² (2 sides of 12.5 mm medium duty panel). 90–95% gypsum + 5–10% additives and paper.	Direct reutilization possible but compromised by impact of common fasteners. High recycling potential in the case of basic panels, but value of most raw materials is destructed (i.e. downcycling). Low recycling potential in the case of boards with enhanced properties. No direct take-back system in place, but gypsum recycling market is growing in the Netherlands.
			Recycled Gypsum	Construction residues	State; Continent		
				Demolition waste	State; Continent		
			Natural Gypsum	Mined gypsum	Currently not applicable		
			Recycled Paper/ Card-board	Paper and cardboard waste post-use	State; Continent		
			Secondary Paper/ Card-board	Residual flows from industry	State; Continent		
			Additives: process accelerant, foaming agent, fluidizer, fire retardant, filler, bonding agent, binding retardant, reinforcement	Chemical industry	State; Continent; Globe		
	Niaga ECOR Panel	The Netherlands and Serbia	Fibers (paper, cardboard, flax, wood chips, straw etc.)	Post-use and residual flows	Region; State; Continent	Roughly 25 kg/ m² (2 sides of 12.5 laminated NEP). ≈ 95% fibers, 5% polyester	Direct reutilization possible but compromised by impact of common fasteners. High recycling potential: polyester binder can be "unclicked", liberating the ECOR fiber material and Niaga binder as two separate flows that can be fully reused without quality-loss. Additives for enhanced properties are not anticipated yet. Options for Take-back model are being explored.
			Polyesters based on carboxylic acid and glycol	Chemical industry	State; Continent; Globe		
			Additives: none reported, but potentially a fire retardant or biocide	Unknown	Region; State; Continent		

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TABLE 6.2 Side-panels and insulation: Materialisation, origin, and reutilisation [Source: Bob Geldermans].

Component	Material	Production Location	Raw Material	Raw Material Origin	Geogr. Scale	Material/m²	Reutilisation Potential
Insulation	Mycelium-fiber composite (MFC)	The Netherlands	Mycelium	Fungal mycelium species	State; Continent; Globe	<1 kg/m² (30–50 mm). Dry weight. Dependent on mycelium/fiber ratios	Direct reutilization possible, within limits of service life. Product is fully biodegradable.
			Agricultural fibres	Agricultural by-products and residual flows	Region; State; Continent		
			Additives: none reported, but potentially a process accelerator	Wheat flour	Region; State; Continent		
	Everuse®	The Netherlands	Cellulose	Post-industrial paper residues	State	<1 kg/m² (30–40 mm)	Direct reutilization possible, within limits of service life. Take-back system in place. Product is recycled in manufacturer's facility. No details available
			Additives: fire retardant, biocide	no data	no data		

Sources: Gypsum board [54,95–98]; Niaga ECOR Panel [75,76,81,99]; MFC [84,88,89,100,101]; Everuse [67,102,103]

Table 6.3 combines product specifications to facilitate a quick-scan regarding functional performance of partitioning components, and to identify any remarkable differences from the study's perspective. Apart from basic product performance, Table 6.3 ties in with the category 'Perceived Performance' as part of the *Circ-Flex* assessment guidelines. The data are based on information from manufacturers and literature. In the case that data are unavailable, it is indicated in the given column.

TABLE 6.3 Side-panels and insulation, selected technical specifications and price indications [Source: Bob Geldermans].

Component	Material	Density	Nail Pull Resistance	Dimensional Stability: Linear Expansion Coeff.	Fire Rating	Thermal Conduct.	Whole-Sale Price Indication
Side-panel	Gypsum board-reinforced, medium duty (12.5 mm)	≈ 1000 kg/m3	≈ 15 kg (safetyfactor 4)*	0.0065 mm/m/Δ RH (change in relative humidity)	Class A1-B = not (easily) combustible	0.19–0.25 W/mK	≈ € 7–10/m²
	Niaga ECOR Panel (12.5 mm)	≈ 1000 kg/m3	NEP: no data FlatCOR (2,5 mm): ≈ 30 kg**	NEP: no data available yet. FlatCOR (2.5 mm): 0.029 mm/m/Δ RH	NEP: no data available yet. FlatCOR raw panel: Class B = not easily combustible	No data	NEP: no data FlatCOR (2.5 mm): € 3–4/m²
Insulation	Mycelium-fiber composite	80–110 kg/m3			Class A: not (easily) combustible, reported for Ecovative product. Otherwise Insufficient data	0.035–0.06 W/mK	€ 10–50/m²
	Everuse®	≈ 75 kg/m3			Class A1-B / s1 /d0 = not (easily) combustible / little smoke production / no production of burning parts	0.035–0.04 W/mK	€ 17.50/m²

*Sources: Gypsum board [54,94–97,104–106]; Niaga ECOR Panel [75,76,81,99]; MFC [84,88,89,100,101,107,108]; Everuse [67,102,103,105,106]. *Safe working load (SWL) calculated with an average wood screw in a hollow wall, and safety factor 4 [104]. **No data concerning SWL and safety factors.*

6.5.4 Operational Value-Chain

From the materialisation matrix of Table 6.2, various changes to the regular value chain can be observed. For example, in the case of gypsum-board, the most apparent shift is related to the sourcing of gypsum with a high enough level of purity. The share of FGD gypsum will decrease, due to the closure of coal-fired power-plants. This will likely lead to an increase of both recycled and natural gypsum, whilst applying modifications to the manufacturing process to safeguard the required product quality [95]. Furthermore, the gypsum-board product is comprised of multiple additives sourced via regular channels. Although the associated European (chemical) industry is the primary supplier, market mechanisms are increasingly a global game [109]. Moreover, in anticipation of changing partitioning requirements, a basic gypsum-board is not sufficient. Enhancing the properties, such as robustness, has a direct, negative effect on the recyclability. In the case of insulation, a main observation is the difference in end-of-life scenarios, linked to take-back systems as part of a supplier's business model, but also additives that provide restrictions in this respect. A lack of data made it difficult to fully assess the Everuse® product with regard to such aspects.

Niaga ECOR Panel (NEP)

With regard to the production of fibres for the NEP, raw materials can be found locally. Apart from post-industrial and post-consumer residual flows, agricultural by-products could apply. Based on proximity, sourcing beyond national boundaries may apply, depending on the manufacturing location. At this moment, ECOR manufactures their FlatCOR panels in Serbia, while a NEP production facility is set-up in Venlo, the Netherlands. Raw materials (fibres and polymers) are transported to that location. The polyester polymers, based on regular chemical feedstock (carboxylic acid and glycol), are produced in Germany and transported in big bags of granulate pellets [99]. Next, the panels are transported to wholesale or retail locations if not directly to the building. Temporary storage is also an option. ECOR is currently developing a 'product-as-service' business model for the NEP that takes account of the take-back stage, so that materials are recovered and reutilised [99]. This activity can be deployed by ECOR itself or outsourced to another service-provider. Concerning the service life of the NEP, no data exist yet, but based on estimations of similar products, approximately 30 years can be assumed [105,106,110]. Within this period, the material can, theoretically, be reused and remanufactured several times before it is recycled.

Mycelium Fibre Composite insulation

The raw materials for mycelium-fibre composites (MFC) can be divided into: Fungal mycelium, fibres and, potentially, additives. Fibrous agricultural residues are cleaned and pasteurised before being introduced to mycelium in standardised moulds [89]. These moulds (ideally transparent and plastic for reasons of control and hygiene) are essential in the cultivation process, but are not included in this exploration of (raw) material use. The mycelium grows due to its symbiotic relationship with the fibres that feed it, forming a strong yet flexible composite. A process accelerator may be added, such as wheat flour [91,101]. The binding process takes up several days, after which the panel is dried and the growing process stopped [85]. Fungal species, suitable for the MFC process, can be found on the global market or be cultivated in local laboratories [89,91,101]. For this exercise, I assume the fungal strain comes from a local source. The wheat flour, which may be used in the process, is a ubiquitous agricultural commodity. Although this raw material can come from local (Dutch or European) sources, the wheat market is essentially a global one. Wheat on the Dutch market is 50% of domestic origin and 50% from abroad [111]. The largest share, in weight, are the fibrous raw materials. Multiple substrates have provided good results in terms of mechanical, thermal, fire, and acoustic performance [89]. Ecovative, a pioneering company, with a head-start in mycelium technology, has brought an insulation product to the market based on hemp [88]. The ratio is 95% hemp residues and 5% mycelium. No use of additives is reported for this product. A Dutch associate of this American company has successfully applied combinations with other substrates, such as cattail reed [101]. Production of the MFC can be done locally, close to the area of distribution, use, and recycling. For example, in proximity to fibrous residues from agriculture or public land maintenance.

6.6 Discussion

6.6.1 Technical Reflection

Fasteners and Coatings

The focus of this chapter has been on products that may radically alter value chains, but not so much the interaction with users and contractors. Both NEP and MFC can be applied in common implementation configurations. This study did not prominently include fasteners. Common fasteners were anticipated, also in relation to screw tightness. Disassembly of the NEP cannot be done without minor damage to the product due to screw holes. Although this may lead to an initial decrease in value with regard to flexibility and inner cycles, such as reuse and remanufacturing, it has no impact on the recycling stage provided the NEP retains or regains its purity. The latter aspect is closely linked to the application of coatings and finishing layers. Finishing was not part of the scope but is clearly an essential intervention in the light of health, flexibility, and circulation, as stated in Section 6.4.2. The Niaga technology can be combined with various materials. The expectation is that coatings can also be compatible in this respect. Several manufacturers of coatings, known to comply with the ethics of health and circularity, make use of readily available natural products and processes that can safely be recycled with the ECOR fibres [68,69]. However, being in the development and experimentation stage, evidence is still scarce. What is more, a limited range of applicable products will impact the user’s freedom of choice. Research, innovation, and marketing efforts in this direction are thus required.

Properties

The NEP is currently in a pilot phase aimed at the furniture sector. From Table 6.3 it can be seen that multiple tests are required to steer production towards interior partitioning components. The performance of the FlatCOR product indicates that robustness will not be a main concern for the NEP, but dimensional stability may be, specifically in respect to relative humidity fluctuations. Furthermore, Table 6.3 displays unknowns with regard to fire safety and thermal performance, which thus requires further testing. Another relevant factor, not included in Table 6.3, is acoustic performance. This is best tested on a whole wall module rather than on separate materials. Potential changes in the function of space over time need to be taken into consideration. For example, shifting from residential uses (such as living rooms or bedrooms) to meeting-rooms or working spaces. If a regular drywall performance is assumed, ranging between softly spoken and normal conversation, extra measures may be necessary. For example, by doubling the side-panels or applying a thicker alternative, ideally with a honeycomb core to reduce weight and raw material requirements [96–99]. Specific attention in this respect should go to the connection with adjacent parts, such as ceilings, floors, and doors. Holes at the partition heads and cable-duct cavities will have a substantial negative effect on acoustic performance. Additional materials may thus apply, with an inherent impact on the *Circ-Flex* performance.

With regard to the MFC insulation, specific attention should go to the service life. Based on estimations, approximately 20 years is anticipated. This is shorter than that of regular insulation products and side-panels, which may lead to undesirable effects regarding replacement interventions.

Raw materials

The NEP technology allows for multiple fibre feedstocks. Focusing on Dutch biogenic residues that apply, but are currently incinerated, it can be assumed that supply-risk is not a main concern. As an example, Annevelink et al. [112] calculated roughly 170 kton of clean fibrous biogenic residues per year from agriculture alone that is currently incinerated but could be used at a higher utility. Addtionally, about 6,000 kton of similar material, albeit in diverse qualities, from other sectoral categories, most notably Households (2,750 kton), and Trade, Services & Government (1,300 kton), are incinerated [112]. A rough calculation (dividing 170 kton by 25 kg per m^2, based on Table 6.2) indicates that this residual flow could provide raw material for seven million metres squared. Regardless of the crudeness of this calculation, it provides a favourable order of magnitude regarding supply-security. Biogenic residues are also relevant in relation to the mycelium fibre composites (MFC). With regard to the shift from linear to circular value chains in the construction sector, the application of MFC has been studied before in the AMA context [113]. Designated buffer-zones for temporary water storage were identified as high potential territories for growing crops (grasses, reeds), capitalising on local opportunities for renewable insulation materials and other ecosystem services [114]. Production of the MFC can take place in local facilities at temperatures between 20°C (for growing) and 80°C (for baking). The main issues are (1) the time it takes for the mycelium to bind the fibres and for the material to dry, and (2) the space needed for those processes. Automatisation will have a decisive impact on production volumes per m^2 of land used [101].

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Mould

Lastly, mould control is addressed, particularly important with regard to transportation, storage, use, and maintenance conditions [5]. As in the reference case, the products themselves need to be in line with the standards. However, this may imply additional additives which can compromise the performance concerning circularity, flexibility and/or health. Further testing is required, not least in relation to the use of coatings. Moreover, consistent quality control is indispensable throughout the whole operational cycle.

6.6.2 Organisational Reflection

Value-chain Modifications

In order to adhere to familiar use and construction models in the design conceptualisation, I did not deviate too much from existing partitioning configurations. However, radical changes occur with regard to raw material sourcing, manufacturing, reutilisation, and data-sharing. The use of secondary raw materials, of a renewable nature, contributes greatly to the potential of the design. Moreover, it can add a local narrative to the value-chain. Even if that narrative was to play no role of importance in the end-user's perception, it is considered meaningful for other networked partners in the value chain [99]. Acting collectively can make a big difference in opening up market barriers, knowing that innovative building materials and concepts often encounter critical hurdles in the implementation stage and fail to become proper innovations [115,116]. Proximity, both culturally and geographically, and a shared understanding of value creation, can drive that collective act, lubricating the social process through which innovations spread throughout an industry [117–119]. The Amsterdam Metropolitan Area (AMA) and its articulated ambitions with respect to circularity in the built environment provides fertile ground in that respect, at least in theory. If raw material sourcing, manufacturing, supply, operation, and reverse supply logistics are aligned, the chain still needs to be activated by a key actor; namely, the client. This could be the end-users but also – and arguably more importantly at this stage – public or private organisations, such as housing associations, in close conjunction with local authorities. Finally, it can be expected that the prices and availability of materials remain decisive factors in the value model, based on current purchasing behaviour [120,121]. In the case that a take-back service is integrated in the value proposition, the manufacturer, retailer, or another appointed intermediary might claim ownership, offering the customer access to the performance without responsibilities concerning material cycling [122].

Otherwise, a specialised secondary material 'broker' is likely to manage appropriate processing routes.

Data and Communication

Alongside design, material and manufacturing aspects, the appropriate use and operational processes are vital for establishing healthy material cycles in flexible applications. This strongly links to aspects of co-creation and performance evaluations, as incorporated in the *Circ-Flex* criteria (see Table 6.1), whilst necessitating advanced data exchange and communication. Knowing how a product or material functions within a value chain requires meticulous and consistent monitoring. Feedback loops are an essential part of the model in this respect and dynamic data-sets (for instance in the form of material passports) are crucial carriers of information. The latter are also valid for streamlining moments of intervention and associated transport movements, which puts an emphasis on activities of storage and logistics. The role of logistics is thus expected to intensify in the circular model. This aspect underscores the necessity to establish value chains in which the various stakeholders are well-connected, both concerning data-sharing and relational bonds.

Tenant Satisfaction

The construction, use, and maintenance stage of the value chain represents a wide diversity of actors, such as users, contractors, housing associations, and service companies. Focusing on multi-family housing in the AMA, a main role is reserved for housing associations. Multiple housing associations in the AMA are exploring ways to integrate circularity. However, at this moment, there is not much experience to build upon. One example, related to circular kitchen concepts, showed that outsourcing (parts of) kitchen implementation, maintenance and repair cycles had incentivised housing associations to think along in this direction [123]. A preference was reported for a 'hybrid concept' in which the housing association provided a basic kitchen-module, whereas additions and adjustments were left to the tenants and external suppliers [123]. Success rates depend on the DIY capacity of the tenant and on the viability of contracts with suppliers or external service providers. Such developments are only in their infancy, and substantial conclusions cannot be drawn yet. That said, the beginnings of new relationships are tangible with regard to the (circular) value chain around a building's infill. The importance of tenant-satisfaction for housing associations plays a key role. The kitchen example revealed that the primary concerns of tenants were freedom of choice, costs, and "hassle-free" systems [124]. This is probably no different for partitioning, and as such, is an important focus for further steps based on the design conceptualisation in this chapter.

Validity in Other Contexts

The Amsterdam Metropolitan Area has been the main geographical reference point. A fair question is related to the validity for other contexts. From a technical and materialisation point of view, there is not much reason to expect highly diverging results between geographical contexts. With regard to applied methods, the REPAiR project has shown that the generic AS-MFA (beta version) works well in six different European case-study areas, leading to context-specific results. The *Circ-Flex* guidelines have not been applied to other contexts yet, although this tool integrates categories from internationally applied assessment methods, notably C2C Certified™ and WELL Certified™. Recognised barriers to their application are related to data-availability, data-sharing, and continuous value-chain collaboration [5]. This relates to multiple factors, with an apparent emphasis on organisational capacity, although technology-absorption can also be an issue. Follow-up research in this direction should provide more insight in that respect.

Amsterdam has positioned itself at the forefront of CE development, in anticipation of National and European goals. It can be assumed that cities or city regions with high ambitions in this direction might be more inclined than others to embark on implementation adventures. Implementation generally requires 'harder' engagement from multiple perspectives and actors. Safeguarding the appropriate circulation of materials necessitates commitment from e.g. waste logistics and processing companies to become secondary material 'brokers' and producers. This requires an intrinsic motivation, as well as financial and regulatory incentives. It will depend case by case to what extent subsystems relating waste and resource management provide leeway for such shifts. Moreover, the value proposition embedded in the partitioning innovation revolves around co-creation between networked partners, with strong user-centred accents. There may be contexts where such an approach finds more fertile ground than elsewhere. With regard to the AMA, developments in this direction are in their infancy [125].

6.7 Conclusions

In this chapter I focused on materialisation and operation of partitioning wall components in relation to *Circ-Flex* performance. The hypotheses were, that: (1) a stronger integration of materialisation and operational aspects is indispensable in establishing sustainable value-models; and (2) recent innovations, concerning the reversibility of material connections, will help disrupt the status-quo. It was found that the presented materialisation, based on renewable and reversible natural fibre composites, can tackle issues that are found in current value-chains, most prominently regarding circularity performance. For example, relating gypsum-board, particle board, and mineral wool manufacturing and reutilisation logistics, as addressed in sections 6.4 and 6.5. The increased circularity performance does not compromise material health, and could even provide solutions for current bottlenecks. With regard to flexibility performance, potential damages during disassembly and reassembly may compromise reuse and remanufacturing cycles. At the same time, flexibility for the user is facilitated when it comes to ease of assembly, disassembly, and design freedom. As in any other partition system, finishing layers are desicive factors in the overal performance.

Modifications in the value-chain occur, above all, in raw material sourcing, manufacturing, reutilisation logistics, and data-sharing. Raw materials for the components can be secured by local supply, reducing the dependency on international markets. Value-chain integration is essential to streamline logistics and data-sharing. Although this research did not focus on financial aspects, it is assumed that the innovative products and materials could fit in both regular transaction models and product-service systems. It is expected that the benefits in this respect are not so much for the user, but for the supplier or secondary material 'broker.' The outcomes are estimated to be valid for multiple building components, other than indoor partitioning, such as kitchens and furniture, but also insulation, and the interior side-sheeting, of walls and roofs in energy-renovations. Focus areas for further research are related to the facts that multiple tests are still needed to assess the technical performance, and substantial efforts are required to engage key actors in bringing such innovations up to scale.

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7 Discussion of the Findings

Prior to drawing final conclusions from my research, in this chapter I trace out overarching themes explored in this dissertation. The aim is to bring together my core findings, whilst linking them to specific relevant developments and perspectives. In Section 7.1, I reflect on my findings in the context of the current state-of-the-art, highlighting connections with the circular building practice as well as future actions for research and practice. At the end of this chapter, in Section 7.2, I briefly reflect on the strengths and the limitations of the research methodology.

7.1 The Iceberg Principle

With melting ice-caps as a powerful illustration of changing planetary systems, at least to some extent attributable to mankind [1], it seems fitting to begin this section with the iceberg metaphor regarding a better understanding of what is not immediately obvious. In this dissertation, my focus has been on partitioning as a complex systemic manifestation. Throughout the chapters, the aim was to explore and explain systemic aspects that in unison define whether or not a partitioning-model supports circularity, flexibility and health & well-being.

Figure 7.1 is based on the assumption that in contemporary linear production and consumption systems there is an emphasis on the physical object, designed and manufactured to fulfil a specific service, such as partitioning. Usually, products and their intended functions are obvious to the user. And, from a Dutch and European perspective, it can be assumed that products are tested and certified to be fit for that function, albeit at a basic level (see Section 7.1.7 and Chapter 5, Section 5.6.1). However, there is not necessarily any substantial awareness of other aspects that are critical to the product's functioning.

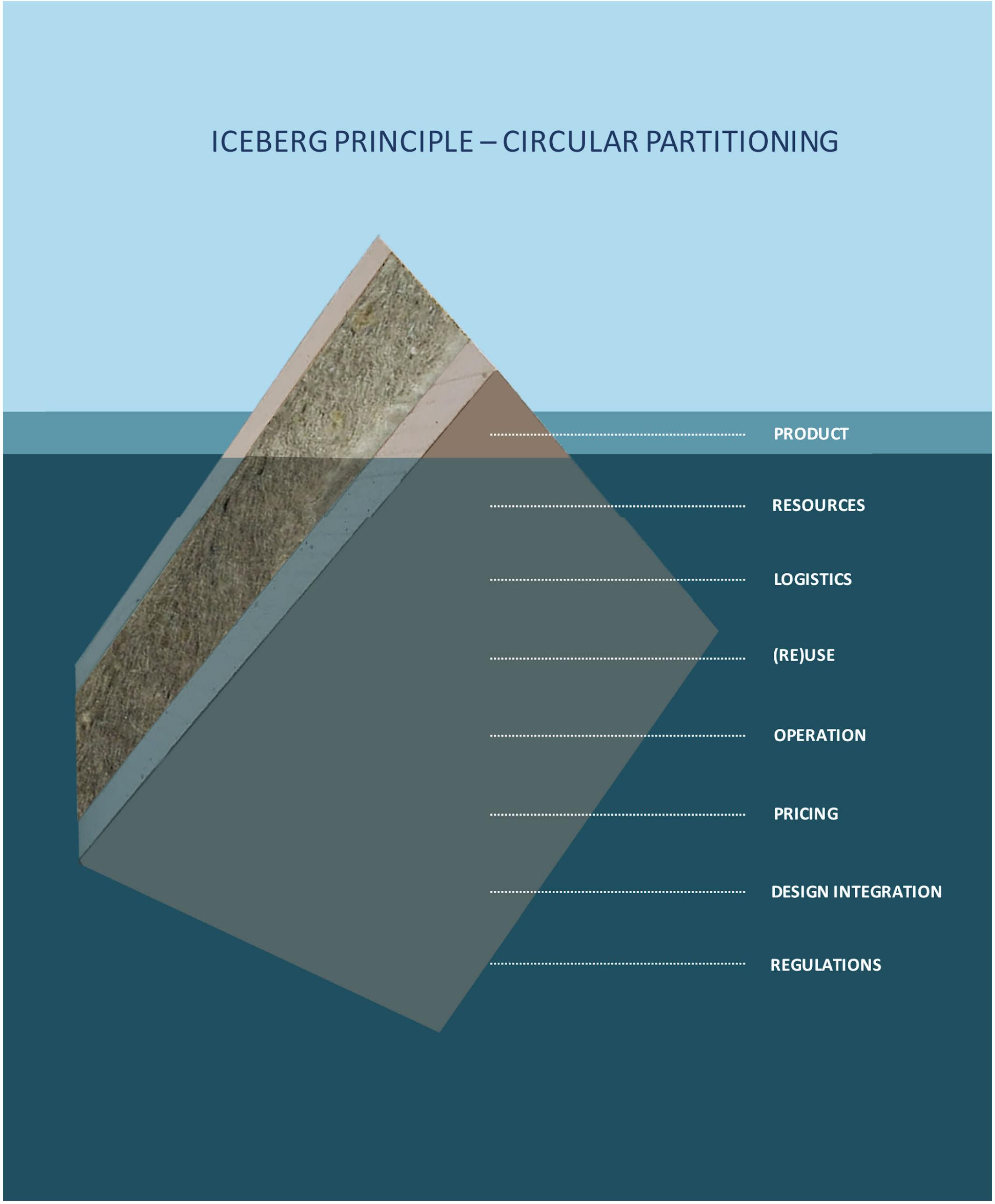

FIG. 7.1 Iceberg principle applied to circular partitioning [Source: Bob Geldermans]

This differs from a context in which material use is directly related to local material sourcing and ecosystems, knowledge, skills, and project engagements, such as is the case in many vernacular typologies. The disconnection between user and material is magnified by increasingly complex manufacturing recipes and processes, as was addressed in Chapter 5. By consequence, most aspects that define a product's overall performance remain obscured from general view. In parallel with the estimated 7/8 of an iceberg's subaqueous existence, Figure 7.1 sketches the situation relating to partitioning products [2]. Whereas the product as such is well represented across the stakeholder network, knowledge about other aspects of the value model is diffuse and fragmented. This is the case in most linear models, but is incompatible with circular value models. As addressed throughout this dissertation, resources are required in all stages: from raw material sourcing and product manufacturing to product implementation, use, and reutilisation. It was shown that the raw material profile of the partitioning component goes beyond what a materialisation-snapshot can show. In Chapter 5, I argued that even manufacturers are not always aware of all the raw material ingredients that go into the goods they fabricate, let alone the chemistry of certain compounds. Hence, it is not surprising that such information is currently completely inaccessible for stakeholders further upstream in the supply-chain. Something similar is valid for other aspects, such as those mentioned in Figure 7.1: logistics, operation, (re)use, pricing, design integration, and regulations.

This iceberg metaphor allows us to explore a much needed integrated approach towards circular building in general, and circular partitioning in particular, opening up to a larger set of value-chain stages and characteristics, as well as associated actors. This underscores the fact that neither sustainability nor circularity can be approached in a static way, but rather as a condition of constant motion and interactions between elements in a system [3,4,5]. As long as a system can deal with changes, while staying within the borders of its sustainable state, a claim of sustainability is justified. This adheres to complex systems thinking and concepts of 'strong sustainability', as was addressed in Chapters 1 and 2. An assessment of strong sustainability performance thus needs to integrate all aspects that are part of the given production and consumption system. Once that notion of complexity is accepted, appropriate analyses, diagnoses and conceptualisations are required to unravel it. The following sub-sections are structured around twenty-one themes that further reflect on the aforementioned aspects. Figure 7.2 displays the themes, whilst linking them to the specific sub-sections of this chapter and preceding chapters

FIG. 7.2 Overarching themes (centre) linked to sub-sections (right) and to preceding chapters (left) [Source: Bob Geldermans]

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7.1.1 Circular Operations

In Chapter 3, intrinsic and relational properties were identified for products and materials, alongside seven preconditions for circular building. In Chapters 4-6, these conditions were further elaborated, accentuating user benefits and operational processes throughout the whole value network. The circularity potential of given products and materials is thus relative to the operational performance.

Throughout this dissertation, I argue how circularity potential can easily be compromised from the vantage point of the user and during specific operational stages. Operational management needs to be rethought against the backdrop of a circular economy with effective product and material loops. Velte and Steinhilper (2016) note great uncertainties and risks perceived by the actors involved [6]. This is not simply the resultant of a risk-averse industry, but rather of well-rooted and concrete individual business models and incentives, sometimes diametrically opposed to the abstract projection of collective circular value. Many businesses wait until high commodity prices create the case for CE transitions [7]. Thus, at the end of the day, conventional market mechanisms and short term strategies often rule. This remains a barrier for the transition to a circular economy, hinging on initial investments, process-modifications, feedstock, equipment and output, retraining staff, and wider value-chain coordination [7]. Chapters 5 and 6 examined the world of plasterboards and common particle boards, indicating that these industries themselves will not establish the shift from linear to circular. Rather, such change should occur at the intersection between industries, authorities and society at large. In this case, concerted efforts are needed from and between the plasterboard and particle board industry, construction industry, infill industry, designers, waste and resource logistics, legislators and clients. Until that happens, the industries are likely to explore their own alternative routes, even if those routes are dead-ends from the vantage point of circularity.

In Chapter 6, examples of side-panel and insulation innovations were introduced and explored that could disrupt the infill market and its mechanisms. However, those innovations/innovators face challenges, in some cases not much different from those in traditional business models. The key elements put forward in this research also feature in advanced circular business support models, such as the Circular Value Hill Business Model Tool of Achterberg et al. (2016), see Figure 7.3. This concept integrates circular design (pre-use), optimal use (in-use), value recovery (post-use), and support (management) models, in combination with a hierarchy pyramid of alternating value: increasing value with each step from extraction to use, and decreasing value in the steps towards secondary (or third, fourth, etc.) extraction [8]. In that respect, this model is fully compatible with *Circ-Flex* partitioning intentions, as put forward in Chapter 6, Section 6.5.

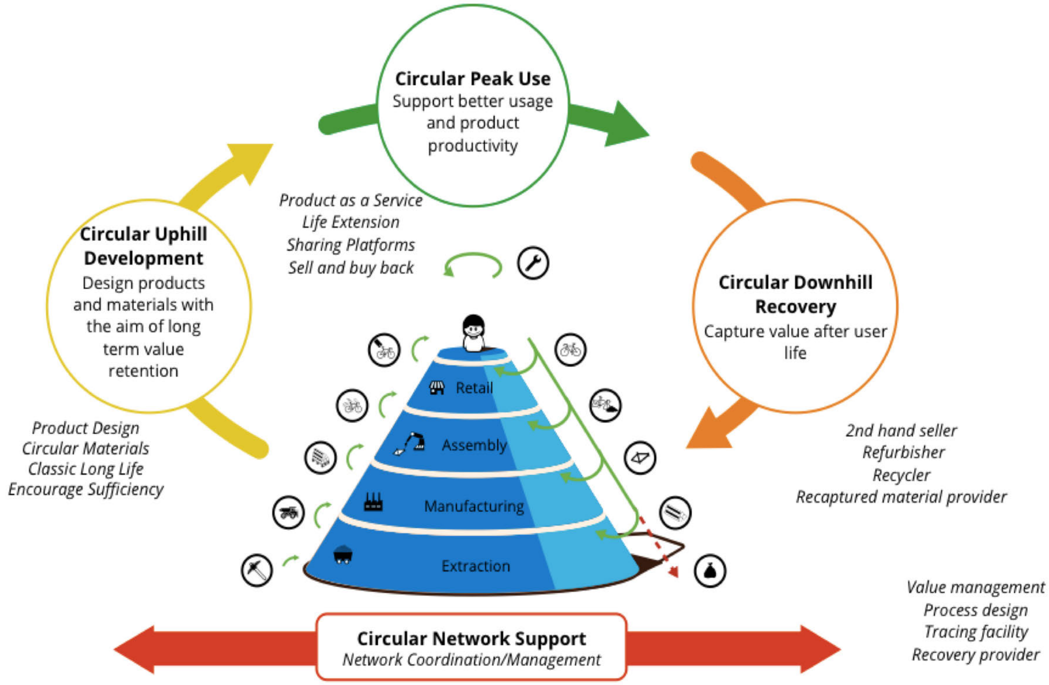

FIG. 7.3 Business model categories mapped on the Value Hill [Source: Achterberg et al., 2016]

Future Actions

Innovations that enable circular operations usually put R&D efforts in coupling circular product/service design models and material or product value recovery models. But the models that are essential for making the actual connection in practice, the “optimal use” and “circular support” models, remain largely undeveloped. In anticipation of *Circ-Flex* partitioning, the distinction between supplier and user needs & benefits must be well understood. This requires an explicit separation of decision domains. In this dissertation, user inclusion was addressed in essentially two assumptions: (1) an Open Building approach has been applied within the design and construction stages of the multi-family building, so free infill ‘traffic’ on a household level is facilitated; and (2) user willingness to invest is addressed by adhering to partitioning concepts that follow familiar purchasing and implementation routes, whilst at the same time acknowledging a certain level of design-freedom. In addition, coordination of the overarching value proposition needs to be secured. For connecting and coordinating design, use and post-use stages, Achterberg et al. [2016] identified several interrelated strategies [8]. These strategies concern:

1. take-back systems and collection services to recover resources;
2. services to secure reutilisation potential;
3. management of information, materials, transparency, payments, and governance;
4. services to facilitate the tracing, marketing, and trade of raw materials.

The proponents of the Niaga ECOR Panel (NEP) and Mycelium insulation innovations discussed in Chapter 6 may have some of those strategies on their radar, but not at the core of their focus nor developed to any significant extent. In order to prevent their products from becoming part of linear business cases, efforts should thus also be directed at establishing liaisons with stakeholders from the broader 'circular landscape'. Moreover, information systems to support those liaisons must be established. In the case of NEP, it is fundamental that the product finds its designated biological and technical reutilisation route.

In the case of the mycelium panel, only the biological cascading route applies. Although this simplifies matters, it is still required to secure the appropriate reutilisation (ultimately becoming feedstock for the earth) at an appropriate moment, ideally not long before the product reaches the end of its technical performance. This necessitates the coordination, communication and documentation of relevant adjustments to the product throughout its lifespan.

Figure 7.4 is a simplified exploratory inventory of building layer and parts in relation to reutilisation routes, as introduced in Chapter 3. Figure 7.4 indicates that the NEP/Mycelium insulation as an assembled component could follow maintenance iterations during use or be redistributed to another location for the same use, within its technical service life. Remanufacturing, recycling, or biological handling are not relevant on this level. As a separate product, NEP and Mycelium board can both be redistributed, whereas remanufacturing is only relevant for the NEP. On the (raw) material level, the NEP is divided in a technical route (for the polyester adhesive, as well as the natural FlatCOR fibres) and a biological one (only for the natural fibres). The allocated route for Mycelium board, after its technical service life, is to become bio-feedstock.

As was stressed, in Chapters 5 and 6 specifically, interventions during use, such as the addition of coatings, have strong implications for the reutilisation routes in Figure 7.4. The more stakeholders potentially involved in modifying the partitioning component or the implementation context, the more robust the whole system needs to be. The resilience of the value network is thus essential, being able to respond promptly to perturbations: for example, regarding actors/links who disappear from the network, wether voluntarily or not (due to ill-functioning, bankruptcy, etc).

LAYER	*category*	PART	Bio-cascades	Bio-feedstock	Maintenance	Redistribution	Remanufacturing	Recycling
SPACE-PLAN	*Partitioning walls*	COMPONENT			assembly	assembly		
		PRODUCT/ MATERIAL				NEP/Mycelium board	NEP	
		RAW MATERIAL	Natural fibres	Mycelium				Polyester adhesive, and Natural fibres

FIG. 7.4 Matrix of parts in building layer 'Space-Plan:', category 'Partitioning Walls', with reutilisation pathways [Source: Bob Geldermans]

7.1.2 Collaboration, Communication and Data

As I have argued in this dissertation, open and adaptable buildings are not only serving the building owners (anticipate change = quality) and users (flexibility and healthy materials = quality), but are also better equipped than non-adaptable ones to facilitate circular building material flows. By consequence, *Circ-Flex* partitioning concepts may positively contribute to environmental, social and economic quality. This relates to the growing interest for a circular economy in the Dutch building sector. However, adequate metrics to underscore better performances are lacking. There are multiple data, tools and methods available that can put numbers and arguments to pieces of the puzzle, but there is no broadly accepted, harmonised instrument. This currently leads to linear decision-making and consumption processes on governmental, corporate and human levels, in which value is eventually destructed rather than created. This research aimed to work towards an integrated set of indicators, as a necessary step to achieve evidence based (quantified and qualified) guidelines with regard to user benefits and supply-chain implications.

An essential aspect in this context is data-sharing. Many scholars and practitioners have advocated that data-exchange methods and platforms are instrumental in overcoming barriers relating to uncertainties and (perceived) risks [9,10,11]. Data-sharing is a precondition for creating transparent value networks, acknowledging complexity, whilst breaking it down into more manageable pieces. However, a broad acceptance and application of enhanced data-sharing activities needs to be nurtured. This relates to top-down motivation, through tax incentives or regulatory frameworks, for example, and bottom-up, intrinsic motivation. Furthermore, a nuanced approach is required, with respect to issues of confidentiality and patents. The interplay between factors justifies a PhD trajectory in its own right, but aspects can be explored in the light of this dissertation. One perspective is that of the alignment between subsystems within one (or more) circular value model(s).

In order to enable transparent communication between stakeholders and the harmonious documentation of partitioning products and activities, a shared data-platform is indispensable. Different types of data apply in this respect. Data can be based on agreed measurable and verifiable units ('hard data') or on human observations and perceptions ('soft data') [12]. Hard and soft, in this context, do not mean strong and weak. The two types of data complement each other and are both essential with regard to *Circ-Flex* partitioning performance. Chapter 4 in particular addressed the gap that exists between housing quality as approached by the construction and real estate sector, on the one hand, and perceived value of the user, on the other. Moreover, a communication gap was detected between the supply and demand sides. This is most tangible when the time-factor is taken into account, in other words: when change occurs. Chapters 4 and 5 addressed the notion of Post Occupancy Evaluation (POE). Thus far, POE has been applied moderately and predominantly in relation to energetic and climatic performance. For *Circ-Flex* partitioning to take root firmly and unambiguously, the range and reach of POE needs to increase substantially. This necessitates the development or crystallisation of evaluation methods, as well as backing from regulatory frameworks in the implementation of a harmonised POE approach. Simultaneously, data from the users can be extracted through some form of co-creation. Co-creation, as adopted from the business and marketing realm, concerns the interaction between a firm or organisation and users of their products or services, aimed at value creation and value extraction [13]. In a broader sense, co-creation implies the collaborative development of new value, shared between stakeholders. Thus far, there is little experience with this method in the Dutch housing sector, beyond small-scale projects around "self-organised" buildings (a DIY approach, in which the buyer/user of the house has a large say in the design, construction or renovation trajectory). In general, the Dutch building industry perceives residents as consumers or beneficiaries, rather than actors with any specific expertise [14]. By consequence, communications in the light of co-creation and circular building primarily take place between the developer and supply-chain partners. An example in the commercial sector in which co-creation did play a role is the renovation of the Alliander Headquarters in Duiven, the Netherlands, where 'Cradle to Cradle', 'positive energy balance', and 'collaborative building process' were among the conditions as of the initial tendering [15]. An example in housing is Stadstuin Overtoom (Amsterdam, the Netherlands), developed following a co-creation concept in which developer, contractors, architect, and various other supply-chain partners work together in an innovative collaborative engagement [16].

Enhanced communication with regard to material performance can be achieved in multiple ways, for example by information-embedded materials, digital modelling and monitoring tools. Building Information Modelling (BIM) is an increasingly common tool for transmitting data in a standardised way, enabling a collaborative working process for the design, construction and maintenance of a building. BIM-compatibility often resonates in the discourse around and development of so-called material passports, for example in the Buildings as Material Banks project (see Figure 7.5) or Circular Cloud [17,18]. Material passports - or similar documentation tools - that anticipate systemic circular building practices go beyond what BIM currently allows for, and usually integrate multiple methods, tools, and data-sets. In order to accommodate diverse uses (and users), multiple bottlenecks are detected in BIM, relating to: specialised know-how; data availability, format, and sampling; data and software maintenance; data-interpretation; additional workload; confidentiality; and the compatibility of regulatory frameworks [11,19].

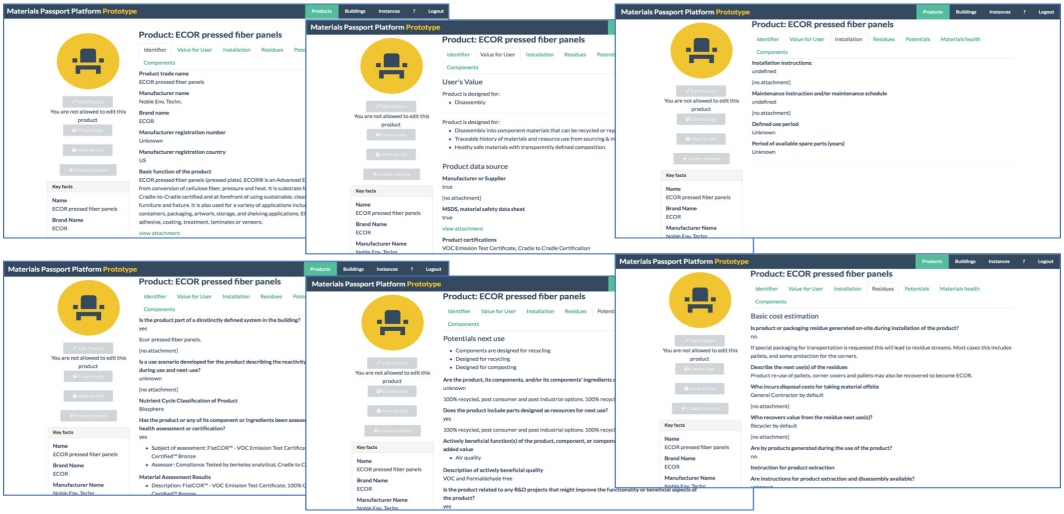

FIG. 7.5 ECOR panels in the Material Passport Platform prototype of the Buildings as Material Banks (BAMB) project, showing six tabs, clockwise: Identification, Value for user, Installation, Residues, Potential next use, and Materials health [Source: Materials Passport Platform Prototype]

In Chapters 3-6, conditions, criteria and indicators have been proposed, studied and discussed. With regard to the uncompromised circulation of materials, modifications in the use stage need to be 'tracked and traced'. If users themselves have no access to the registration system, then the housing corporation or an intermediary specialist must safeguard appropriate monitoring. With regard to flexibility, the operational performance of products and materials should be evaluated (at customised, irregular intervals), for which, again, the users are a prime source, or the infill expert they hired. Concerning health and well-being, monitoring the performance may be a joint venture of users, owner, and specialists in IAQ issues. These examples, relating to the operational stage of *Circ-Flex* partitioning, indicate that more stakeholders may come into play, who cannot be known upfront in detail. In this respect, strongly simplified predictions, use-profiles, and simulations, usually applied in modelling environments such as BIM, are not trustworthy [20,21]. These models fail to integrate the diversity, subjectivity, and change that define (perceived) building performance in real life. More sophisticated feedback loops and track & tracing systems are thus required, which in turn can help to improve modelling software.

Table 5.3 (Chapter 5), based on C2C Certified™ , WELL Certified™, and PRP®, provides an integrated set of criteria with assessment guidelines in response to the existing gaps in current approaches. Although it is estimated that this set is instrumental in establishing healthy *Circ-Flex* partitioning models, the proof of the pudding is in the eating. Effective utilisation is inextricably linked to the way associated stakeholders collaborate and communicate, and the quality of the data-sets. Overcoming the aforementioned barriers for appropriate exploitation, such as diverging data-interpretation, uneven workload and costs, and confidentiality issues, is a multidimensional endeavour. From the analysis of assessment schemes in Chapter 5, only PRP® seems to offer a monitoring and registration structure resilient enough to deal with such dynamics, distinguishing (interventions on) resource, material and item level based on real-time information. As stated in the discussion section of Chapter 5, this currently concerns theoretical potential, as experience with this scheme needs to build up, specifically with regard to housing.

There are potential mitigating circumstances in the case of *Circ-Flex* partitioning, that is, (1) its value residing in sustained circularity potential, and (2) its relative simplicity. Concerning point 1, *Circ-Flex* partitioning components lose value if the circularity potential is compromised. Pricing mechanisms are inextricably linked to good stewardship throughout the supply, use and take-back iterations, and value cases revolve around this fact. Concerning point 2, the product is in principle not intertwined with other building components, physically nor legally, and its narrative is straightforward and local, as referred to in Chapter 6. It should not be too hard to figure out how to handle the product in the case of relocation or discharge.

Future Actions

Current developments are promising with respect to more advanced tools and methods for understanding buildings as material depots. Although there is no harmonised model in place, the documenting of materials and products is increasingly approached in a more integrated and detailed way. Some examples are the aforementioned BAMB Material Passport and PRP®. Another platform worth mentioning in this respect is Madaster (the Netherlands), that offers an online library, whilst coupling material identities to a location [22]. Madaster developed the 'Madaster Circularity Indicator' to provide a circularity score in percentages, based on the Material Circularity Indicator (MCI, Ellen MacArthur Foundation and Granta Design), as referred to in Chapter 5. A downside of this approach is the narrow scope and resulting contestable calculation method. This relates to aforementioned bottlenecks in securing operational performance. In a recent study into the functioning of the Madaster Circularity score method, material handling was dealt with by applying a sensitivity analysis for recoverable content [22]. Such a sensitivity analysis is arbitrary at best, from this dissertation's angle: if handled incorrectly, the chance of appropriate circularity may easily be reduced by 100%. The MCI methodology is, however, a work in progress that gradually moves towards more systemic significance, covering a broader picture of actual circularity performance.[8]

In conclusion: modelling and assessment schemes to facilitate circular building practices are becoming more and more advanced. Yet, specific challenges prove hard to tackle, notably concerning operational performance and inclusion of the user, that are vital for an appropriate continuation of intended cycles. The issue of data-quality remains a concern. Data-sets applied in information modelling and performative assessments are often based on statistical data, if data are available at all for those operations and the local scale. With regard to the synthesised set of criteria and assessment guidelines, as presented in Chapter 5, estimations based on statistics and other secondary data can only be sufficient in a couple of the categories, such as those based on embodied impact. For most categories, however, *Circ-Flex* assessment requires a different tool-set. Looking at Category 2: Material Reutilisation, for example, the validity of initial estimations regarding 'end-of-service' strategies needs to be checked up to and including interventions and secured continuation of the flow in reutilisation routes. This way, circulation processes can be safeguarded or avoided in the case of impurities, and future assessment predictions can be improved.

8 For this purpose, the Ellen MacArthur Foundation recently announced the launch of 'Circulytics' in 2020 [Source: https://www.ellenmacarthurfoundation.org/resources/apply/measuring-circularity]

CUSTOMER RELATIONS

Customer relations, such as those associated with mobility services, represent an asset that might be also applicable to infill products as well, regardless of large differences in type of product and sector.

When looking at two competitors on the Brussels' shared-bike market, Billy Bike and Jump/Uber, a clear distinction can be made: Jump/Uber does not provide direct means of contact but refers to an app form with a significant response-delay-time, whereas Billy Bike has a 24/7 service department reachable by phone. One phone number and personal assistance - where specific know-how can be sourced - represents value.

Another example is the existence of a logbook with photos, descriptions, contacts, warranties, or other relevant information concerning the infill component's history/timeline. Such documents can be decisive elements of any material-ID system, yet more explicitly customised for the user.

7.1.3 Ecology of Production

This section zooms in on a method to track and trace actions of human agents and interactions between parts and people, related to the act of house-building in general.

The Matrix of building parts and reutilisation routes, introduced in Chapter 3, communicates directly with the spatial distribution of a value chain, as addressed in Chapters 5 and 6. In Chapter 3, a building's components, products, and (raw) materials are linked to differentiated reutilisation routes. Next, in Chapters 5 and 6, the system boundary for interior partitioning was expanded to include the whole value chain. The control of parts that enable and support an appropriate functional performance is thus distributed over time and space. This phenomenon can be referred to as ecology of production (EOP) [23]. In essence, the concept provides more grip on the connection between technical building systems, and interrelations in the building and manufacturing sectors, not least to pinpoint success and failure factors. Kendall (1995) developed a diagramming tool that models the complex reality of production into three core aspects: (1) the agents who physically control or change parts; (2) the physical parts subject to control; and (3) the operations used to control the parts [23].

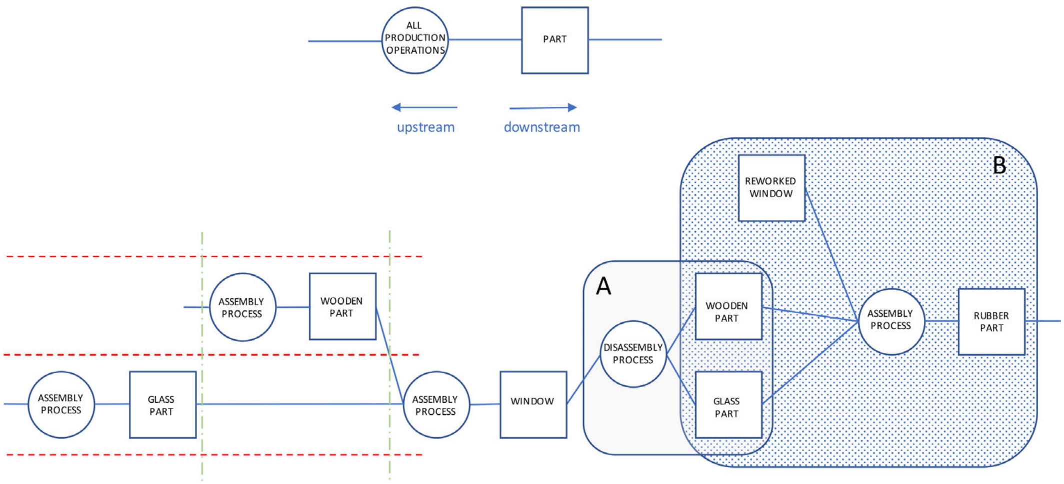

FIG. 7.6 Two elaborations of the diagramming tool [Based on Kendall, 1995]

Figure 7.6 displays examples of the diagramming tool, with the simplest configuration above, and a more elaborate one below.

The diagram above in Figure 7.6 represents one or more *operations* (= circle) making one *part* (= square) in a value added chain, and the diagram below in Figure 7.6 combines multiple factors: on the left it displays two separate assembly processes making two separate parts. These parts come together in a final part (a window in this example) through another assembly process. On the right, the window is taken apart in a disassembly process into the two separate parts, which are then connected with a third part to assemble a reworked window. The red dashed horizontal lines on the left signify a distinction between different activity sites (e.g. onsite/offsite), whereas the green dashed vertical lines indicate different operation sequences. The A and B zones, finally, represent two different control agents that have overlapping control but different relations with regard to overlapping parts and a hierarchical division: in this example, B instructs A. Although the more elaborate diagram below in Figure 7.6 is still relatively straightforward, it gives an idea of the interwoven organisational and technical forces at work in multi-agent activities [23].

Future Actions

The notion of *parts* in relation to *actors* is a key aspect to better understand and streamline contemporary building design, and is closely related to aspects of Design for Disassembly (DfD) and, more recently, Reversible Building Design (RBD), as put forward within the framework of ‘Buildings as Material Banks’. RBD is a precondition for a high transformation-capacity (TC) of buildings, which in turn enables a circular economy in construction [24]. The aforementioned BAMB project contributes to a more advanced approach to TC, adaptability and flexibility of the building stock. This has been done in the past as well, as was addressed in Chapter 3, but two aspects provide additional meaning, namely: (1) the explicit connection with circularity, and (2) the translation into computer modelling. EOP and its distributed control of parts can be modelled nowadays much better than before, given the giant leaps made in computing capacities. It can complement existing tools and methods, helping those to become more sophisticated in the light of a circular transition. For example, in relation to material passports and BIM (see Section 7.1.2).

In conclusion, EOP emphasises the importance of interactions between parts and people, experts as well as non-experts, in the act of house-building. It addresses the complexity of distributed design by disaggregating building components to their constituent parts and connecting these parts to those actors that have the highest level of control over them. Coupling parts and people is essential in the light of underlying study into circular and flexible design. This helps unveiling overlooked processes relating to technical and organisational material(-flow) interventions, offering a more nuanced model of real practice.

7.1.4 Value Network and Spatial Representation

Five main stages associated with closed-loop partitioning-material supply chain activities have been distinguished throughout the dissertation, see Figure 7.7. The first stage concerns the generation of primary or secondary raw materials, either with a biological or a technical profile. The next stage concerns a production or manufacturing step, in which the raw materials are transformed into intermediate or final products. These products then flow towards a storage and handling facility, as a logistical 'epicentre', without imposing any significant change on the product itself. Subsequently (or circumventing the former stage), the product may end up in a wholesale or retail store, including the second-hand market, before it becomes part of the construction, use & maintenance stage. Adhering to a circular model, the phenomena of waste and energy recovery are phased out. Several waste management activities are still relevant, but essentially taken up by one or more of the other activity groups. The resources required for and the residues (and emissions) resulting from the value chain processes are indicated with a dotted line.

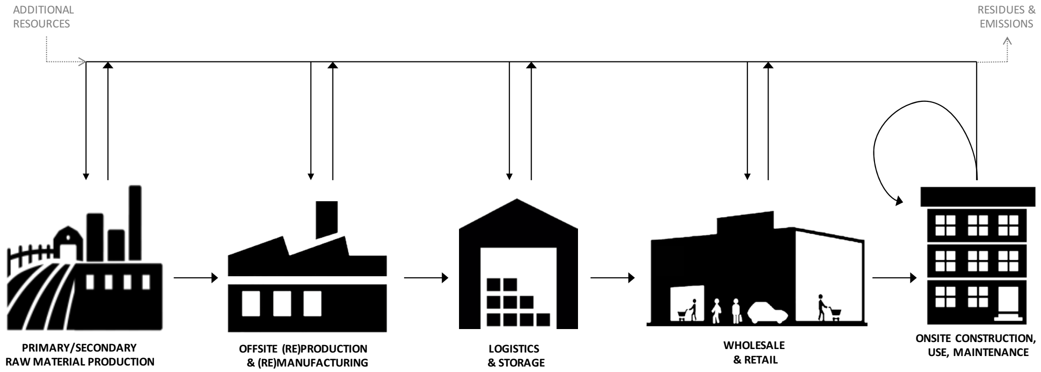

FIG. 7.7 Basic representation of a - two-directional - value network associated with partitioning materials [Source: Bob Geldermans]

This chain can operate in both directions and does not have to include all stages. Each arrow in Figure 7.7 represents a flow from one place to another, following shorter or longer cycles. Those flows are facilitated by means of transport that are dependent on aspects such as distance and volume. In the case of many building products and materials, such flows will not be that straightforward, but rather part of a more complicated network of steps to regain, retain, or increase value, following differentiated itineraries. Value chains associated with construction are constantly transforming, under the influence of technological, social and institutional dynamics. What the value network will look like exactly and to what extent it disrupts common routes depends on the type of innovations regarding production, supply and demand. Based on the findings described in Section 6.5, and reflection thereof in Section 6.6, it could look something like this:

At the start of a new use iteration regarding a partition wall in an individual housing unit of a multi-family building an old wall is perceived as redundant and a new one is chosen. Assuming the old wall was designed for *Circ-Flex*, it is disassembled and either reused within the unit, within the building (in conjunction with the building's owner or manager) or offered to an external actor: resource-logistics company, wholesale or retail actor (including online platforms), or a (re)producer/manufacturer. Thus, multiple variations apply, depending on ownership-allocation and associated agreements and preferences valid at that moment in time. The logistics company can store the wall-parts or distribute them to other actors/activities, be it wholesale, retail, (re)manufacturing, secondary raw materials producer, or to another building/renovation site. Essentially, something similar is also applicable to the wholesale or retail actor and offsite (re)production & (re) manufacturing actor. Multiple routes are possible in this theoretic exercise, which provides a level of resilience to the system. However, it is likely that ownership and financial agreements come with restrictions, or more positively: with guidelines for optimal transfer routing. For the new wall, the user makes a deal with a retailer. The retailer checks whether appropriate wall parts are available in its own stock or from the logistics & storage centre. Alternatively, parts are ordered from the (re) production & (re)manufacturing supplier. The latter works with materials in stock or sourced from a primary/secondary raw material producer. This raw material producer adheres to biological or technical cycles in its production. For example: biological fibres for board-panels and technical polymers for reversible adhesives. That said, raw materials do not necessarily have to establish closed loops for similar products, they can also be building blocks for other goods, as long as these comply with the systemic preconditions. Hence, a highly differentiated network of material cycles can emerge. All aforementioned steps and stages are monitored and documented in a shared logbook-system. Figure 7.8 provides a generic model of such a circular value network, focused on activities and interrelations, to be fed by data on qualities and quantities, timing of supply & demand, and spatial differentiation (see below).

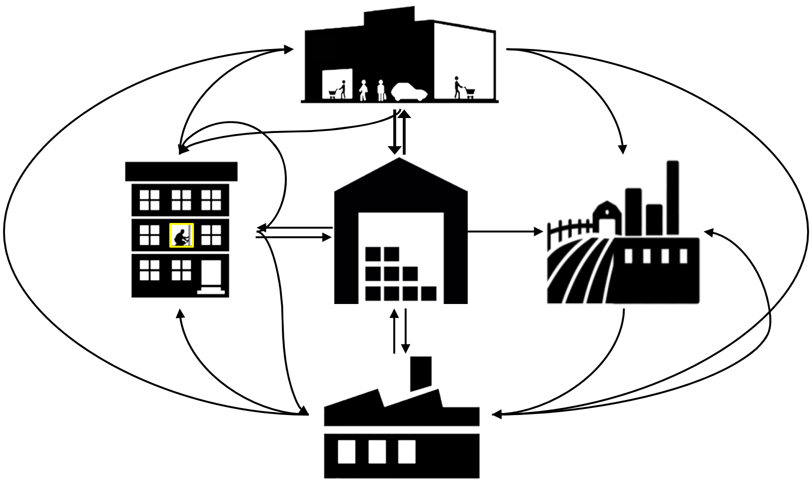

FIG. 7.8 Envisioned circular flow model for indoor partitioning parts [Source: Bob Geldermans]

The boundaries between activities usually represent spatial differentiations, as addressed in Chapters 5 and 6. Commonly, the flow-range spreads from a local housing block to the global scale, see Figure 7.9. Wholesale and Retail facilities that serve the partitioning project are expected to be located on the neighbourhood, city or region level. This is also assumed with regard to the Storage & Logistics stage. Concerning Processing & Manufacturing, as well as Primary or Secondary Production, the whole range from local to global level currently applies.

In the *Circ-Flex* partitioning concept presented in Chapter 6, the importance of locally sourced raw materials increases. In correspondence with Figure 5.3 (Chapter 5), Figure 7.9 shows the spatial representation of conventional value chains associated with side-panels and insulation (left), compared to Niaga ECOR Panels (NEP) and Mycelium insulation (right). Where conventional value chains cut across all scale levels, both NEP and Mycelium insulation can essentially depend on local raw material sources and processing activities, positioned at the scale of region and state (or just beyond: the NEP plant near the German border is a specific example in this respect). For NEP, however, larger spatial scale levels currently apply, taking account of existing panel and polymer manufacturing, see Section 6.5.4.

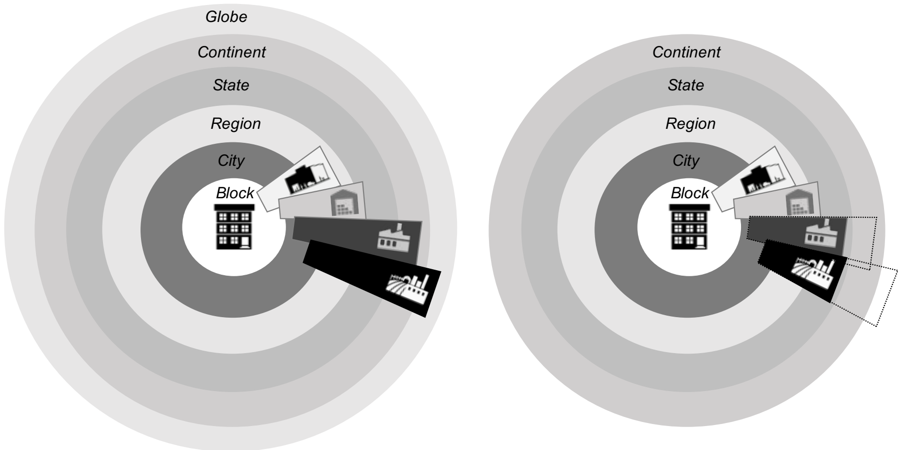

FIG. 7.9 Value chain activities in relation to spatial scale levels: (left) conventional side panels and insulation, and (right) Niaga ECOR Panel and Mycelium insulation [Source: Bob Geldermans]

Future Actions

There is a break-even point regarding effectiveness of a value chain, for example related to transport miles and fuel use. However, the globalised model that currently prevails can easily lead to excessive transboundary behaviour, when externalities are insufficiently incorporated in the pricing [25]. Think of large volumes of waste that are transported cheaply to the other side of the world in containers that would otherwise go back empty. Such phenomena require further research, specifically concerning current market mechanisms. Furthermore, the boundary distinction of Figure 7.9 is primarily administrative: supply chain logistics are not necessarily bound to that arrangement. In the case of plasterboard, for example, a practical challenge is the sourcing of gypsum with a high enough level of purity. The share of FGD gypsum will decrease, due to the closure of coal-fired power-plants. This will likely lead to an increase of both recycled and natural gypsum, whilst applying modifications to the manufacturing process to safeguard product quality. Furthermore, the gypsum-board product comprises multiple additives sourced via regular channels. Although the associated European chemical industry is the primary supplier, market mechanisms are increasingly a global game [26,27]. Moreover, in anticipation of changing partitioning requirements, a basic gypsum-board is not sufficient. Enhancing its properties, such as robustness, may have a direct effect on the weight and/or recyclability, as addressed in Chapter 6. These interrelations need to be taken into account when measuring the impact of panels (see also 7.1.2).

In Chapter 6 (Sections 6.5 and 6.6), the aspect of locally sourced materials is addressed. Both the mycelium insulation panel and the Niaga ECOR panel concern platform technologies, for which a large variety of natural fibres can be utilised. This increases likelihood of actually establishing new local supply routes, of tapping into existing ones, and of their resilience. The Activity-based Spatial Material Flow Analysis (AS-MFA) was referred to as a method and tool to identify valuable residual flows. Although this concerns work-in-progress, as yet restricted to food and CDW flows for the focus area (Amsterdam Metropolitan Area), the potential for applying this method to any other material or waste flow is high. AS-MFA has been applied to other European regions where the focus was on organic waste flows in a broader sense, including natural fibrous residues, for example from agriculture or tree nurseries. Whereas too often those flows end up in incinerators, with or without energy-recovery, they can be suitable feedstock for the manufacturing of insulation and board panels in construction, furniture or packaging. Such strategies not only comprise technological changes but larger process innovations, and are in line with the EU's ambition of a paradigm shift towards a Circular Economy and a near-zero waste society [28,29,30]. There is, however, great tension between those two ambitions (see also Section 7.1.7).

7.1.5 Diversity in Wholeness

Whether an Open Building approach is the best way forward depends on the context of the building or renovation/transformation project in question. In this dissertation it is argued that for multi-family housing, OB is indeed the more logical choice, as it acknowledges “diversity in wholeness”, providing the required short-term flexibility (asset for the individual user) within a collective support that adds long-term value (asset for the owner and the collective/community). The value case for flexible infill thus goes hand in hand with the quality of the superstructure. Moreover, other typologies remain valid alongside, such as temporary constructions that are completely disassemblable.

From the viewpoint of partition-innovation, an accommodating support context is fundamental: meaning that a home unit either comes with a basic yet fully adaptable layout, or with an open floor plan. To say this is not common practice is an understatement, but there are successful examples in the Netherlands and beyond, as put forward in Chapter 4. It is argued throughout this dissertation that a real breakthrough is dependent on the interplay between influencing forces, such as the engagement of key stakeholders. At this moment, the urge to guide and streamline OB construction and infill markets in the Netherlands is simply lacking, as addressed in Chapters 4 and 6, even if accommodative capacity and flexibility are increasingly acknowledged as guiding principles [31]. An example of implemented OB principles in the Netherlands, is the Solids in Amsterdam, initiated by housing corporation Stadgenoot and finalised in 2011. Solids are open building shells, without a fixed zoning plan, in an urban setting [32].

In an evaluation, based on input from residents, potential residents, and experts, it was stated that the 'legacy' of Solids is strongly linked with societal response to economic fluctuations [32]. In other words, the call for co-creation, self-organisation and, by association, freedom of choice came up as a grassroots phenomenon only when the housing and real estate sectors encountered severe adversity after long periods of prosperity. As yet it is unknown if this is a temporary or more structural movement. Next to reported developments with a potential negative connotation, such as the fact that the share of hotel-functions is much bigger than anticipated, the Solids receive enthusiastic response from pioneering residents [32]. Although the Solids have not directly led to replications, several aspects have furthered design, institutional and legal considerations in housing developments. This can be seen, for example, in the recently finalised Patch 22 complex in Amsterdam, particularly relating to mixed functions and open zoning plans.

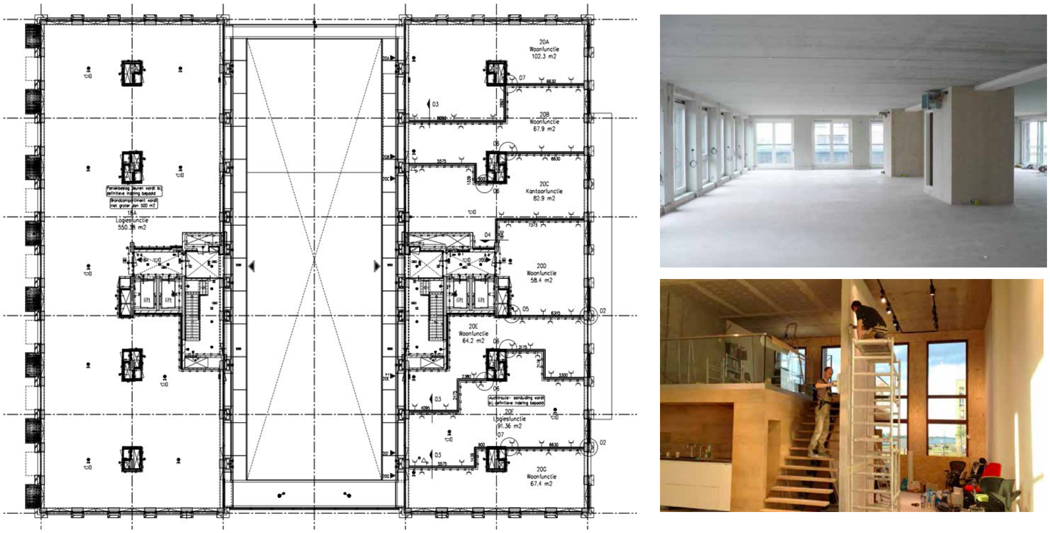

FIG. 7.10 Example floor plan of a Solid, with residential and commercial functions (left) and assembly/finalisation of a partition wall in one of the residential units [Source: INBO/Platform31]

FIG. 7.11 Curved and leaning non-bearing partition framework, as a variation of the standard [Source: Leimgardt Contracting Inc.]

Figure 7.10 provides sketches of a Solids interior and floor plan, Figure 7.11 is an example of a non-standard partitioning.

Removing the infill domain from the realm of the architect to the realm of the user implies that space is created for an infill market that goes beyond furniture alone. This infill market should be able to respond better and more promptly to the needs and wishes of individual users. Players on the infill market can bring - and benefit from - customisation in all its diversity, enabled by advances in social media and digital tools [31]. However, constraints relating to the function of semi-fixed partitioning do require specific expertise and focus, not least concerning national and European building standards. Nonetheless, a global player like IKEA is already active on the housing market in Scandinavia, and in the UK since recently, through its daughter firm BoKlok [33]. Either way, many other existing or emerging companies may find competitive advantage in such an infill market. Although product service systems around partitioning may benefit circularity more than a traditional linear transaction model, the latter is also a possibility, as long as appropriate resource management at the end of a functional iteration is in place.

Lastly, one of the more abstract terms referred to in this dissertation is 'perceived value'. Perceived value is in the mind of the beholder, hence subjective by definition. The technical material and design capacity to accommodate change can be expressed in rather conventional units for compatibility reasons, as has been done in the *Improved Factor Method*, *FLEX* (latest version 4.0 from 2016) or the recently launched '*Losmaakbaarheidsindex*' [34,35,36]. But this is not necessarily the case with health, well-being and comfort as experienced by the occupant, as was addressed in Chapters 1, 2, 4, and 5. Perceived well-being and comfort will differ with time, either by changed preferences of the same user or those of a new one.

Future Actions

It was not part of this research to detect determinants of behavioural patterns. However, this topic comprises several relevant questions for further research. Such as: how can we measure the roles of all the senses, and their essential interactions, in the way an interior layout, and architecture in general, is perceived? For this, it first needs to be acknowledged that those roles and meanings are significant. Elaborating on his criticism of ocular-centric design (see Chapter 1 Section 1.2.3) Pallasmaa (2017) states "In addition to taking a critical position to the exaggerated and often forced visually, we also need to recognise our simultaneous bias for "rational" thinking and cognition as well as the priority of language over our embodied existence and the tacit wisdom of the body." [37]. Projecting such insights on the infill leads to the conclusion that leaving space for play is preconditional, as it allows users or designers to make required adjustments, based on what the senses inform. Even if this may sound far fetched to many practitioners in the (circular) building sector, it has everything to do with living quality and a deeper level of knowledge about what that entails. And for whom. From that point of view it seems self-evident that aspects of flexibility, distributed control, and distributed decision-making receive more elaboration in housing strategies.

7.1.6 Sustainable Development Goals

The impact of new interior partitioning concepts may seem small in the light of global SDG challenges. However, for transitions to take place, appropriate niche innovations need to come into effect, not least linked to behavioural changes in production & consumption systems [38]. Circular value models, speaking to multiple stakeholders in a building-value network and relating to more than one societal issue, might prove to be an important passage in overhauling traditional systems. In the translation to SDG, multiple direct and indirect links can be identified.

Direct links between CE and SDG are found with SDG 11: Sustainable Cities and Communities and SDG 12: Responsible Production and Consumption.

- With regard to SDG 11, the findings are relevant for achieving sustainable cities and communities in various ways. Adhering to an Open Building approach is a response to the phenomenon of vacant and malfunctioning buildings as a result of design and policy choices that ignore change. This is specifically tangible and problematic in cities, as has been addressed in Chapters 1, 2, 4 (and 6). The first two chapters focused on general aspects of circularity in relation to cities, whereas in Chapter 4 the core aspect was the importance of individual quality in relation to the overall urban sustainability.
- SDG 12 is closely related to aforementioned opportunities and, particularly, threats. Production and consumption systems associated with infill components and turnovers will arguably become more responsible by nature, when implementing the innovations sketched in this dissertation, but the impact of those systems could eventually also lead to increased pressure on local land-use and environmental or aesthetic quality. Furthermore, jobs that may emerge locally could take away jobs elsewhere. The Netherlands, and many other European countries, are currently dealing with a mismatch in the labour market [39]. Proposed shifts in production systems may have an impact on the labour market, also in the light of people with a distance to the labour market and international (European) agreements on migration (linking to SDG 10: Reduced Inequalities, indicator 10.7: Facilitate orderly, safe, and responsible migration).

Furthermore, links are detectable with SDG 3: Good Health & Well being; SDG 9: Industry Innovation and Infrastructure; and SDG 13: Climate Action.

- Within SDG 3, health and well-being is addressed, also relating to adequate indoor air quality standards and occupational health (section Non-communicable diseases, mental health and environmental risks). The avoidance of (potentially) toxic chemicals and appropriate evaluation schemes in the operational stage will help increase the standards in this respect. This could be pioneered in the Netherlands, but has substantial relevance for other geographical contexts, in different stages of development. Parameters such as flexibility and freedom of choice have strong bonds with (mental) health and well-being. However, the evidence-base for this is still scarce, as was indicated in Chapters 4 and 5.
- SDG 9 links to developments in manufacturing, as well as in research & innovation, below global averages in the least developed nations. If such nations are to leapfrog mistakes made in other economies (e.g. polluting industrial processes), whilst implementing healthy (building, furniture or packaging) materials and operations, effective progress can be made.
- SDG 13, finally, has received quite a lot of attention lately. It has been advocated that the Circular Economy is instrumental in fighting climate change [40,41]. Although the infill innovation put forward in underlying research does not represent key areas in this respect (priority materials are cement, plastics, steel and aluminium), it is still illustrative of an envisioned paradigm shift. Both the flexibility aspect and the circularity aspect are interrelated with climatic concerns coming from fossil energy use. Flexible partitioning schemes in adaptable housing makes for more resilient living environments, reducing the need to waste real estate and building components. Furthermore, circular materialisation and operation schemes that integrate embodied aspects avoid the destruction of value comprised in the material, including caloric value, whilst depending on renewable energy to feed the associated processes. Chapters 5 and 6 explored another relation, namely that of flue-gas desulphurisation gypsum from coal-fired power plants in the manufacturing of traditional plasterboards. This dependency on fossil fuels is a telling example of the interactions between (sub-)systems in complex economies, certainly with respect to potentially conflicting policies.

7.1.7 Law & Regulations

Chapter 5 (Section 5.1) explored briefly current building standards for indoor partitioning, identifying a discrepancy between the norm and the *Circ-Flex* ambition. There are signs that this discrepancy might decrease, influenced by developments in sustainable and circular building decrees, both on a national and EU level. However, there is a large difference between voluntary guidelines and reporting frameworks, such as *Levels* (specifically developed as a tool for establishing a circular built environment [42]), on the one hand, and enforcement, on the other.

On a national level, there are a few indications that material circularity and health are gradually becoming embedded in policy directives. Industry, government and academia join forces to create frameworks for the transition towards a circular construction economy [43]. Furthermore, attention for health aspects are increasing in widely applied assessment schemes, such as Breeam. However, such developments are predominantly with regard to commercial buildings, less so in residential typologies [44]. One important development is the shift towards a new Environment and Planning Act ('Omgevingswet'), when the current building decree is meant to become part of the Environmental Structures Decree ('Besluit bouwwerken leefomgeving'). This is foreseen for 2021. In this framework, the new Environmental Performance of Buildings instrument ('Milieu Prestatie Gebouwen') will come into action, boasting better databases, easier entry-levels for (circular) innovations, and a stronger emphasis on the integration of partners in the supply chain [45]. At this moment the details are not yet revealed.

Furthermore, open and adaptable building principles are preconditional for *Circ-Flex*. Embedding those principles in the building decree is thus required, much as is done in Japan. The Long Life Housing Law was implemented in Japan in 2008, based on three notions associated with the state of the built environment, according to Minami (2010): (1) a large part of the population was excluded from the wealth and welfare they should experience as member of the Japanese society; (2) a rapidly ageing Japanese society; and (3) increasing global environmental and waste concerns [46]. Japanese society thus needed incentives to move from a build and demolish ('scrap and build') paradigm into a 'stock society' based on high-quality buildings and scrupulous maintenance. Expanding the lifespan of housing is seen as a solution to the problems. Particularly relevant elements of the law, in the light of this research, are the sections on adaptability and the ease of maintenance and renewal. This encompasses the division between support and infill, while permitting modifications of room layouts according to changes, and dimensioning spaces so multiple uses are accommodated. A well-known example of OB in Japan dates back long before the Housing Law, namely NEXT21 in Osaka (see Chapter 2, Section 2.1.4).

Future Actions

Stringent law enforcements for material recirculation, avoiding downcycling, are not yet integrated into Dutch building regulations. Such instruments, however, will be necessary to thoroughly invest in a circular built environment. Current waste legislation is not designed to implement optimal mechanisms, as waste is its inherent point of departure, but it can enable certain aspects of the Circular Economy, notably with regard to the qualities and status of secondary raw materials. Current fiscal incentives associated with specific material and waste streams need to be reviewed against the backdrop of a systemic circular approach. A barrier for the Netherlands in this respect is the dependence on energy recovery from waste incineration (currently earmarked as sustainable energy) as well as the role and position of biomass. In this respect, mindsets, management strategies, subsidy frameworks, and legal systems, on individual, company, and governmental levels, require radical reassessments.

Lastly, when in 2050 the circular organisation of building works is mandatory in the Netherlands, a more interdisciplinary collaboration needs to be embedded in building agreements. This has consequences for the current legislation [47]. Fragmented and bilateral legal contracts need to be adjusted or replaced in order to match with the foreseen complex network structures with regard to value chain modifications.

7.1.8 Practical implementation

The point of departure in this subsection is the Technology Readiness Level (TRL), previously referred to in Chapter 6. With respect to use in construction, both mycelium insulation and Niaga ECOR Panel are in the experimental stage. Progress regarding the performance of mycelium insulation in building applications is more advanced than that of NEP, with an estimated TRL of 7. However, more testing is needed, see the 'Future Actions' sub-section below. The NEP has a TRL of 6-7, ready to be tested in an operational setting, with a primary focus on the furniture domain. Furniture is a part of the infill that comes with technical requirements different from those of partitioning, especially when focusing on semi-fixed partitioning with the capacity to support multiple spatial functions (i.e. beyond mere room-division). A range of tests applies, relating, for example, to dimensional stability, nail pull resistance, fire proofing, thermal conductivity and sound insulation. At the moment of writing, agreements are being made to perform those and other tests at Delft University of Technology as well as other lab facilities in the year to come. It will depend on the tests whether and how soon the NEP can move up towards TRL 10, that is, market introduction.

Mould has been identified as an important issue in this context, concerning human health and product performance (notably in Chapter 5). *Circ-Flex* criteria and assessment guidelines prominently include mould control, stressing the importance of mould susceptibility declarations and indications of moisture conditions during implementation and storage. Furthermore, additives, coatings and other (protective) layers are usually applied to improve performance characteristics regarding mould, amongst others. With regard to the former, ECOR is currently testing bio-based additives to improve moisture related performance. Such additives should not compromise the quality of the overall material in the light of circularity. Concerning coatings and layers, the benefits as well as the challenges are significant. First, coatings and layers can enhance the intrinsic properties, while at the same time increasing the range of decorative colours and textures designers and users can choose from. On the flipside, coatings increase the complexity of the product, adding materials that may not comply with the *Circ-Flex* criteria. Here, the reversible adhesive technology of Niaga brings partial solution: if a layer is added by applying the same technology, it can also be safely separated, collected and reused.

Figure 7.12 shows raw subparts, not yet processed into NEP. On the right is a first rudimentary sketch of what could become the basic partitioning component, consisting of NEP and mycelium insulation. Figure 7.13 shows a variety of NEP products, including various layers of FlatCOR, honeycomb core, and veneers.

FIG. 7.12 Niaga polyester-resin pellets (left), and a basic NEP/Mycelium configuration (centre and right)

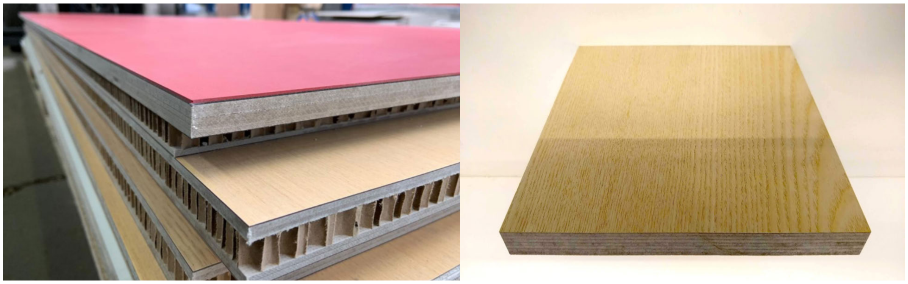

FIG. 7.13 Various NEP versions (left) and NEP with 7 FlatCOR layers and veneer (right) [Source: ECOR]

Their practical implementation also relates to the likelihood of clients purchasing these new products once they are on the market. Next to proven performance in terms of functional and safety aspects, clients will need to be trained and encouraged to apply new innovations. As argued in Chapters 4, 5 and 6, familiarity with material, purchasing routes, handling process, and cost-range are important incentives to influence willingness to engage. However, in order to bring such an innovation to scale, supply security and freedom of choice are essential enablers. Although the platform-technologies are estimated to secure the availability of local raw materials, there is currently no manufacturing capacity in place. Moreover, a limited number of manufacturers associated with current production also means a limited amount of choice with regard to supply. It has yet to be seen to what extent the market matures in a healthy fashion, that is, diverse, robust, and resilient. One obstacle may be related to trade-secrets and patents. Particular attention in this respect should go to the reversible adhesive of Niaga, which defines to a significant extent the disruptive potential of the overall *Circ-Flex* partitioning innovation. The technology and chemistry behind this innovation is not completely disclosed, and patents apply. It is thus uncertain whether and when replication can take place. Housing corporations could play an important role in the large scale application of this innovation if it is part of new infill or renovation schemes. However, procurement and tendering regulations are barriers to take into account. Moreover, particularly when renovations or transformations are concerned, it needs to be assessed if and to what extent the separation of support and infill can be employed, both technically and legally.

Developments worth mentioning in this respect are the European project Circular Housing Asset Renovation & Management (CHARM, 2018-2022) and the Climate KIC project Circular Kitchen (CIK):

- CHARM develops an asset management approach aimed at strategies for high-value procurement and reuse, avoiding the down-cycling of secondary building materials. Of particular interest is the way the project's output will be jointly generated by social housing organisations from 4 European countries [48].
- CIK focuses on specific kitchen components that can replace existing ones during maintenance and renovation, leading to a bottom-up implementation of circular aspects into the built environment [49].

Propositions that come out of these projects can challenge the status quo, also with regard to the individual freedom of the users, which is currently very limited (see Chapter 4). Notions of Open Building resonate in such projects and this may be a precursor for further innovation in the direction of distinguishing support from infill.

Future Actions

The *Circ-Flex* perspective adheres to a user-centred approach at all times. Thus, even if housing corporations can boost the utilisation of proposed innovations, it is up to the users to alter or overrule partitioning choices. This implies that bottom-up incentives to work with such innovative materials and products need reinforcement. Regardless of all (potentially opposing) forces, the proposed innovations boast a set of characteristics that can prove to be disruptive, not least in relation to the traction for circular building practices and policies in the Netherlands, and to the search for innovations that fit the bill. Both mycelium-board and NEP have that potential. Nationally and internationally, the attention for such innovations is growing. In the case of NEP it is fair to state that the attention is growing *exponentially*, given its wide applicability (not least regarding the infill realm: furniture, kitchens, partitioning) and the ongoing international quest for adhesives that tackle primary drawbacks, notably: irreversibility and potential toxicity [50].

For mycelium insulation to be applied optimally in circular building configurations, further testing should particularly focus on understanding and controlling inconsistencies, resulting from: (a) the composition of the mycelium/fibre mixture; and (b) testing conditions. Other key aspects for testing are: thermal conductivity, hygrothermal behaviour, fire-safety, and acoustic performance.

Next to the development and testing of products, value propositions need to be developed and tested concerning ownership, whilst enhancing regular transactions (i.e. ownership shifted to customer) and more innovative pay-per-use, buy-back, or deposit models (i.e. ownership stays with supplier or shifts to an intermediary actor). Specific challenges addressed in this dissertation require further elaboration. For example, with respect to 'contaminations' that occur throughout the use-stage, and that reduce the value of the NEP. An interesting line of thinking is the application of top-layers that, on the one hand, protect the circularity potential of the NEP, and on the other, open up to numerous decorative choices, in anticipation of user-diversity and flexibility aspects. It goes without saying that such top-layers need separate assessments, and may not be compliant with *Circ-Flex* criteria. However, the reversible adhesive technology allows these top-layers to be detached safely, and handled separately. These are valuable developments, knowing that awareness and actions associated with health and circularity are ever growing, also in the sector of veneers and high-pressure laminates.

Lastly, the performance of side-panels and insulation for partitioning products strongly relates to the supporting framework and to the adjacent parts (see e.g. Section 6.4). Interfaces and fixing devices are key in this respect, establishing connections that are in accordance with *Circ-Flex* as well as Design for Disassembly and Reversible Building Design characteristics [51]. Furthermore, coordination between subsystems, particularly with respect to the infrastructure of building services, requires additional attention in research and development. This aspect relates explicitly to precondition 4 in Section 6.4 and the elaboration in cable-ducts, being both a physical component and a metaphor for flexibility.

CABLE-DUCTS

Cable-ducts are essential for alternating cabling and wiring configurations of the wall system. Coordination between subsystems of the building infill is required, and all subsystems should facilitate modifications in other subsystems. This has particular relevance for installations and their associated infrastructure, likely to change more often than the partitioning to which they relate [52]. This ranges from simple changes in the positioning of electricity or data connections, to the addition of smart installations to improve indoor air quality or lighting performance, for example. Such interventions, driven by changes in function or fashion, need to be anticipated optimally. From the materialisation point of view, cable-ducts should be as simple and homogeneous as their function allows. Examples in Chapter 6 consisted of either (reinforced) plastics, (cold-formed) steel or aluminium ducts. The plastic cable-duct variant comprises a type of polymer that can be injection-moulded into any shape. To enhance the properties, most notably with regard to strength and fire-safety, fibres and fire-retardants are added, alongside other additives that may be required to optimise the manufacturing processes. Green chemistry concerning renewable feedstock and recycling technologies are being developed, but far from common practice [53]. Of roughly 26 million tonnes of plastic waste, under 30% is collected for reuse and recycling routes, whilst a significant share leaves the EU [54,55]. Moreover, in recycling processes, plastics with diverging chemical properties are mixed and ground together, making it hard to control the transfer of specific characteristics [54]. The steel cable-duct variant concerns an alloy of iron, carbon and additives to enhance the performance, such as a coating to prevent oxidation and corrosion. This type of metal generally has well developed reutilisation pathways [56]. However, coatings and alloys may complicate recycling processes, and it is estimated that a mature circular economy model for (global) metal markets cannot function without strong policy regarding, for example, virgin metal taxes [57,58]. The aforementioned aspects are to a large extent also valid for aluminium, which is inherently lightweight and corrosion resistant, alongside its high recycling and upcycling potential [59].

7.1.9 Markets, Products & Geography

The innovative partitioning parts in Chapter 6 are selected because of their potential to comply with *Circ-Flex* intentions. This relates to purity of the materials and products, as well as transparency of the associated processes, such as manufacturing and resource management. Moreover, with respect to the parts' identity, their handling specifications, pricing (as far as reasonably predictable), and stakeholder engagement has been anticipated. The materials proposed in Chapter 6 are associated with familiar construction systems and purchasing routes, relative to the residential user-oriented scope. At the same time, the materials ought to be resilient enough to fit into a variety of known and unforeseen schemes, relating to prefab and digitisation, for example. Conventional products and materials in a similar market segment, such as plasterboard, particleboard and mineral wool, are discussed extensively in Chapters 4, 5, and 6. Other products on the market, with potentially equal qualities, can be found relating to insulation: for example, based on hemp/lime composites; cellulose from residual paper and cardboard (such as Everuse®, see Chapter 6); or eelgrass (Danish co-production of the companies Convert and Zostera). With regard to the latter product, no details could be obtained regarding (additive) ingredients, manufacturing procedure, and price, which makes it hard to compare. In general, the production of seaweed material is best done in optimal cultivation-contexts, especially concerning the freshwater variety of eelgrass, which needs (sub)tropical conditions [60,61]. This leads to restrictions with regard to local supply. Hemp/lime composites are closer to the mycelium-board innovation, in the sense that they also concern a toxic free, recyclable product, made out of abundantly available materials. Being already on the market for some time, several benefits are well-understood, and could even outperform the mycelium-board innovation: for instance, concerning service-life; fire-safety; and CO_2 absorbing capacity. However, origin, processing, and (local) availability of lime provides barriers for the envisioned *Circ-Flex* innovation. Furthermore, the platform technology behind mycelium-board offers a feedstock resilience that is unprecedented, and essential with regard to the *Circ-Flex* scope. Hemp/lime composites lack that characteristic. Moreover, proven products in this range apply multiple additional ingredients to enhance the performance, amongst others with regard to fire-proofing and continuous CO_2 absorption, details of which are not disclosed [62]. This hampers statements about their recyclability.

Various other infill components and initiatives relevant to the innovation at the heart of this dissertation have already been mentioned, such as the cable-stud (Chapters 6 and 7), Circular Kitchen (Chapters 4, 6, 7) and IKEA/BoKlok modular housing (Chapter 7). Other developments that deserve a mention, are The New Makers and Katerra, especially as representants of a larger movement. The New Makers'

(TNM) scope is: circular, digitally customised infill components. TNM developed a building system for flexible transformation solutions. Their flagship innovation is a modular “box-in-box” system, digitally customised and easy to adjust to building-transformation contexts. Currently, TNM uses regular engineered wood boards, but innovative materials, such as those manufactured by ECOR, are on their radar [63]. Katerra’s scope is prefab, industrialised building components and systems. Katerra is an American start-up that entered the Dutch market and aims to bring industrialisation, digitisation and standardisation to scale in Dutch construction [64].

In Japan, customisation is more firmly integrated into the building culture. Japanese construction thus has potential benefits with regard to the *Circ-Flex* strategy conveyed in this dissertation, also in the light of OB principles embedded in the regulatory framework, as referred to in Section 7.1.7. That said, in discussion with Professor Shuichi Matsumura, Chairman of the special committee on renewal of the Long Life Housing Law (see 7.1.7), it became clear that the developments in Japan lag behind with regard to several aspects that are at the heart of *Circ-Flex*. First, the *link* between flexible building systems and re-utilisation of materials and components is not made in Japan. According to Matsumura, this is primarily related to the absence of financial incentives for the industry [65]. Secondly, the market share of certified housing units is insignificant in multi-family dwellings, namely 0,3% [65]. Thirdly, the renovation market has increased in Japan over the last decades, but infill innovations as referred to in this dissertation do not benefit from this [65]. Conventional methods and components prevail, because they are familiar, often cheaper, and do generally fit well in flexible configurations.

Future Actions

Although the Dutch and Japanese cultures are very different, and so are the building paradigms and societal needs, there are certainly mutual interests and lessons to be shared. The knowledge and know-how that is currently built up in the Netherlands around circular building may become relevant to the Japanese context, with its limited natural resources. The embedding of and experience with OB principles in Japanese law and regulations, on the contrary, can prove to be very relevant for the Netherlands. In Chapter 4, Section 4.6.2, several other geographical contexts were mentioned, such as Sweden, Denmark, Finland and the UK. Here, similar developments can be discerned, concerning a shift from linear to circular built environments, as well as an increased emphasis on health aspects. (Future) EU policies may play a role with regard to replication and harmonisation of standards, guidelines, and frameworks.

Finally, prefab modular building is growing but does not play a major role yet in the Netherlands, while its estimated impact for the built environment is substantial, not least with regard to dense urban areas [66]. Prefab may be a good companion for circularity, but this relationship needs further exploration, not least in the light of user engagement and whole-systems thinking. It remains a question whether and to what extent Katerra and similar companies, such as Bensonwood in the USA or BIG (Bjarke Ingels Group) in Denmark, can implement these notions.

7.1.10 Trade-offs: Circularity, Flexibility, User Health

Circ-Flex partitioning comprises essentially three parameters: (1) circularity of associated products and materials, up to the level of raw materials; (2) accommodating flexible use, in accordance with the adaptable building context and user desires; (3) the application of healthy materials and prevention of conditions perceived as undesirable, associated with the partitioning performance. Such an integrated scope inevitably leads to areas of friction. Below, four potential conflicts are further reflected upon:

- the coordination of subsystems increases material complexity;
- a multi-functional scope requires over-dimensioning;
- additives compromise performance parameters;
- familiarity & freedom of choice are hard to combine with early material markets.

Coordination of subsystems

In Chapter 3 (Section 3) and Chapter 6 (Section 4) the relation between subsystems is examined explicitly. Partition walls have a coordinating role in this respect, particularly concerning adjacent parts and service installations with their associated infrastructures. Flexibility has at least two implications for material use and user engagement here. First, connections with adjacent parts need to be reversible, requiring specific connecting devices on the interface between partitioning and adjacent part. This may complicate the choice of products and materials, due to constraints regarding availability and ease of utilisation. As such, it can have a negative impact on user capacity, such as demotivating the willingness to invest (see Section 4.5). Secondly, the vital role of cable-ducts comes with its own material requirements. Cable-ducts cause cavities in the partitioning, disrupting specific functional characteristics. In Chapter 6, I have drawn particular attention to acoustic and fire performance. Additional materials may be required, depending on the intended function of the space and, by consequence, performance of the partition. Those additional materials in turn may compromise the overall *Circ-Flex* performance. This represents a key area of future research.

Multi-functional scope

An open and adaptable building context will be able to accommodate multiple functions by *over* rather than *under*-dimensioning. As long as supporting structures are strong enough, this does not automatically mean more mass in the foundations, but it does imply extended floor heights. Depending on the chosen space lay-out, partition walls may have to follow. If so, larger amounts of materials are required. Moreover, the materials, products and components in question need to be able to accommodate such applications. In other words, it has to be tested how the partition performs in such conditions, and what measures are required in the case of under-performance. Furthermore, in design guidelines for sustainable construction, the reduction of material use is rather high up in the hierarchy. This needs to be corrected with regard to *Circ-Flex* dimensioning, in Chapter 3 (Section 3.3.6) referred to as *intelligent dimensioning*. This can also be applied to raw material use and required densities for the side-panel or insulation in question. Last but not least, Chapter 6 addressed that enhancing the properties (e.g. weight and robustness) for multi-functional performance has implications for materialisation and manufacturing of the product, whilst affecting the performance of other parameters, such as circularity.

Additives

Additives come back throughout the dissertation as complicating factors with regard to circularity and health in particular. Simultaneously, additives exist because they enhance certain performance characteristics. In Chapter 5 it was shown that seemingly simple partition components, currently dominating the market, comprise dozens of ingredients that are taken for granted. Chapter 6 is dedicated to conceptualising partitioning products that avoid potentially negative impurities as well as obscured manufacturing processes. However, two considerations are particularly relevant here. First, patents and trade secrets are important instruments to secure a viable market position. This is usually at odds with full transparency for all, making it hard to pinpoint or exclude potential health and circularity conflicts, certainly in the case of innovative materials and networked partners in value chains. For example, with regard to the reversible adhesives (the Niaga® technology), access to the manufacturing recipes and processes has been restricted. Despite advanced experience with this technology in other applications (carpets, mattresses) the route towards market-introduction relating building products has not yet been completed. Secondly, additives may be vital to make the material or product fit for purpose. Fire-safety is an important example in this regard (see Section 6.5). As indicated before, further testing is required for innovative materials, such as mycelium-board insulation and NEP. Trade-offs may pop-up during this stage regarding reversible connections to facilitate flexibility and threats of wall fire flashovers to adjacent parts and compartments.

Another example is mould. Mould in homes is usually a combination of properties that originate in the infill materialisation and contextual conditions, such as room ventilation. Protective measures may thus be required where materials are concerned. In the case of mycelium-board and NEP, experiments are ongoing. In this respect, additives need to be assessed on multi *Circ-Flex* criteria. Although there may not yet be many alternatives available, ample research & development efforts are heading in this direction. This is also true with regard to decorative coatings and maintenance products, which forms another prime area of friction, concerning user-freedom, on the one hand, and health and circularity potential, on the other. Cost-benefit calculations of compliable products and the purchasing preferences of powerful clients (such as governments) are important parameters in this respect, both of which are moving into favourable directions [67,68].

Familiarity and Freedom of choice

The *Circ-Flex* partition conceptualisation adheres to a level of familiarity, in order to engage clients and users, as argued in Chapters 4 and 6. However, innovative materials, by definition, are less familiar than the conventional counterpart. This thus comprises a paradox. That being said, the type of products, construction and handling processes, as well as pricing and sourcing routes, are indeed considered compatible with familiar mechanisms. One aspect of familiarity, and the extent to which clients and users are expected to engage, is freedom of choice. As yet it is unknown what the market landscape around the innovative partition products and materials will look like, in terms of supply channels. This question is pivotal with regard to freedom of choice. In Chapter 6, *Circ-Flex* criteria and preconditions have led to a design conceptualisation based on materials and products with idiosyncratic specifications. For mycelium-board this revolves around *growing* materials, whereas for NEP the *reversible connection* is key. Both products share the fact they are platform technologies able to deal with a range of residual fibres. Although mycelium-board production is rather open source, some alloys work better than others. Professionality and precision is thus essential for the growing processes. It will depend on multiple variables whether this leads to a mature, healthy market that can produce the required quantities and qualities in time. In the case of NEP, there are additional trade secrets and patents that may hinder the market to reach maturity. Such forces and factors are exemplary of the relation between pure circularity potential of materials, on the supply side, and satisfaction with regard to availability and price-tag, on the demand side.

Future Actions

In Chapter 6 it was advocated that shaping a strong (local) narrative around a product may create a high level of user-engagement and familiarity. However, further research and practical experience is needed with regard to this assumption.

Furthermore, reflecting on the main typology referred to in this dissertation, i.e. multi-family housing, fundamental questions concern discrepancies between supply and demand sides. Housing corporations are expected to provide quality housing for reasonable prices, complying with the regulatory framework. Whether or not adaptable units and flexible partitioning walls are perceived by the residents as added value depends on specific needs and expectations. The paradigm shift that is required in the real estate and building sectors should thus be accompanied by a paradigm shift in the community of citizens that takes residence in those houses. Challenging basic concepts does not necessarily imply radical change. However, an effective gradual transition will require a concerted effort of housing corporations, authorities, residents, manufacturers, architects, constructors, resource managers, infill product & service providers, and monitoring system developers. It goes without saying that threats of trade-offs between the parameters of circularity, flexibility, and user health can emerge on multiple levels, intersections, and moments in time, underscoring the complexity of a seemingly straightforward value system around non-bearing interior partitioning.

7.2 Reflection on the Methodology

The described mixed-method approach contributed to an iterative way of establishing and streamlining goals, understanding, support, and evaluation, in line with the DRM framework (see Section 1.4). As such, it helped me greatly to reveal hidden or unknown aspects of potential circular solution routes from a transdisciplinary viewpoint. The methodological emphasis has been on qualitative approaches, where applicable supported by quantitative methods and tools. As addressed throughout the dissertation, the complex and relatively new field of circular and user-inclusive building has shown discrepancies in interpretations and elaborations, within and between academia and practice. This necessitated, first and foremost, an overview of the landscape, for which literature review, expert consultations, and workshops proved to be fitting methods. Furthermore, the different vantage points of each research chapter required specific approaches.

In Chapter 3, I derived basic preconditions and guidelines, for which the aforementioned methods sufficed. In Chapter 4, additional study and consultations were necessary to better uderstand residential user-centred perspectives. In this section, the possibility of surveys and user interviews was considered as well. Yet, the integrated scope of the research asked for a more pragmatic approach, knowing that extracting meaningful results from residential surveys is a long, laborious and time intensive trajectory, weighing disproportionally on the overall goals, scope and planning of the dissertation framework. Short-cutting this aspect allowed me to achieve meaningful results in other domains and with regard to the research as a whole. The four cases and expert consultations in this chapter were primarily targeted at the residential user, building on the experiences in projects with a strong occupant-driven perspective. That being said, giving the floor to residents in a more participative manner could further validate and contextualise the outcomes in follow-up research efforts. Chapter 5 demanded a deep analysis of assessment schemes. Those schemes comprise qualitative and quantitative components, which have been reflected upon and, where applicable, integrated into an enhanced set of *Circ-Flex* criteria (*Circ-Flex II* in Figure 1.17, of Chapter 1). These criteria, in turn, were applied and evaluated in Chapter 6, by means of a design conceptualisation. Applying the design conceptualisation method gave me more practical understanding of what thus far had been a predominantly theoretic exercise. The key aspects of the design conceptualisation were: materialisation, and operational value chains. Particularly interesting to me are the interrelations between those two aspects, not least with regard to the use of secondary materials. This required a sophisticated approach to qualitative and quantitative details of material availability. The applied Activity-based Spatial Material Flow Analysis method was, although rather novel, found to be robust enough to connect local materials, actors, activities and spatial manifestations.

Finally, I utilised external lab results with regard to properties and behaviours of mycelium materials. As addressed in Section 7.1.8, on the way to market introduction more lab tests are required, as well as testing in an operational setting. Preparations for such tests are made within and beyond the framework of this dissertation, to unfold in the coming year, that will hopefully provide missing pieces of the puzzle.

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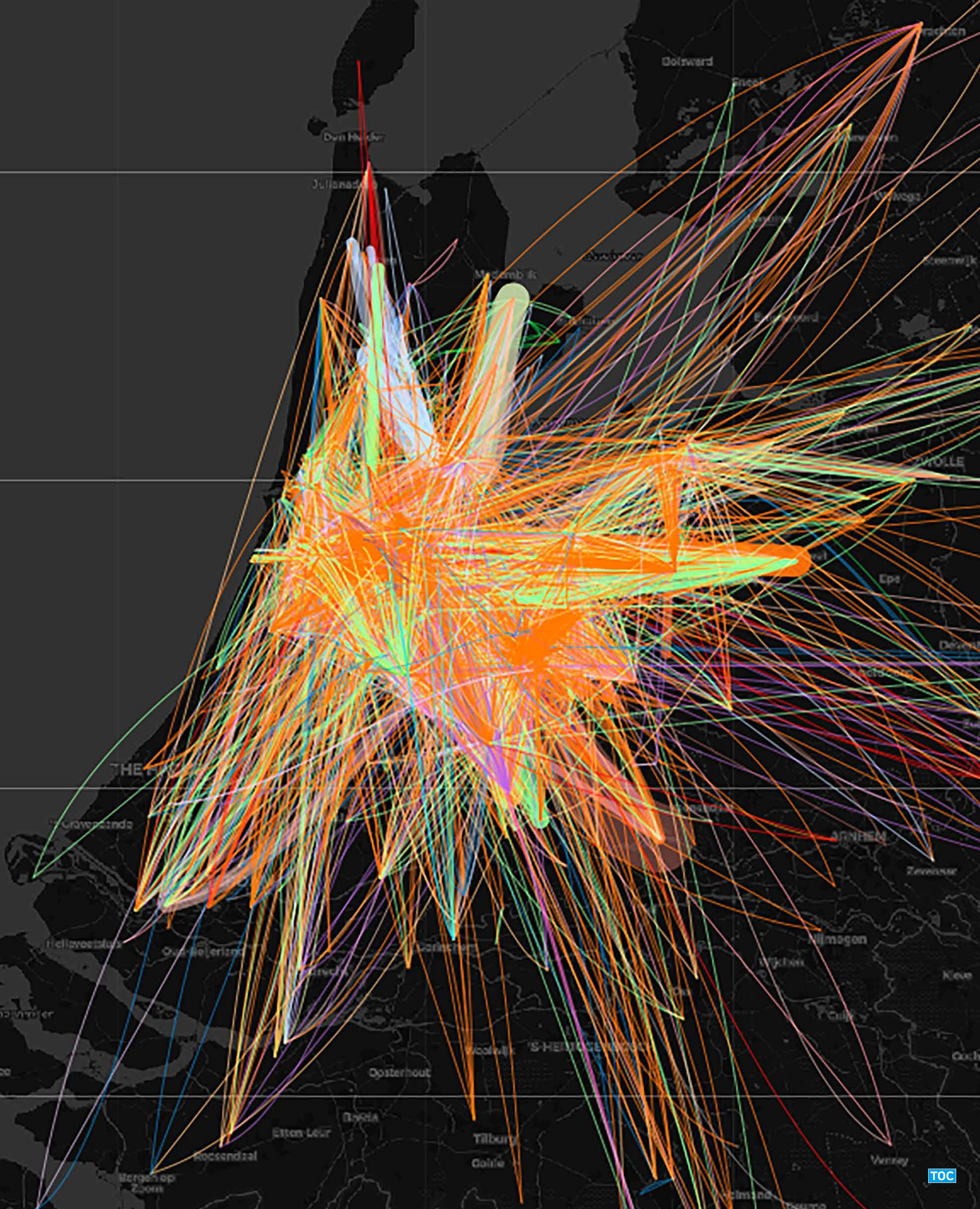
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Tilburg
Goirle
Roosendaal
Bergen op Zoom
Hellevoetsluis
Oud-Beijerland
Venray

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8 Conclusions & Outlook

In Section 8.1, the overarching research objectives and questions, formulated in the introduction, are discussed and conclusions are drawn. Where applicable, conclusions from Chapters 3-6 are revisited. Next, in Section 8.2, a brief outlook and final recommendations are formulated.

8.1 Conclusions

In this section, the two main research questions and their sub-questions are discussed and conclusions are drawn. In Table 8.1, at the end of this chapter, the conclusions are summarised.

8.1.1 Research Question I

The first research question (RQ I) and the associated sub-questions (SQ 1 and 2) are formulated below, followed by two paragraphs that successively introduce conclusion 1 and 2.

RQ I: In an Open Building division of support and infill, to what extent can the infill contribute to sustainable circular material & product flows?

- *SQ 1: What are the preconditions for the performance of materials, products, services and buildings in the case that circularity is a leading ambition? (Chapter 3)*
- *SQ 2: Which aspects are key with regard to - the relationship between - flexible partitioning, circular material flows, and user benefits? (Chapter 3 and 4)*

Circularity and Flexibility

RQ I starts from a two-level approach (separation of support and infill) in the design and construction of a given multi-family building. The underlying hypothesis is that such an approach is indispensable for accommodating user dynamics, while simultaneously facilitating infill parts to circulate in tailored ways. Something similar goes for the shearing layer approach of Duffy and Brand, addressed in Section 1.3.1, albeit with less emphasis on decision-making concerns. The common denominator is: flexibility over time. As stated in, most explicitly, Chapters 2, 4 and 7, thus far the Dutch building sector has hardly taken that into account. However, the current attention for circular building provides leverage for change. A first realisation in this respect is that circularity in the built environment can only be facilitated if flexibility becomes fully integrated in the whole building paradigm. I found that, against the backdrop of strong sustainability concerns, particularly regarding SDG11 (Sustainable Cities & Communities) and SDG12 (Responsible Production & Consumption), the opposite also holds true: flexibility in the built environment, being a dynamic property, cannot be seen in isolation of circular handling and management of the associated parts up to the raw material level. This implies that infill parts should always be coupled with appropriate, differentiated materialisation and operation routes. In other words, flexibility should not be established without conscientious detailing of material and material-flow profiles, nor should circularity be established without close consideration of flexible use and associated service lives, as these are two sides of the same coin, which quite literally represents value. This paragraph thus underscores the reciprocal relationship between circular and flexible. The first conclusion is formulated as follows:

CONCLUSION 1:

Circularity in the built environment can only occur if flexibility is fully integrated in the whole building (component) value network, and conversely, flexibility in the built environment increasingly depends on the handling and management of materials designated for healthy, circular applications.

Interplay and Attitudes

Conclusion 1 is linked to the fact that, beyond materialisation and operational facets, *Circ-Flex* partitioning depends on a framework that facilitates and stimulates appropriate codes of conduct among the value network (e.g. regulations, contracts, and monitoring). Moreover, in Chapter 5 in particular, other features were mentioned that are decisive factors for the overall sustainability of a *Circ-Flex* system, such as embodied energy and social fairness.

The diagram of Figure 7.8 (Section 7.1.4) is an example of a circular flow model for indoor partition-parts, with a central role for logistics & storage. This stage will gain prominence, streamlining material flows based on stakeholder requirements, quality and quantity of materials and products, as well as spatial and temporal specifications. A prime stakeholder is the residential end-user.

Currently, residents are usually referred to as consumers, part of a consumer society. If infill components shift from the domain of architects and builders to the private domain of users and retailers, a production/consumption model may arise based on product-customisation and associated market mechanisms. IKEA has been mentioned as an example frame of reference in this respect. For this to develop into a model that also supports circularity, however, more is needed. The question is whether and to what extent these users can and will anticipate circular value cases, whilst becoming *pro*sumers rather than *con*sumers, in analogy of empowerment in the renewable energy transition. This largely depends on the incentives and the engagement, or force, of other cogs in the machine, such as suppliers, secondary-material brokers, financiers, and authorities. When projecting the circular value model of Figure 7.8 to the users of common residential typologies (or actors representing these users) who are about to replace a partitioning wall, current shortcomings in the system are clear: levels of sophistication and differentiation in operation, supply logistics, material management, and data exchange are simply insufficient. Figure 8.1 visualises this. These shortcomings resonate also in the limitations I observed concerning performance evaluations. Incentivising and engaging users to act in accordance with the new model is inextricably part of the envisioned transition, for example through co-creative processes of familiarising and sensitising, and resident-friendly monitoring, as addressed in Sections 3.4, 4.4, 5.6, 6.6, and 7.1.2. This leads to the second conclusion:

CONCLUSION 2:

Infill parts, implemented in an Open Building context, enable multiple short to medium length cycles within the longer service lives of multi-family building structures, following changes in user requirements. As such, this model accommodates more sustainable product and material flows. However, decisive success factors are the attitude of and interplay between actors in the value network, not least the end-user.

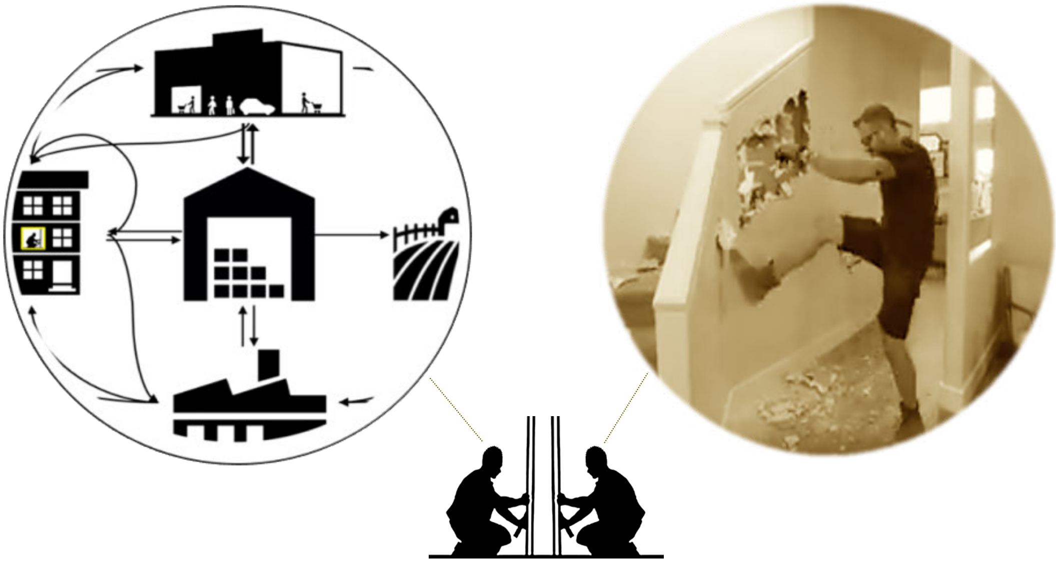

FIG. 8.1 What's on a resident's mind? [Sources: Bob Geldermans and 'Mr. Build It']

8.1.2 Research Question II

The second research question (RQ II) and its associated sub-questions (SQ 1-6) are formulated below, followed by five paragraphs that introduce conclusions 3-8. The first paragraph relates to SQ 1 and 2; the second paragraph to SQ 3; the third paragraph to SQ 3, 4 , and 5; the fourth paragraph to SQ 4, 5, and 6; and the fifth paragraph relates to SQ 6.

RQ II: Which qualitative and quantitative criteria and preconditions are central to integrating notions of user health & well-being, circularity, and flexibility in infill configurations?

- *SQ 1: What are the preconditions for the performance of materials, products, services and buildings in the case that circularity is a leading ambition? (Chapter 3)*
- *SQ 2: Which aspects are key with regard to - the relationship between - flexible partitioning, circular material flows, and user benefits? (Chapters 3 and 4)*
- *SQ 3: How can residential health & well-being be integrated in the design and performance assessments of indoor partitioning products adhering to a circular model? (Chapters 4 and 5)*
- *SQ 4: How can materialisation be integrated in the design and performance assessments of indoor partitioning products adhering to a circular model? (Chapters 5 and 6)*
- *SQ 5: How can operational processes be integrated in the design and performance assessments of indoor partitioning products adhering to a circular model? (Chapters 5 and 6)*
- *SQ 6: What are notable disruptive innovations that have the potential to challenge the status-quo, enabling the implementation of appropriate, systemic circular value models? (Chapter 6)*

Technical accommodation of circularity

To answer RQ II, I have first unravelled it into sub-parts, starting with an examination of basic design aspects concerning the technical accommodation of circular material and product flows in construction. In Chapter 3, I highlighted that the level to which intrinsic and relational properties are aligned is a decisive factor. The intrinsic is linked to material and product characteristics, the relational to building design and intended use characteristics. Furthermore, a subsequent step was taken in Chapter 3, by linking building layers and regeneration routes in an inventory matrix (Figure 3.4). The building layers (vertical columns in the matrix) follow Design for Flexibility and Design for Disassembly concepts, adhering to Stewart Brand's shearing layers of change, whilst further breaking them down into (raw) materials, (single) products, and (assembled) components. Reutilisation routes (horizontal rows in the matrix of Figure 3.4) follow multiple biological and technical cycles as proposed within C2C® and Circular Economy frameworks.

CONCLUSION 3:

Technical circularity potential of building products and materials resides at the intersection of intrinsic and relational characteristics.

CONCLUSION 4:

The differentiation of building layers and parts, in combination with differentiated reutilisation routes, provides leverage for more advanced approaches to circular building strategies, anticipating multiple handling and treatment processes.

Residential user integration

In Chapter 4, I extended the circular building discourse to the domain of the residential user. In a first set of *Circ-Flex* criteria, user related criteria became part of an integrated set addressing flexibility, circularity and user capacity. The latter concerns the mental and behavioural engagement and response that precedes or follows activities by the user. This user response is subjective and may overrule solutions chosen by designers and engineers. Multiple drivers can be decisive forces in this respect, leading to purchasing behaviour that is either in favour of or at the expense of circular and flexible aspects. Two criteria were highlighted: the willingness to engage or invest (in time and money) and freedom of choice. Providing the user with more control over the infill can positively impact the perceived value of existing real estate, while simultaneously opening up to new collaborations and ownership configurations with regard to infill customisation. Flexibility aspects of *Circ-Flex* partitioning can benefit end-users, housing-owners, and suppliers of parts, whereas circularity aspects would predominantly benefit suppliers and actors in secondary material processing or trade. Furthermore, the residential health aspect was put at the forefront of this research, centred around the end-user but essentially benefitting the whole value chain. The search for new value models should thus depart from shared incentives, explicitly empowering residential users. In the Dutch housing sector, developments in this direction are in their infancy, and business case innovations tend to emphasise the supply side.

CONCLUSION 5:

To bring circular building to scale in a socially engaged way, value models need to take account of actors' shared incentives around flexibility and health, as well as split incentives around circularity.

Health, Well-being, and Operational Performance

In a further analysis of standards and assessment methods, I examined criteria and preconditions in relation to health, well-being, and operational performance. In a synthesis step, based on three existing frameworks, an elaborated set of *Circ-Flex* criteria was developed in Chapter 5. Eight categories, comprising eighteen criteria, were defined to provide more grip on the dynamic nature of circularity potential, as well as the impact of partitioning products in relation to residential health. A main outcome of this exercise was the identification of 'orphan operational processes', that is, those processes that are likely to play a decisive role in determining the *Circ-Flex* potential, but which continue independently from any 'parental links' and become blind spots in assessment schemes. From the study in Chapter 5, I concluded that most schemes take a limited scope and approach, with little attention for residential health and operational processes. Moreover, these approaches lean heavily on assumptions, statistics, and scenarios that can be arbitrary or even misleading. To secure healthy circular material flows, inventories of buildings and their constituent parts should anticipate all flow characteristics that may impact the quality, whilst including feedback loops dealing with interventions and evaluations by stakeholders over time. This will contribute to gradually establishing more sophisticated and comprehensive data sets.

CONCLUSION 6:

Monitoring the operational performance is key for capitalising on the intrinsic health and circularity potential of building components during their service life.

Trans-disciplinarity

Product performance from an expanded system-boundary perspective, including supply and reverse supply in the whole value chain, has been further elaborated in Chapter 6. Next to the utilisation of the *Circ-Flex* criteria and guidelines, a novel method was applied to analyse secondary material flows, namely the Activity-based Spatial Material Flow Analysis (AS-MFA), developed within the framework of the European Horizon 2020 project REPAiR (see Section 6.3). This method enabled an advanced perspective on current waste flows that may be utilised as secondary raw materials. Although initially developed for six specific European case-study areas, including the Amsterdam Metropolitan Area, the model can be applied anywhere, depending on the available data. These are important developments in assessing qualities and quantities, as well as current treatment and processing routes, of materials that could function as raw material for partitioning, and other infill products. This provides a deeper look into current waste behaviour and management, and local sourcing potential for supply chains. In Chapter 6, I have given a few examples regarding raw materials for partition parts, directing specific attention at materials that currently end up in the incinerator. This links with the (inter)national discourse around pros and cons of energy recovery from waste, against the backdrop of a society's sustainability strategies and ambitions. Furthermore, I have coupled value chain activities to spatial scale levels (Chapters 6 and 7), comparing the status-quo with innovative partitioning concepts. By spatially positioning the activities depicted in Figures 7.7 and 7.8, existing gaps between resource management, urban metabolism, and spatial development can be detected. The AS-MFA thus brings us a step closer to understanding circular material flows in the light of urban ecosystems.

CONCLUSION 7:

Research and design exercises into circular building concepts and products benefit reciprocally from data and experience in adjacent disciplines, such as urban planning and waste management, whilst integrating multiple sub-systems associated with value creation in circular models.

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Innovative Materialisation and Value Network

In Chapter 6, I included a design conceptualisation based on innovative materialisation, aimed at sub-question 6. Two bio-based innovations came out of the selection procedure that preceded the conceptualisation. That said, one of the two (the Niaga ECOR Panel: NEP) actually boasts a reversible hybrid of biological and technical materials. This underscores the applied interpretation of the term 'renewability', including both the biological and technical domain. In the NEP case, however, operational proof is needed to show that the technical material can indeed be used over and over again without addition of resources that contribute to depletion. When comparing conventional partition materialisation and operations, I indicated that primary modifications are thought to occur in raw material sourcing, manufacturing, reutilisation logistics, and data-sharing. However, even if those stages are perfectly streamlined and conditioned for circularity, the chain needs to be activated by a client. This client could be a housing corporation, for example, or their target group: users of residential buildings. Freedom of choice, costs, and "hassle-free" systems have been referred to as key concerns for that group. The behavioural patterns behind such requirements, in relation to circular value model development, are a prime area of attention for follow-up research.

CONCLUSION 8:

Modifications associated with the innovative partition concepts occur above all in raw material sourcing, manufacturing, reutilisation logistics, and data-sharing, of which the latter should extend to the end-user.

TABLE 8.1 Research questions and main conclusions derived from the answers [Source: Bob Geldermans]

Research Question	Conclusion
RQ I. In an Open Building division of support and infill, to what extent can the latter contribute to sustainable circular material & product flows?	1. Circularity in the built environment can only occur if flexibility is fully integrated in the whole building (component) value network, and conversely, flexibility in the built environment increasingly depends on the handling and management of materials designated for healthy, circular applications.
	2. Infill parts, implemented in an Open Building context, enable multiple short to medium length cycles within the longer service lives of multi-family building structures, following changes in user requirements. As such, this model accommodates more sustainable product and material flows. However, decisive success factors are the attitude of and interplay between actors in the value network, not least the end-user.
RQ II. Which qualitative and quantitative criteria and preconditions are central to integrating notions of user health & well-being, circularity, and flexibility in infill configurations?	3. Technical circularity potential of building products and materials resides at the intersection of intrinsic and relational characteristics.
	4. The differentiation of building layers and parts, in combination with differentiated reutilisation routes, provides leverage for more advanced approaches to circular building strategies, anticipating multiple handling and treatment processes.
	5. To bring circular building to scale in a socially engaged way, value models need to take account of actors' shared incentives around flexibility and health, as well as split incentives around circularity.
	6. Monitoring the operational performance is key for capitalising on the intrinsic health and circularity potential of building components during their service life.
	7. Research and design exercises into circular building concepts and products benefit reciprocally from data and experience in adjacent disciplines, such as urban planning and waste management, whilst integrating multiple sub-systems associated with value creation in circular models.
	8. Modifications associated with the innovative partition concepts occur above all in raw material sourcing, manufacturing, reutilisation logistics, and data-sharing, of which the latter should extend to the end-user.

8.2 Outlook

This research revolved primarily around indoor partitioning, but the findings can transfer to other infill components as well, including kitchen cabinets, furniture, stairs, and the interior side-sheeting & insulation of walls and ceilings in energy renovations. Although many findings from this dissertation concern biological materials and products, validity extends to their technical counterparts: based on the thorough, secured integration of upstream, downstream, and in-use stages, the *Circ-Flex* criteria do not favour one or the other. The combination of materials in partitioning is key, particularly in regard of functional combinations, integrating room division and electric or ICT provisions, for example. Research and development in this direction is becoming increasingly advanced, often in collaborations between knowledge institutes and partners from the industry. Nonetheless, regardless of several great initiatives, the gap between conceptualisation and large-scale practical impact needs to be bridged. Given the accent on biological materials in this dissertation, I would reccommend to conduct follow-up research efforts specifically aimed at technical materials. Some were already referred to, such as steel and aluminium, but many other building materials apply. In that respect, *Circ-Flex* criteria can go beyond what are considered regular infill components, for example façade elements. Reversible connections are most relevant here, notably with regard to *renewability* in the context of technical material cycles.

Securing healthy circular material flows in the built environment cannot be the objective of one industry, let alone one organisation, but demands a reshuffle of value propositions, impacting arguably all networked actors. This includes binding agreements and multi-criteria learning loops. Binding agreements immediately put the spotlight on legal frameworks. This would thus be a prime area for further action. The aspect of multi-criteria learning loops leads to the necessity to include residential end-users of infill components. The group of end-users has one of the main keys to bring the discourse to the next level, primarily relating to *health & well-being* and *flexibility*. With respect to *circularity* of material flows, other important factors are revealed, resulting from a growing body of knowledge and experience. Here, multi-scale pespectives are indispensible, based on the cross-cutting nature of circularity. Circularity potential depends on:

- intrinsic material properties and the way materials are assembled into a product;
- the adaptibility of a building’s design to accommodate the product in the intended way;
- the way the building is used;

- the logistics that facilitate safe circulation;
- the way land is used effectively to produce, store, and reprocess goods that can continue to function in differentiated circular service iterations;
- and the quality of data-exchange concerning the aforementioned aspects.

Over half a century ago the Open Building discourse began from the desire to separate decision-making domains in relation to spatial scales, emphasising the required accommodative capacity on each level. Today, this notion gains new meaning, catalysed by the momentum around Circular Building. Although this research confirmed that Open Building and Circular Building can be two sides of the same coin, it has nonetheless led to nuances in this relationship. Accommodating *unforeseen* use of space is one thing, but accommodating *foreseen* circularity-conditions for material management, which cuts through scales and decision domains, is something different. Tension between interests and perceived value of stakeholders is likely, not least between housing residents and professionals in the building sector. Now that the Circular Building discourse becomes more advanced, research efforts should continue to enhance the debate in this respect, taking account of different, and dynamic, socio-economic and socio-cultural contexts.

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Curriculum Vitae

R.J. (Bob) Geldermans

Beverwijk, 1970

Education

- Doctoral Education Programme, Delft University of Technology, 2015 – 2020
- Master of Science Industrial Ecology, Leiden University and Delft University of Technology, 2007-2010. Graduation Topic: *Cradle to Cradibility of Two Material Flows in Construction: Wood and Composites*
- Bachelor of fine Art, Utrecht University of the Arts, 1992-1996

Professional Experience

- Researcher and Lecturer, Chair of Climate Design & Sustainability, Department of Architectural Engineering + Technology, Delft University of Technology, Delft, the Netherlands, 2011 – present
- Circularity Expert, Team Sustainability Campus Real Estate, Delft University of Technology, Delft, the Netherlands, 2020 – present
- Program Manager Circular City Research at the Amsterdam Institute for Advanced Metropolitan Solutions, Amsterdam, the Netherlands, 2016-2019
- Head of Section Climate Design, Department of Architectural Engineering + Technology, Delft University of Technology, Delft, the Netherlands, 2015 – 2016
- Consultant at Except Integrated Sustainability, Rotterdam, the Netherlands, 2010 – 2012
- Advisor at the Ministry of Economic Affairs, The Hague, the Netherlands, 2009-2011
- Freelance Designer: eco-design & green architecture, Utrecht/Rotterdam, the Netherlands 1996 – 2007

Selected Publications

- Circular Building Design for the Infill Domain: Materialisation and Value Network Study of the Niaga ECOR Panel Innovation. Geldermans, B., Tavakolly, N., Udding, H-J. IOP proceedings on the Earth and Environmental Science Journal, Conference Beyond2020, Gothenburg, Sweden, 2020 (Submitted, March 2020).
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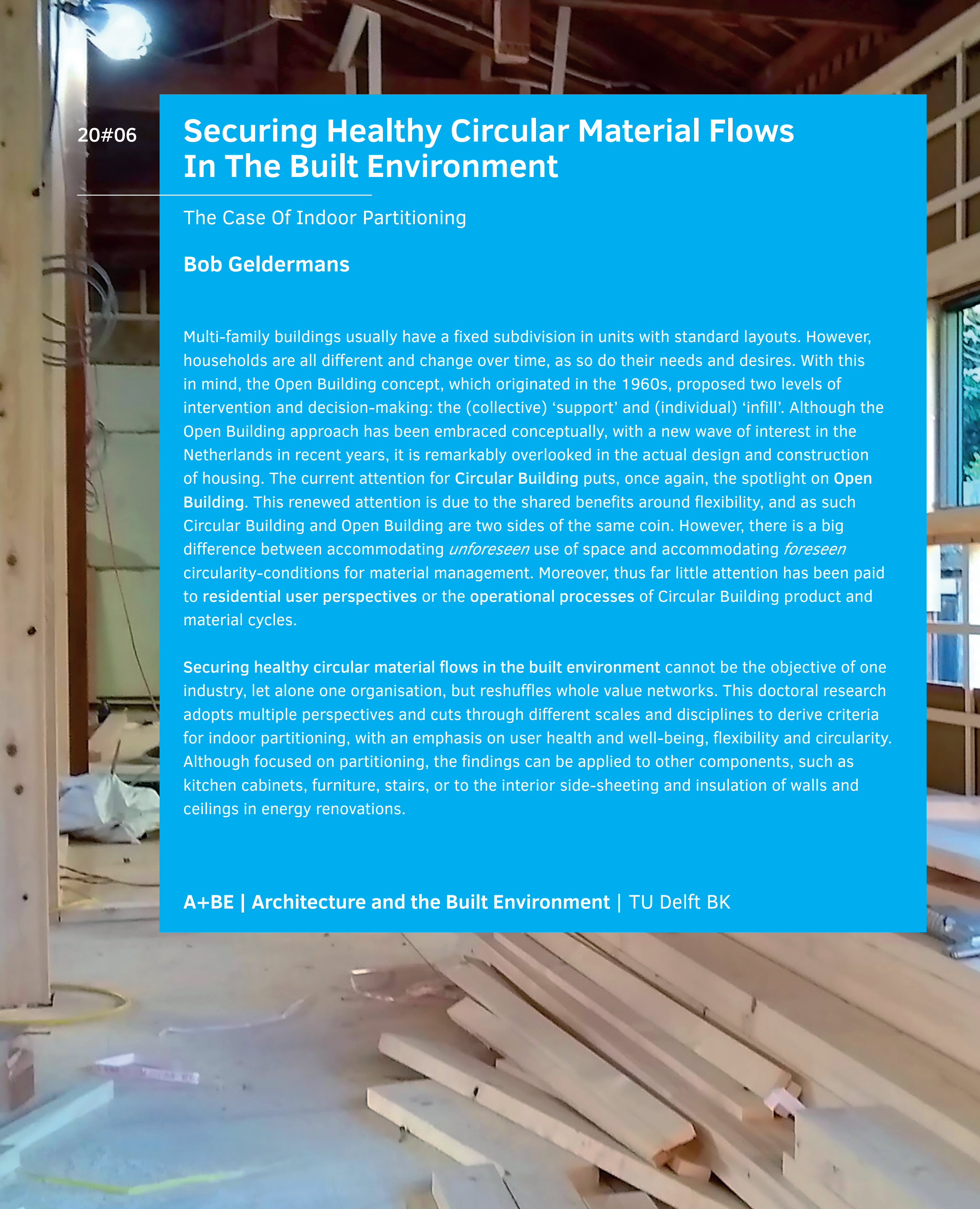

20#06

Securing Healthy Circular Material Flows In The Built Environment

The Case Of Indoor Partitioning

Bob Geldermans

Multi-family buildings usually have a fixed subdivision in units with standard layouts. However, households are all different and change over time, as so do their needs and desires. With this in mind, the Open Building concept, which originated in the 1960s, proposed two levels of intervention and decision-making: the (collective) ‘support’ and (individual) ‘infill’. Although the Open Building approach has been embraced conceptually, with a new wave of interest in the Netherlands in recent years, it is remarkably overlooked in the actual design and construction of housing. The current attention for **Circular Building** puts, once again, the spotlight on **Open Building**. This renewed attention is due to the shared benefits around flexibility, and as such Circular Building and Open Building are two sides of the same coin. However, there is a big difference between accommodating *unforeseen* use of space and accommodating *foreseen* circularity-conditions for material management. Moreover, thus far little attention has been paid to **residential user perspectives** or the **operational processes** of Circular Building product and material cycles.

Securing healthy circular material flows in the built environment cannot be the objective of one industry, let alone one organisation, but reshuffles whole value networks. This doctoral research adopts multiple perspectives and cuts through different scales and disciplines to derive criteria for indoor partitioning, with an emphasis on user health and well-being, flexibility and circularity. Although focused on partitioning, the findings can be applied to other components, such as kitchen cabinets, furniture, stairs, or to the interior side-sheeting and insulation of walls and ceilings in energy renovations.

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