Towards circular and energy-efficient management of building stock: an analysis of the residential sector of the Netherlands

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Chapter 7

General discussion

7.1 Introduction

The overall aim of this thesis was to understand the potentials to enhance the material circularity and energy efficiency of the Dutch building stock through circularity strategies at different levels: lifetime extension of buildings, reuse and production of building components with recycled materials, and recycling of materials, all with a focus on concrete. For the analysis of functional units at the level of specific products and materials, the analytical tools life cycle assessment (LCA) and life cycle costing (LCC) have been applied. To scale up the analysis to flows and stocks of certain construction materials and buildings in the Netherlands as a whole, LCA and LCC were combined with dynamic MFA (material flow analysis). This chapter synthesized the main findings and provided general discussions. Having these insights can help developers and policymakers make better-informed decisions in the sustainable design of construction products and political interventions.

This thesis started by exploring the life cycle environmental and economic impacts of four technologies (as examples for circularity interventions at the material level) for high-quality concrete recycling (Chapter 2). The recycled concrete aggregates are used to produce prefabricated concrete elements (PCE), PCE-new for new construction and PCE-refurb for energy refurbishment. Two separate LCA-LCC studies were carried out to capture the life cycle environmental and economic profile of the PCE-new and PCE-refurb (as examples for circularity interventions at element level; Chapters 3 and 4). To understand the future application limits of PCEs, a dynamic building stock model was constructed to estimate the future supply of construction and demolition waste (CDW) (e.g. concrete aggregates) and the demand of secondary raw materials for PCEs in new construction and building energy renovation (Chapter 5). As a final step, the product-level assessments were scaled up to a country-level by connecting the LCC and LCA studies with the dynamic MFA study (Chapter 6). Based on the findings reported in Chapters 2 through Chapter 6, this concluding chapter will provide answers to the research questions posed in Chapter 1.

7.2 Answers to research questions

This section presents answers to the five research questions and the overall question.

7.2.1 Assessment of concrete recycling at the product (material) level

Research question 1 was formulated as follows:

RQ1. Is it possible to achieve environmental-economic win-win situation in high-grade concrete recycling? Would the innovations trigger any potential problem-shifts between different impact categories?

High-value recycling is the circular strategy at the material level. Waste concrete is the most voluminous constituent of CDW generated in the EU member states. In most cases, CDW is crushed and downcycled to low-grade applications such as road foundations and filler under buildings. There are technologies that lead to high-grade recycling of concrete. The case study in Chapter 2 investigated the eco-efficiencies of four technological systems for the high-value-added recycling of concrete. It concluded that it is possible to achieve an environmental and economic win-win situation by recycling the waste concrete as local as possible and producing as much as possible high-value secondary products (e.g. cementitious fines). We found the most environmentally sound and cost-saving way for concrete recycling is the integrated advanced dry recovery (ADR) and heating air classification system (HAS), which had the highest eco-efficiency score.

Potential problem shifts between different impact categories were noticed. In order not to leave out any impact category that may have a significant impact, a comprehensive ILCD method recommended by the Joint Research Centre of the European Commission was selected as the impact assessment method for LCA. The integrated ADR and HAS technology is superior to the other technological system for 10 out of 15 investigated environmental impact indicators. At the same time, it has the highest environmental impact in photochemical ozone formation, particulate matter, acidification, terrestrial eutrophication, and marine eutrophication. These drawbacks are due to the fact that the pilot-scale HAS still uses fossil fuel (diesel) to thermally decompose the concrete waste. An industrial-scale HAS using cleaner energy such as renewable electricity could be a direction to go. This case study evidenced the need for a broader environmental perspective.

7.2.2 Assessment of the PCE-new system for new building construction at the product (element) level

Research question 2 was formulated as follows:

RQ2. What are the environmental and economic implications of using the prefabricated element system (PCE-new) for cladding walls to improve building energy efficiency in new constructions in the Netherlands?

Improving the thermal insulation level of façades is seen as an essential method in the proposed energy-efficiency interventions to upgrade the energy performance of building stock. This can be achieved by using the high thermal performance PCE systems to construct the wall of new buildings, either "green PCE-new" made of recycled aggregates and aerogel or "baseline PCE-new" made of primary aggregates and EPS for cladding walls. A combined LCA and LCC study (see Chapter 3) was carried out to assess the carbon mitigation potential and the life cycle costs of using the green PCE-new as façade for a new building over 120 years, in comparison to those of manufacturing and using a baseline PCE-new. The results show that the GHG mitigation potential of the green PCE-new is only slightly better than the baseline PCE-new. This is because the implementation of the experimental thermal material – aerogel, which although achieves a lower thermal transmittance than the conventional insulation EPS, the production of aerogel is much more energy-intensive and emits more GHG. From a life cycle point of view, using green PCE-new is slightly cheaper if it considers the internal costs only. If on top of this the external costs of GHG emissions are included, avoided emissions lead to an additional cost advantage. By internalizing the environmental revenue, the extended life cycle costs enhance the economic advantage of green PCE-new, though a wider uncertainty in cost estimation needs to be considered.

7.2.3 Assessment of the PCE-refurb system for existing building renovation at the product (element) level

Research question 3 was formulated as follows:

RQ3. What are the environmental and economic implications of using the prefabricated element system (PCE-refurb) to over-clad existing buildings for energy refurbishment in the Netherlands? How is the applicability of the PCE-refurb under different climatic conditions?

Design for reuse is an important circular strategy for new buildings at the element level. The majority of existing houses in the Netherlands and Europe are still energy inefficient. Therefore, renovating those old houses is of great significance towards a low-carbon built environment. Chapter 4 presents an LCA-LCC study that assesses the potential life cycle impacts of using 'green PCE-refurb' for energy refurbishment of existing houses on energy conservation, carbon mitigation, and cost reduction in the Netherlands. As the remaining life spans of old buildings in the Netherlands vary widely, the life spans for the assessment cannot be directly determined. Therefore, the payback period is used to combine LCA and LCC to investigate a breakeven point. We analyzed if the carbon emission, investment, and energy use of the PCE-refurb embodiment can be paid back by the savings in operational energy use, costs, and emissions of the building during this period. It appeared indeed to be positive energy and carbon payback (approximately 17 years), however not to be the case for economic payback (more than 100 years). This indicates that manufacturing and using a PCE-refurb for energy renovation will reduce energy use and GHG emissions but it is costly. The PCE refurb can however be designed in a reusable way by applying easy-to-disassemble joints. Such design allows them to be reused again after one service life, which helps to overcome this cost gap. It was found that using secondary materials in the PCE-refurb can just slightly reduce the three types of payback periods, while the reuse of the PCE-refurb can considerably shorten the three types of payback periods in three cases. To comprehensively examine the applicability of the PCE-refurb system, two additional Swedish and Spanish cases were conducted. Results show that implementing the PCE-refurb in a colder zone would result in shorter payback periods for energy conservation, carbon mitigation, and costs.

7.2.4 Assessment of turnover of housing stock at the country level

Research question 4 was formulated as follows:

RQ4. How much CDW from the construction, demolition, and renovation of the Dutch housing stock will arise from 2015 to 2050? To which extent the CDW can be recycled as a feedstock in building energy renovation in the Netherlands?

Implementing circularity interventions at a country level needs to additionally consider the local market condition and material constraints. Enhancing building energy efficiency by energy renovation will lead to structural changes in demands for construction materials and CDW generation in the Netherlands. An illustration is the use of novel insulation for better thermal insulation performance and that of non-structural lightweight concrete for weight load reduction. To explore to which extent the use of recycling materials in the PCE system for building energy renovation can improve the recycling potential, a case study on the Dutch residential building stock was carried out (see Chapter 5). Using a dynamic material flow analysis, this work explores the supply-demand balance of secondary raw materials made from CDW (including normal-weight and lightweight concrete, glass, insulation mineral wool, steel) and the secondary raw materials demanded for manufacturing PCEs in building energy renovation from 2015 to 2050. The main results show: with the advanced recycling system ADR and HAS, the secondary raw materials recovered from normal-weight concrete waste, glass waste, and insulation mineral wool waste will be more than sufficient to support the manufacturing of PCE-new walls. However, secondary material made from lightweight concrete will not be sufficient in a near future to meet the raw material demand. For large scale refurbishment with PCE-refurb walls, virgin expanded clay, sand and cement would be needed to complement the available amounts of recycled materials. It was also found that the Netherlands still will have to rely on imports to satisfy its demand of specific mineral materials (e.g. gravel, expanded clay, cement, and limestone). Using the novel technological system ADR and HAS to recycle concrete waste has the potential to supply all the normal concrete aggregates needed for housing energy renovation in the Netherlands. Additionally, the Dutch case study projected the amount of CDW generated from the construction, demolition, and renovation activities for the period 2015 to 2050.

We found that CDW generated from demolition activities is still the primary waste stream; while the amount of CDW from renovation activities even exceeds the amount of CDW from construction activities. If the Netherlands and the EU hence will embark on an extensive renovation of houses to make them energy-efficient, it is hence important to pay more attention to the management of renovation waste.

7.2.5 Assessment of implementing the recycling and the prefabrication systems at the country level

Research question 5 was formulated as follows:

RQ5. What are the up-scaled environmental benefits and economic consequences of implementing the recycling and prefabrication systems in the Netherlands? To which extent can the proposed recycling and prefabrication system achieve the prospective circularity goal and decarbonization goal of the Netherlands?

An integrated framework was proposed to combine a top-down dynamic building stock model with the LCA and LCC models to evaluate the scaled-up impacts of applying the proposed PCE solutions to improve the thermal performance of the residential building stock in the Netherlands from 2015 to 2050. We considered three scenarios: (i) business-as-usual (BAU) scenario that which does not apply any renovation strategy, (ii) (rebuilding) REB scenario in which old houses are demolished and reconstructed, and (iii) Renovation (REN) scenario in which old houses are demolished and refurbished instead of reconstruction. The building stock model was used to simulate the sizes of construction, demolition, renovation floor area per annum, and stock cohorts in the three scenarios. The LCA and LCC models were deployed to estimate per unit life cycle GHG emissions, costs, and material footprints of the proposed PCE system. Then the unit results were up-scaled using the sizes of the stocks and flows estimated from the dynamic building stock model.

The results were expressed via an annualized-value approach and an actual-value approach. The actual-value approach adds up actual costs and impacts of the energy use of the Dutch housing stock and construction and demolition activities each year to a total in that year. The annualized-value approach calculates the operational energy use the same way as the actual-value approach but distributes costs and impacts, which occur in the construction and demolition phases, as annualized values per year per m^2 per housing type over the lifetime of a house. The selection of different estimation approaches led to different conclusions. The actual-value approach suggests the use of the PCE system for Dutch housing energy renovation would achieve GHG mitigation with increased material use and financial cost. However, the annualized-value approach suggests the overall benefits of the PCE system on all three aspects.

This study also evaluated the extent to which the circularity and decarbonization goals can be realized by applying the proposed PCE system to the Dutch residential building stock. The Netherlands aims to achieve a reduction of 50% of primary material use by 2030 compared to the 2015 level. The results show all three scenarios cannot reduce resource use till 2050. Regarding the circularity goal by 2050, advanced technological systems in the REN scenario can raise the recycling rate from the current 25% to 98%. However, the associated embodied emissions of the REN scenario is twice as the BAU scenario, resulting from using aerogel as insulation. Therefore, applying the PCE system alone is less likely to let the Netherlands reach the circularity goal by 2030 and 2050.

Furthermore, operational GHG emissions of the residential building stock in 2030 and 2050 were quantified under different scenarios. We found that the BAU scenario which does not have any energy renovation strategy, will not achieve the decarbonization goals for 2030 or 2050. In the REN scenario, implementing the PCE system for extensive energy renovation in the Netherlands can achieve the interim goal of 49% carbon mitigation by 2030, but still cannot realize the carbon-neutral level by 2050. However, the REN scenario can possibly reach the long-term goal by replacing traditional gas-based systems with electricity-based systems and supplying renewable electricity nationwide. This study hence shows too that the development from the energy sector would significantly influence the realization of the carbon neutrality goal in the Dutch housing sector.

7.2.6 Answer to the overall question

The overarching research question posed in this thesis is: *what are the potential impacts of the application of selected novel technological systems to enhance circular use of materials, energy efficiency and carbon neutrality in the residential sector of the Netherlands?*

Since the need to realize a carbon-neutral environment will be a dominant factor in the adjustment of the Dutch residential sector in the next decades, we first look at energy efficiency. Chapters 3 and 4 demonstrated that improving the insulation level of existing houses is more necessary than upgrading the insulation level of new houses. This is not surprising given the large number of existing houses, usually with low energy efficiency, compared to the number of houses that will be newly built until 2050. The case in Chapter 6 shows that demolition of old energy-inefficient houses followed by rebuilding new houses (REB scenario) in combination with the decarbonisation of the energy system results in the lowest carbon footprint. This comes however at very high financial costs and at significant growth in material footprint. The renovation (REN) scenario has much lower costs and material footprints (although still higher than the BAU scenario), but can realise significant carbon emission reduction by the installation of electrical space heating systems and supply of renewable electricity. In short, the REB scenario has much more material use and capital costs, while the REN scenario can only realize carbon reduction goals by switching to electrical heating systems and renewable electricity.

This result illustrates also another conclusion that can be drawn from this research: i.e. that to realise circularity goals, lifetime extension is to be preferred over component reuse, which in turn is to be preferred over material reuse. As indicated the **lifetime extension** in the REN scenario in Chapter 6 has much lower costs and material footprints than the REB scenario. The PCE-refurb case (Chapter 4) shows **element reuse,** i.e. taking out PCE elements from houses that are to be demolished and using them to renovate other houses, is a more preferable option to material recovery regarding GHG mitigation, cost saving, and energy use reduction. With regard to material recycling of concrete, we found that technological systems, such as transportable ADR-HAS, have the likelihood to achieve environmental-economic co-benefits compared to downcycling. But when such materials are incorporated into manufacturing the green PCE-new and green PCE-refurb we did not find obvious environmental and economic benefits from a life cycle perspective of a PCE (Chapter 3 and 4). The life cycle impacts of material production (and hence potential benefits of recycling) are relatively low compared to the life cycle impacts of the PCEs.

We see however too, particularly in Chapter 6, that even if implementing three circularity interventions simultaneously, this is still unlikely to reduce the primary material extraction by 2030. This is due to the contradiction between achieving circularity goals and energy efficiency ambitions. Recovery, reuse, and lifetime extension can reduce material use, while constructing new houses and renovating old houses to achieve carbon-neutrality require a large amount of raw materials. Therefore, the Netherlands needs to seek more ambitious and advanced technologies and policies to realize circularity goals, such as more lightweight design more efficient production processes of materials.

7.3 Methodology discussion

7.3.1 Integration of LCA with LCC

Integrated LCA-LCC assessments have become a widely used approach for analyzing the environmental pressure and economic costs of specific products. Researchers and practitioners have been developing and implementing different methods to integrate LCA and LCC. Miah et al. (2017) reviewed frameworks for the combination of LCA and LCC and classified them into the following six categories:

(i) Independent LCA and LCC: LCA and LCC are conducted independently for the same product system.

(ii) Independent LCA and LCC as part of an overarching framework: LCA and LCC are conducted independently to form important dimensions within the overarching framework and the final output is a portfolio of results similar to Type i.

(iii) Independent LCA and LCC integrated by multi-criteria decision analysis: LCA and LCC are conducted independently as part of an overarching framework for the same product system. There is some overlap with type ii, however, the key difference lies in the multiple-criteria decision analysis to determine the "best" alternative from a group of options.

(iv) Optimization of LCA and LCC analysis: it is similar to type iii, however, the key difference addresses the optimization of environmental and financial parameters to find the optimal solution via multiple-objective decision-making methods.

(v) Environmental LCC: LCA-based costing method where the functional unit, scope, and system boundary are the same.

(vi) eco-efficiency assessment: an assessment that evaluates "the aspect of sustainability relating the environmental performance of a product system to its product system value" that was standardized in ISO 14045 (2012).

This thesis contains three cases where LCA and LCC have been applied, which cover three of the approaches mentioned above:

1. a case of recycling waste concrete in which an eco-efficiency assessment and diagram was applied (Chapter 2; approach vi),
2. a case of the PCE-new system with a method that monetizes the external costs of environmental impacts from the LCA and combines them with the internal costs from the LCA (Chapter 3; approach v),
3. a case of the PCE-refurb system, using independent LCA and LCC as part of an overarching framework based on a payback period (Chapter 4, approach ii).

In the first case where the eco-efficiency approach was applied, we visualized an eco-efficiency index through a two-dimensional diagram. This gives an easy to interpret insights into the trade-offs between environmental and cost aspects of multiple systems, which is suitable to make a quick comparison between multiple alternatives. However, if one system is better than another for some environmental impact categories but poorer for others, it is difficult to figure out whether the total environmental performance was improved or deteriorated, so does the eco-efficiency. The second case used monetarization of environmental impacts which allows expressing monetary costs and impacts in the same unit. The case shows that when environmental externalities are taken into account, the (economic) performance of green products improves. Such monetary results on internal and external costs can also support policy-making with regard to e.g. taxation of environmental impacts and resource use. However, monetization of environmental impacts will lead to greater uncertainty in results because monetary costs of environmental impacts are difficult to quantify, especially if such impacts take place far in the future. Such future impacts often are discounted, a practice which is still heavily debated since even at a moderate discount rate potentially large impacts only taking place in e.g. a century have a negligible net present value. In the third case, LCA and LCC were conducted independently but under a joint payback framework. This case study showed a payback method is suitable to explore an LCA or LCC study of which the temporal scope cannot be directly defined.

These case studies illustrate some methods of integrating how LCA and LCC, and how this helps to support the strategy exploration in material circularity and building energy efficiency projects. However, a large number of methodological inconsistencies between LCA and LCC still need to be solved by the scientific community. For example, discount rates are usually applied in LCC and not in LCA; the concept of “value-added” in LCC has no counterpart in an LCA; LCC is conducted from a perspective of an actor to clarify costs, prices, and revenues while an LCA focuses on a functional unit.

With the growing concerns about sustainability and its environmental, social, and economic pillars, the emerging overarching framework of life cycle sustainability assessment (LCSA) could provide a direction of how to improve integrating LCA and LCC. LCSA is an umbrella concept that combines life cycle thinking with the concept of sustainability. At a product level, LCA was seen as the environmental dimension and LCC was formulated as the economic dimension of LCSA via a conceptual equation (Kloepffer 2008, 2003): LCSA = LCA + environmental LCC + social LCA. A broader conceptualization of LCSA even shows the potentials of analyzing meso-level and economic-wide issues (Guinée et al. 2011). However, LCSA still has not provided solutions for the mentioned inconsistencies between LCA and LCC. The development of LCSA may contribute to a more consistent integration of LCA and LCC.

7.3.2 Integration of MFA with LCA/LCC

MFA and LCA/LCC are two core analytical methods in the field of industrial ecology. In ISO 14040 (2006a) and 14044 (2006b), the LCA was defined as a product-oriented assessment of the inputs and outputs and the associated potential environmental impacts of a product or service system during its life cycle. The MFA approach is based on the law of conservation of mass as aiming to assess the metabolism of materials in a system (Brunner and Rechberger 2004). Similarities between LCA and MFA can be identified, such as both are systemic approaches, quantification of material/substance/pollutant flows, distinguishing between direct and indirect flows, etc. (Azapagic et al. 2007).

Meanwhile, clear differences exist. First, regarding the system scale in the definitions, LCA mainly focus on micro-level assessment and the MFA primarily aims to investigate regional or nationwide issues. However, in some minor cases, LCA can also estimate the total life cycle environmental impacts of the total use of concrete products (Arrigoni et al. 2020) in a region, while MFA has also been used to analyze the material flows of CDW at a unit process level (Dahlbo et al. 2015). This flexibility of the system scale used in LCA and MFA shows the potential of combining these two methods. Second, the object to be traced in an MFA has to be concrete substances and materials, while an LCA can explore not only materials but also abstract objects, such as a service and a technology. Third, MFA uses mass-based indicators; LCA uses both mass-based and impact-based indicators. Finally, an MFA system must be determined with regard to four basic variables: space, function, time and materials (van der Voet 1996). However, specific time and space are not necessary for an LCA system.

In general, LCA has a broader scope than MFA—LCA encompasses sources, receptors, pollutants, and impacts, while MFA focuses only on material inputs and outputs and stocks and flows in the economic system. Therefore, MFA can be incorporated into the overarching framework of life cycle management. Hu (2013) proposed an approach to LCSA by combining MFA with LCA (or LCC or SLCA) with a case of concrete recycling. In the LCA-based overarching framework, the functional unit of an LCA is the critical connection to bridge the LCA and results from MFA can be used to build up-scaled life cycle inventory.

Chapter 6 presented an up-scaling study that combined dynamic MFA with LCA and LCC. LCA and LCC were used to estimate the unit benefits of the PCE system at the product level. The Dynamic MFA was conducted to evaluate the material inflow and outflow of the Dutch residential building sector at the country level. The housing stock from the MFA study was used as a size factor for scaling up environmental and economic impacts per functional unit from LCA and LCC. In addition, the temporal inconsistency between LCA/LCC and MFA were addressed. Generally, an MFA is conducted through the synchronic-temporality approach (i.e. all processes that take place in a specific year), while an LCA is modeled from the diachronic-temporality approach (i.e. all processes related to a life cycle of a product, independent of the moment in time that they take place) (Birat 2015). Therefore, in our case study in Chapter 6 in the LCA/LCC calculations the lifetime of buildings was taken into account (assumed to be 120 years), while MFA analysis was done for each year in a clearly defined period (for which we chose the period between 2015-2050). To show both the time-specific impacts that usually are provided by MFA and the lifetime impacts that are usually provided in LCA/LCC, we developed the concept of actual-time value and annual value. This is an innovation in the way of how results of combined MFA and LCA/LCC studies can be presented.

The actual-time value approach provides insight regarding in which moment in time impacts and costs occur. This approach allowed us to show for instance in which year(s) the actual impacts and costs of rebuilding or refurbishing take place, but also at what moment in time the reduction of energy use and GHG emissions in the use phase of buildings starts to become higher as such impacts and costs. This approach is hence highly suitable to assess if e.g. carbon emissions (both operational carbon emissions in the use phase and embodied carbon generated for building materials used in refurbishing) and material use will comply with the 2030 and 2050 targets of the Dutch government. This approach is hence highly suitable to assess if e.g. carbon emissions (both operational carbon emissions in the use phase and embodied carbon generated for building materials used in refurbishing) and material use will comply with the 2030 and 2050 targets of the Dutch government. The annualized-value approach is more suitable for comparing scores for a sound functional unit, such as the impacts and costs per m^2 floor space in use per year, including impacts and costs of the construction phase and benefits of recycling and reuse at the end-of-life (EoL) stage. The annualized-value approach is more capable of a theoretical comparison of life cycle impacts and costs, while the actual time value better reflects the actual emissions and costs incurred in specific moments in time. Such insights can help policymakers, for instance, in assessing how the use of carbon budgets evolves over time.

7.4 Policy implications

7.4.1 Building material circularity

In this thesis, multiple cases have been conducted to evaluate the proposed building circularity framework. We illustrated the potential policies from the three layers of the circularity intervention framework: resource use reduction, element reuse, and material recovery.

Resource use reduction

Waste prevention has the highest priority. CDW can be prevented (i) by adopting ecodesign for constructing new buildings and (ii) by extending the lifetime of existing buildings. For new building construction, the government is supposed to encourage the application of ecodesign. **First**, prefabrication design has been identified as a promising solution to prevent CDW generation (Tam et al. 2006). The practice of prefabricating buildings is well established in the Netherlands, with prefabricated elements used in 55% of all Dutch construction projects in 2016 (de Gruijl 2018). Upscaling the implementation of prefabrication design can further improve the circularity by component reuse in the building sector. **Second**, lightweight design is also a promising solution to reduce material requirements and prevent CDW. It can be applied by either adjusting the structure and decreasing material demand or using lighter materials.

Chapter 5 shows an example of using lightweight concrete that if 1% of normal-weight concrete is replaced by ultra-lightweight concrete, 28 Kt of concrete and associated waste concrete would be avoided. **Third,** waste prevention can also be achieved through long-lasting design (Geissdoerfer et al. 2017), which is also termed 'durability' by the EU's Principles for Building Design (EC 2020b). The EU Ecodesign Directive regulated the minimum guaranteed lifetime, the minimum time for availability of spare parts, modularity, upgradeability, and reparability must be considered for energy-related products (EC 2009). Compared to a normal product, newly constructed houses in the Netherlands have a much longer lifespan, which was assumed 120 years in this thesis. Therefore, the major elements of a building are supposed to have the same or longer service life planning as well as their associated maintenance and replacement cycles.

Extending the lifetime of existing buildings is also an important approach to CDW prevention in Europe. The 'Renovation Wave' initiative claimed in the European Green Deal to lead to significant improvements in energy efficiency in the EU will be implemented in line with circular economy principles, notably, building assets that have a longer life expectancy (EC 2020c). The Principles for Building Design addressed the importance of 'adaptability' that refers to extending the service life of the building as a whole with a focus on replacement and refurbishment (EC 2020b). In this thesis, prolonging the lifetime of existing buildings is realized by adopting the PCE-refurb system. In the Netherlands, it is expected that the lifetime of houses can be extended by at least 15 years after renovation (Duurzaam Gebouwd 2014). Chapter 6 shows that extending the lifetime of existing houses through refurbishing their facades can noticeably reduce the annualized GHG emissions, costs, and material footprints of material use incurred at the construction stage. Refurbishing older houses would yield more economic and environmental benefits. Therefore, renovation activities should start with those houses that were constructed before the 1960s.

Element reuse

Reuse is a second important strategy to realise a circular economy. This thesis explores the example of full reuse of concrete façade elements.

In the EU, such reuse of building elements is not yet a common practice. Although the EU's Waste Framework Directive (WFD) (EC 2008a) addresses the importance of reuse, it did not set a quantitative target for reuse. For instance, the WFD requires member states to (i) take any necessary measures including (reuse, recycling, and other material recovery) to prepare for material recovery of at least 70% (by weight) of CDW by 2020 and to (ii) increase the reuse and recycling of waste materials from households to a minimum of overall 50 % by weight (EC 2008a). Therefore, a quantified target of reuse should be set, such as "10% of material recovery should be realized by reuse" to stimulate the reuse of building components.

In addition, adoption of reuse largely depends on the design of a product at the concept stage. In the Netherlands, waste management transitions did not radically alter product features regarding design for disassembly and reuse (Kemp and Van Lente 2011). In order to strengthen reuse, the WFD also encourages member states to take measures to apply appropriate designs that promote reuse (EC 2008a), such as design for dismantling, and design for deconstruction. Moreover, it is also important to establish procurement criteria and quality standards and to develop repair networks to support reuse.

Material recovery

Goals should be set for material recovery to promote the recycling of CDW. These goals should be challenging. For instance, the Netherlands realised already a much higher recycling rate of 70% of CDW in the WFD in 1995 (92%; (CLO 2021). However, in 2015, only 3% of waste concrete was recycled back into the concrete cycle with the rest being used as filler in e.g. road foundation. While the amount of CDW will continue to rise till 2025 (Zuidema et al. 2016), the Netherlands is already facing a problem since road construction is not growing anymore and the requirement for filler is hence limited (Hu et al. 2013; Bio Intelligence Service 2011). The case study in the Netherlands (Chapter 2) suggests that the EU could set more ambitious goals to encourage the building sector to shift from downcycling to recycling or upcycling. For example, a circular goal could be set as “those member states who already achieved the goal of recovering 70% CDW, are encouraged to upcycle 20% of the recycled volume of CDW”.

Setting more ambitious goals at the EU level is, however, only possible if a clear definition of recycling or upcycling (as opposed to downcycling, or energy recovery) is given, which is currently lacking. Furthermore, the definition of "backfilling" should be strictly clarified to avoid landfilling without useful application operations in this definition. Unfortunately, current waste registration systems and databases are not suitable for estimating end-of-life flows of CDW, and in particular concrete. It is, therefore, necessary to develop a more systematic waste registration system that includes quantities CDW is generated, and how it is treated.

Furthermore, the massive need for housing renovation to meet GHG emission targets in the Netherlands will not only increase the need for resources but raises new problems surrounding the disposal of new types of CDW in the future, particularly posed by new insulation materials used in renovation (Chapter 5). It is urgent for the Dutch government to promote the development of novel reuse technology and standardization of secondary materials made from insulation waste, and to foster a secondary market.

Finally, sustainable public procurement can be a strong potential driver for CDW recycling, but at this stage sustainable public procurement criteria in general do not yet require minimum use of recycled materials. Standards for building materials are based on virgin materials and it is not always easy for secondary materials to comply with them. The VEEP project has demonstrated that with proper quality control of secondary materials, the recycled concrete aggregate will not be noticeably different in terms of quality and strength, compared to concrete made with primary aggregate. A minimum required share of recycled aggregates and cement could be introduced in national and local Sustainable Public Procurement criteria.

7.4.2 Building energy renovation

Building energy renovation is seen by the EU as an essential measure to shift to a carbon-neutral built environment. This thesis proposed a building energy efficiency framework that prioritizes energy efficiency at the operation stage. The energy efficiency of a building can be realized through an active and a passive approach (compare IEA (2021) who mention two main strategies to realize decarbonization of existing building stock: enhancing energy efficiency by refurbishing and electrifying heating and cooling). Via the passive approach, heat transfer through the building envelope can be reduced by optimizing the insulating degree of walls, roofs, floors, and windows. Using the active approach, GHG emission reductions can be realized by adopting efficient installations for building technical systems, renewable heat generation systems, renewable electricity generation systems, and other energy-related measures. For new buildings, the EU Energy Performance of Buildings Directive (EPDB, 2010/31/EU) requires that the Member States must ensure new buildings constructed after 2020 should be nearly zero-energy buildings (nZEBs), which have high insulation level and are highly electrified (EC 2010). Existing buildings are supposed to be renovated so that better insulation and more energy-efficient heating system is realized, ideally based on the electricity that can be sourced from renewable sources, are used.

Passive energy efficiency approach

With regard to the passive approach, improving the thermal insulating level of building elements can effectively reduce heat loss. The country-level study case in Chapter 6 shows that approximately 3.3 Mt of GHG emission can be mitigated by upgrading the thermal insulation level of façades of existing housing stock. Different degrees of energy renovation lead to different ranges of energy savings. In one EU report (Esser et al. 2019), four depths of energy renovation were defined regarding energy savings: (i) below threshold (< 3% savings), (ii) light renovations (3% $\leqslant x \leqslant$ 30% savings), (iii) medium renovations (30% < x $\leqslant$ 60% savings), (iv) deep renovations (x > 60% savings). Renovation to an nZEB level can achieve over 90% of energy savings (Economidou 2011). The EPDB also request EU Member States to set up their own definitions of nZEB that reflect their national, regional or local conditions and national plans to stimulate the transformation of buildings that are refurbished into nZEBs (EC 2010).

In response to the EU, in 2017 the Dutch standard NEN 7120 used an Energy Performance Coefficient (EPC) to define an nZEB, whose EPC is close to 0 (Government of the Netherlands 2012). The Netherlands implemented an energy label certificate for houses when they are being built, sold or rented. The labels range from the worst 'G' level to the best "A++++" level, determined on the basis of fossil energy use in [kWh/(m^2·yr)] (Netherlands Enterprise Agency 2021a). The National Energy Agreement aims to achieve at least an average energy label A in 2030 for all buildings in the Netherlands (MENCP and MIKR 2017). The Netherlands also set standards and target housing insulation requirements (Netherlands Enterprise Agency 2021b). However, the connection between nZEB levels and the current energy label is weak, and thermal transmittance benchmarks of nZEB envelope elements in the Netherlands are still not clear. Therefore, policies and measures for promoting the nZEB solution should be more specific.

High-performance insulation material is the key for housing façade refurbishment. Aerogel is a promising insulation material that has a significantly lower thermal conductivity value (0.0120-0.0157 W/(m·K)), compared to conventional insulation expanded polystyrene (0.0310 W/(m·K)). The aerogel is however too costly to be extensively implemented at the current stage (Chapter 3). Under the EPBD, cost-optimality has been emphasized to improve the energy performance with the lowest life cycle cost. Therefore, more information on the life cycle costs of insulating materials should be generated.

Active energy efficiency approach

The Dutch study case in Chapter 6 shows that the active approach of electrification and the use of renewable energy is at least as important as the passive approach, i.e. insulation. By adopting electrification strategies, traditional gas-based systems (such as boilers, water heaters, and gas stoves) would gradually be replaced with electricity-based systems.

Space heating system is the most important part of electrification. Gas-based heating is currently the primary source of household space heat, accounting for 93% of the heat generated (EZK 2015). The gas is being deployed with increasing efficiency devices in houses, such as high-efficiency boilers and cogeneration. To support electrification, economic policy tools need to be considered. For example, the 2016 Tax Plan increased the rate for natural gas by about 5 cents and decreased that for electricity by about 2 cents to support the process of electrification (EZK 2015). Apart from tax measures, extra encouragements in the form of a subsidy for gas heating replacement can also facilitate the transition.

Moreover, in this thesis, we only considered electricity-based heat pumps, while there are other alternative heating options, such as geothermal heating networks, waste combustion heat work, and locally available biomass. Integrated design of the regional structure of the heat supply should be made to meet both the cost-optimal level and lowest energy requirement of nZEBs.

The development of renewable electricity is the prerequisite for electrification. The structural change in energy supply caused by electrification may also lead to an increase in electricity consumption (EZK 2015). The Dutch case in Chapter 6 shows that electrification may also backfire if the development of renewable electricity cannot keep up the pace of electrification. Therefore, a particularly important task is planning and integrating renewable energy sources in national nZEB implementation. For the Netherlands, offshore and land-based wind farms are expected to be the biggest contributor to renewable electricity generation by 2035 (EZK 2015). Wind power is promising for generating renewable energy but the opportunities are also limited due to the complications involved in its spatial accommodation, particularly land-based windfarm. Off-shore wind power is more productive compared with land-based one. This will probably lead to offshore windfarm expansion in the North Sea. Hence, it is important to identify how more international cooperation in the North Sea region can contribute to more growth of the offshore wind industry. The offshore wind turbine system is also relatively expensive, technological developments are in an urgent need towards a cost-effective wind energy industry.

7.5 Recommendation for further research

This thesis aims to propose an integrated method that combines LCA, LCC and MFA to explore the intertwined issue of material circularity and energy efficiency by taking the housing stock in the Netherlands as a case study. However, there remain many gaps that require further research. It concerns both methodological as case-related topics. Methodological issues include:

- Creating more consistency in the integration of LCC and LCA. This includes issues such as that discount rates are usually applied in LCC and not in LCA; that the concept of “value-added” in LCC has no counterpart in an LCA; and that LCC is conducted from a perspective of an actor to clarify costs, prices, and revenues while an LCA focuses on a functional unit.

- Creating more consistency when combining LCA/LCC and MFA. These include alternative methods to harmonize the temporality mismatch between LCA/LCC and MFA; specifying the sources of imported materials in MFA so that country-specific environmental pressures and cost can be included in LCA/LCC; and developing approaches for uncertainty and sensitivity analysis of an LCA/LCC-MFA upscaling assessment.

Practical and case study related issues include:

- Analysing benefits of other strategies and technologies as researched here in terms of costs, carbon emissions and circularity/resource use (for instance lightweight design and prefabrication).
- Doing similar analyses for the housing sector in other regions, that use different building techniques or have a different historical building stock, especially major economies such as the U.S. and China.