Peak gravel in Zealand? Potentials of secondary aggregate supply based on prospective building stock modelling

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Abstract

The condition of the environment is receiving comprehensive awareness nowadays, and this focus are not expected to be lessen in future as more people are coming to inhabit our planet, putting increased pressure on a limited amount of natural resources. Utilizing these resources as efficient as possible are thus as important as ever and in this regard, proper management of solid waste comprises a crucial area. Housing, as one of the basic requirements for human well-being is one of the main services to be provided to this increasing number of people. And as this sector accounts for roughly 1/3 of all waste generated on a global level, utilizing construction materials efficiently remains decisive and furthermore strengthens the need to extend their useful after becoming obsolete.

Knowing the amount and type of materials contained in the existing building stock and when these are expected to become available as a result of renovation and demolition, would make the management of these resources more convenient. In addition, it would also allow architects and engineers to design new construction works with the materials coming from obsolete building stocks in mind, paving the way for a more circular build environment.

In this project a prospective building stock modelling have been developed, based on the existing building stock in terms of different types of buildings constructed in distinct periods of the past. Based on the factors expected to drive the demand for floor space in buildings, the future development of the building stock has been attempted. The model has been applied to the Capital region and the region of Zealand respectively with a special focus on the aggregate fraction of construction of and demolition waste (C&DW). As these areas are running short on supply of primary aggregates from existing digging areas in the foreseeable future, estimating the potential for secondary aggregate supply would be interesting from environmental and economical point of views.

The outcome of this study unveiled the demand for concrete and clay bricks to decline regularly by time in the Capital region and whereas the obsolete amount of clay bricks tail offs towards 2050, the amount of waste concrete shows slightly increasing trend. In the region on Zealand, the demand for concrete as well supply of waste concrete show slightly increasing trends towards 2050 whereas the demand for bricks and the supply of waste bricks tends to decline gradually by time. In both regions the demand of concrete exceeds the amount coming from obsolete stocks throughout the whole period, while the trend for clay bricks are the opposite. However, application of secondary aggregates in new concrete are only allowed up to a level of 30 %, and until this upper limit gets challenged the full potential for substitution might be obtained. The quality of the concrete remains as a significant barrier though. The demand for clay bricks could apparently be covered completely by waste bricks, but unfortunately application of cement mortar since 1955, restricts this potential significantly.

Content

1. Introduction

One of the greatest challenges of our time is to preserve natural resources and ensure they are consumed as efficiently as possible. In this regard the building stock plays a crucial role as it is one of the most significant energy consumers in terms of volume and mass, constitutes one of the largest anthropogenic repositories of processed materials based on raw resources and generates high levels of construction and demolition waste (Ostermeyer *et al.* 2018). Whereas fossil fuels and biomass are largely consumed to produce energy or as foodstuffs, the vast bulk of metals and building material is retained in the stock of buildings and infrastructure (Schiller *et al.* 2017). And as a result of expansion and maintenance, construction materials contribute the largest annual addition to this stock. The growth of the built environment is linked to multiple environmental impacts but reusing construction materials from this sector could potentially reduce those (Österbring *et al.* 2017). On a global level, the construction and demolition sector use up to 40 % of the total raw material extracted globally and generates 35 % of the worlds waste (Di Maria *et al.* 2018). Construction and demolition waste (C&DW) are characterized by its high volume and weight but with probably the lowest environmental burden and the highest inert fraction per mega gram (Mg) of all waste streams. Although the specific environmental impact (per Mg) is low compared with other waste streams, the associated environmental impact of such a high amount of waste is an important concern mostly derived from its logistics (Styles *et al.* 2018).

Before being able to design demolition waste management it is necessary to understand the amount, composition and flows of the generated waste and in this regard characterization and quantification of the stock of material in existing building and infrastructure is needed (Mastrucci et al. 2017). Architects and engineers have gradually shifted from focusing merely on new buildings and growth of settlements to also include managing saturated steady-state situations and the decline of the built environment (Kohler *et al.* 2009).

One of the main difficulties for waste recovery is the collection of mixed waste (instead of on-site sorting) and the inefficient mechanical sorting of the mixed waste as recovery requires C&DW streams to be thoroughly separated either onsite or within waste sorting facilities. Onsite sorting includes segregation of waste streams at source, reducing the risk of contamination and improving the quality and recycling rate of all fractions. Onsite sorting however increases the number of waste fractions and consequently the number of containers increasing the collection costs and requiring greater space on site. Sorting C&DW in recycling facilities on the other hand, reduces the number of waste fractions and required containers thus also reducing the costs (Sáez and Osmani 2020).

C&DW best practices essentially operationalize circular economy principles within the construction and demolition sector and beyond, mostly oriented towards maximizing the reuse of elements and facilitating recycling and material recovery of construction materials. From the circular economy point of view, the best re-use option in the construction sector is the reuse of the entire building. Selective building deconstruction as an alternative to demolition, involves a systematic disassembly with the objective of maximizing reuse and recycling. Although this strategy is able to separate different types of materials at source, it is often not a preferred option due to the poor economics of dismantling. (Styles *el al.* 2018).

The main barriers for recycling C&DW include low cost and high availability of raw materials decreasing the demand for recyclables and the interest in developing businesses from recycling and the competitiveness of recycling could therefore be increased by raising the price of raw materials through taxation. Setting End-of-Life criteria for certain C&DW fractions could additionally contribute to an increasing market for secondary raw materials obtained from C&DW (Dahlbo *et al.* 2015)

Within Europe, construction and demolition waste (C&DW) accounts for about 33 % of the total amount of waste generated. The European Directive 2008/98/EC on waste set to a minimum 70 % of weight by 2020 the reuse, recycling and other material recovery target of non-hazardous construction and demolition waste. Only a few countries have reached this requirement until now including Denmark, Germany, The Netherlands and Belgium. According to the European Waste Framework Directive, laying down some basic waste management principles, management of waste should be prioritized following the waste hierarchy apparent form **Figure 1**. ("Directive 2008/98/EC on Waste (Waste Framework Directive) - Environment - European Commission" n.d.).

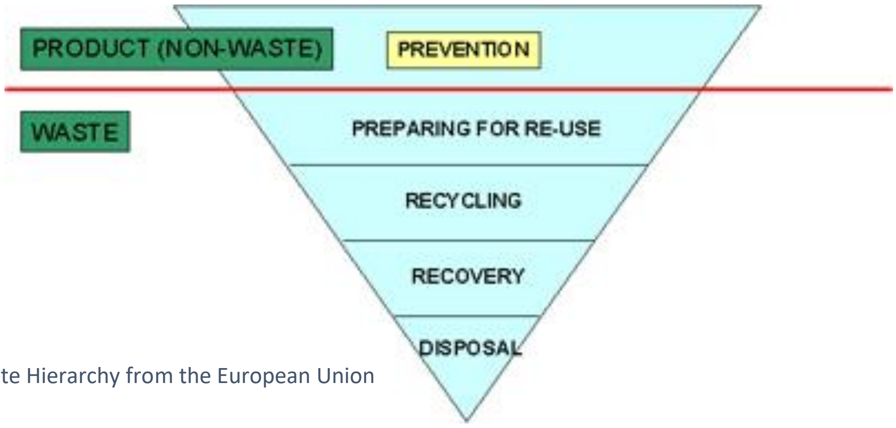


Figure 1 The waste Hierarchy from the European Union

The term "preparing for reuse" apply to situations where products or components are prepared, including inspections, cleaning or reparation in a way rendering them suitable for reuse. This process is part of the practice material utilization and are encompassed by legislation applying to waste materials. The main difference between "reuse" (direct reuse) and "preparing for reuse", are related to whether the material is considered as waste. This is not the case regarding "reuse" but applies to "preparing for reuse" however. The practice of reuse might be handed out by everyone, while "preparing for reuse" must be performed by the enterprise itself or associated waste collectors. Recycling covers all kinds of material utilization, processing the material and utilizing it for the same or another purpose as originally and are thus about reclaiming the resources contained in the waste. Recovery refer to situations where the material substitutes other materials in a way different from reuse and recycling. Covered here are the practice of crushing down concrete waste applying it as filling or incineration of waste with energy recovery. It thus includes situations where the materials fulfill another purpose than originally intended, and this practice, often comprises the last resort, explaining the low placement in the waste hierarchy (Environmental Protection Agency, 2018a).

In a Danish context, construction and demolition waste accounts for approximately 1/3 of the total waste generated and thereby constitutes the largest waste fraction. With a total amount of 11,3 million tons of waste generated by 2015 it amounts to approximately 4,2 million tons by 2015. Within this fraction concrete represents 2/3 together with tiles and asphalt. The major share of this fraction is currently recovered and applied in construction of roads and open places, thus substituting natural aggregates of stone and gravel (Environmental Protection agency, 2014). This practice belongs to the level, recovery, according to the waste hierarchy.

Construction and demolition waste arises in relation to new construction, renovation and demolitions of buildings and constructions. The main share of this fraction originates from demolition and renovation work, while only around 5 – 10 % are associated to new buildings. The term C&DW comprises an array of different fractions including asphalt, concrete, steel reinforcement, tiles, wood, insulation material, gypsum boards, windows etc. The C&DW generated in Denmark in 2016 appears from **Figure 2**, disaggregated by different fractions.

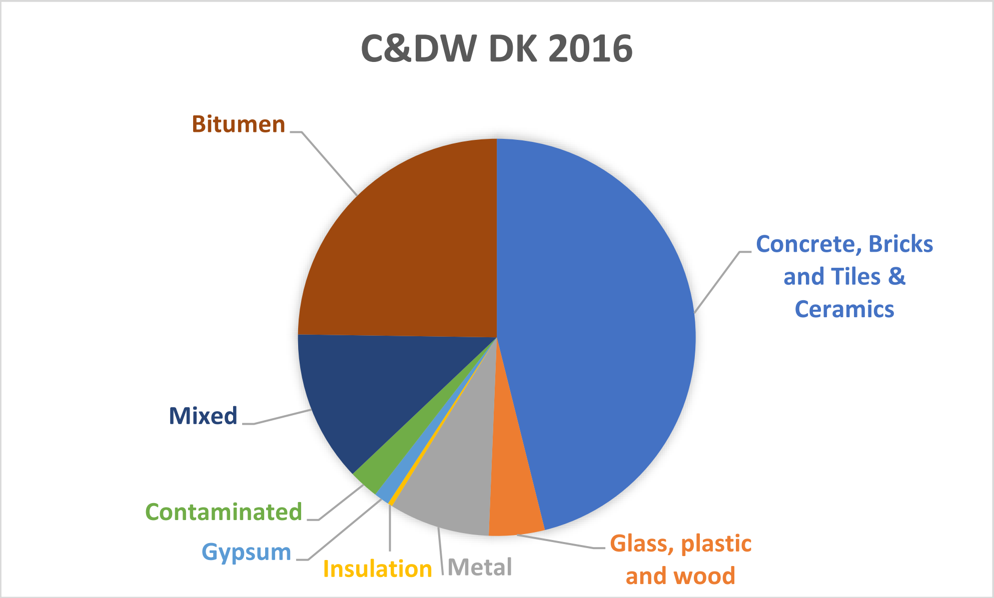


Figure 2 Construction and demolition waste in Denmark, 2016

1.2 Demolition Waste Quantification

Proper quantification of C&DW are of great importance for establishing an effective management system at both project level and regional level. Quantification at project level refers to forecasting C&DW production in a particular project, helping the project managers to arrange the stockpiling on site and to determine the potential waste recycling benefit and disposal costs. Quantification on the regional level refers to estimating the total C&DW of all projects in a specified region, assisting decision makers in making more realistic policies and determining the establishment of new waste facilities. Lifetime analysis is one of the methods applied to quantify demolition waste and the primary principle involved in this method is a material balance. It is assumed that constructed buildings will eventually be demolished and become demolition waste and consequently the amount of demolition waste must equal the mass of the constructed structure and can thus be projected by assuming reasonable lifetimes of buildings (Wu *et al*. 2014).

In order to project the future availability of recyclable material from demolition activities, it is essential to obtain information about the material composition of the building stock and the buildings that will get demolished in future. The challenges lie in generating data about individual buildings and extrapolating this information for selected geographical areas of interest. By combining specific material intensities for different building categories, e.g. based on age and function, with data about demolition activities in a well-defined area, it will be possible to determine the future amounts and composition of demolition waste.

Specific values about the material composition of buildings can be generated by using information about the materials used to construct the buildings, by analyzing the generated waste stream after demolition or by investigating the buildings prior their demolition. Using the first method, one often neglects or underestimate renovations and technical upgrades during the use phase. On the other hand, studies estimating the dynamics of the building stock based on data from the demolition waste face the challenge of under- or overestimating the content of so-called trace materials. Considering these challenges, Kleemann and colleges assumes the end-of-life investigation to provide the most accurate building stock characterization results and information about the materials that are potentially available for later recycling. As a first step in their study, they collected all the available documents of the buildings and analyzed them regarding the materials used to construct and modify the building and as a second step, the data about the built-in materials was collected through an on-site inspection and selective sampling before demolishing the building. Based on the collected data from documents and site inspections, information about different built-in materials were aggregated, and the mass calculated based on the volume, area or number of the particular material and on data about its specific density or weight. Finally, the collected data are compared with the data of waste fractions and quantities reported by the demolition company to the building owner. Information from the construction plans allows one to determine the volume of walls and floors and based on this information, the bulk materials can be quantified using data from literature about the density and composition of different building materials. The report about the investigation of pollutants in buildings prior to demolition is not meant to provide comprehensive information about the total material composition because it mainly focuses on hazardous substances that must be removed prior to the main demolition work. The waste management concept should ideally contain qualitative and quantitative information about the build-in materials, and on-site investigation would allow a quantification of trace materials such like iron, copper and aluminum as well. In addition, knowledge about the location of materials in a building is helpful to plan the recycling process effectively and estimating the effort needed to recover certain materials before demolition of the building. In conclusion, combining the document-based evaluation with knowledge and data from on-site investigations seems appropriate to reduce efforts when characterizing a larger sampling of buildings in future and furthermore a reliable data set is considered a prerequisite to subsequently link the information that is gathered at a building level with GIS data (Kleemann, *et al.* 2016).

1.2.1 C&DW management in EU

A pre-demolition audit is exactly an audit prior to deconstruction, gathering all the necessary information for the future demolition with the purpose of collecting information about the qualities and quantities of the materials that will be released during the demolition and giving site-specific recommendations regarding the hazardous waste to be removed and handled safely. The EU waste audit guideline was published by the European Commission in 2018, providing information about the best practices for the assessment of C&DW streams prior to demolishment of buildings. The aim of the guideline is to facilitate and maximize the recovery of materials and components for beneficial reuse and recycling without compromising the safety (EU Commission 2018).

The earlier the potentials for reuse and recycling are identified, the better the changes that it will happen with high quality and the mapping of resources prior to demolition is thus essential and should be a part of the demolition audit. Resource inventories are a key element in pre-demolition audits and are a developing area due to the increasing focus on circular economy and together with control actions and systems for traceability, it forms an upcoming issue in the field of C&DW (Wahlström *et al.* 2018)

The resource inventory contains a calculation of the amounts of the materials as well as a description of demolition possibilities, application along with the waste hierarchy and a list of companies/projects that might receive the resources. A special concern is put on opportunities for matchmaking between availability of demolition waste with actual needs for recycled material, i.e. how to match the demolition projects with construction projects in need of the materials (Wahlström *et al.* 2018).

The inventory of the materials and the building elements is the basic output of the waste audit and aims to present reliable data about the type and amount of the demolition waste. It is based on a desk study, site visit and additional activities aiming to ensure the quality of data. The waste audit should consider any relevant legislation such as the requirements for environmental permits if waste is to be used on-site or any waste that may be hazardous and which needs to be managed in accordance with specialized waste legislation. Ideally, waste audits should be performed before the call for tenders and should be a part of the specifications for tenders and the audit report should also be revised in light of the final results of the demolition. Waste audits contribute to better demolition waste management, as knowing the quantities and nature of the materials expected, leads to the optimization of the work. Materials assessed should be complemented with consideration of the ease of recovery of these materials and it is advisable to perform an assessment of the materials for each floor (EU Commission 2018).

A desk study aims to gather all the relevant information from the documentation of the building or other work and covers the age of the building, architectural plans and technical drawings and the documentation of use. At this stage, the auditor should collect as much information as possible to plan the site visit correctly. Based on the study of all documentation, a first draft of possible materials and uncertainties will have to be checked under the site visit. During the field survey every room of the building to be demolished are then visually inspected and inventoried often in a destructive manner and if necessary, samples are taken for analysis. The site visit consists of visual inspections, comparisons of findings with collected documents, planning of inspections and measurements, preliminary planning of deconstruction techniques and waste handling on site as well as communication between actors engaged. The site visit should allow the auditor to complete the information collected during the desk-based study and take any sample required to perform the material assessment. Waste management recommendations can include advise and guidelines for the safe removal of hazardous waste materials, re-use or recycling possibilities for certain materials present in the building and conditions for storage, transport and treatment for certain materials. The waste audit should specify the areas of the building potentially affected by contamination and the best way to deal with them and if possible, a selective dismantling should be recommended in order to maximize recovered fractions (EU Commission 2018).

Improved waste identification, separation and collection at source are at the start of the C&DW management process and requires good-quality pre-demolition audits and waste management plans to be prepared and executed. Whilst the pre-demolition audit focuses on the products (“what”), a process-oriented waste management (“how”) is to be prepared if any material from demolition operations is to be reused or recycled. A good waste management plans contains information about how the different steps of the demolition will be performed, by whom they will be performed, which materials will be collected separately at source, where and how they will be transported, what will be the recycling, reuse or final treatment and how to follow up. The better inert C&DW is separated, the more effective recycling will be and the higher the quality of recycled aggregates and materials, as well as the costs and revenues of the separated materials, but it requires available space at the site, however. Typical hazardous waste products include asbestos, tar, radioactive waste, PCBs, lead, electrical components containing mercury, insulation materials containing hazardous substances etc. Even if present in a very small proportion of the total waste materials, the presence of hazardous materials can reduce the markets confidence in the recycled material drastically. On site operations can offer cost advantages and reduce transport needs but must be evaluated on a case-by-case basis depending on site characteristics. Throughout the waste management cycle, monitoring is crucial as it contributes to transparency and trust in the C&D waste management process (EU Commision, 2016).

Quality management is a crucial step towards increasing the confidence in the C&D waste management processes and the trust in the quality of C&D recycled materials overall. The value of recycled construction materials is based on their environmental features as well as their technical performance. Thus, there is a need to promote quality assurance from demolition to waste logistics and processing as well as provision of reliable and accurate information about the performance of the recycled products. To further develop the market for recycled construction materials, the traceability and tracking of waste flows is essential helping to build trust in secondary construction materials (EU Commision, 2016).

Barriers to recycling and reuse exist on a wide scale and effective markets are difficult to establish and are related to the price, quality and quantities of secondary materials. Small volumes of waste/resources with a sufficient quality to be recycled entails that resources are not available at the desired time and place and a lack of match making between supply and demand is apparent. The pre-demolition audit supports the possibilities to obtain larger volumes of quality materials and a market for the materials might be found prior to demolition. As another barrier, strict requirements on new material/products in construction must be met by recycled materials if they are to be used for the same purpose. However, lack of documentation on technical and environmental quality results in little knowledge on the contents of hazardous substances and the performance of the products. Furthermore, there is uncertainty regarding who is responsible for the warranty as no common quality system exists. Pre-demolition audits, as a prerequisite for high quality materials for recycling, ensures hazardous substances to be identified and removed prior to demolition and high-quality materials can be secured during this operation as well. Good availability of virgin sand and stone aggregates might limit the demand for recycled material, but lack of locally available raw materials might work as an effective driver as transportation costs of construction materials are high. It might be difficult to get a profitable business case for recycling and reuse due to demolition, storage, reprocessing and transport. But information gathered in the pre-demolition audit could possibly support the planning of cost efficient waste management and economic savings might be gained through income from recyclables and reduced costs for wastes to be landfilled or incinerated. A tracing system would create confidence in the quality of the recovered material and such a traceability system could be built on pre-demolition audits to ensure that all information is kept throughout the value chain. Precautions in demolition process can be taken to ensure high quality of recycling if a market for some materials have been identified from the pre-demolition audit, but high-quality recycling or reuse requires greater effort compared to material and energy recovery (Wahlström *et al.* 2018).

Proximity of sorting and recycling plants is very important for C&DW which in case of bulky waste such as aggregates cannot be transported by road over longer distances. Unless transported in large volumes by rail or waterway, longer distances are simply not economically attractive and environmental benefits of recycling diminish over longer travel distances as well (EU Commision, 2016). C&DW recycling needs to be promoted particularly in densely populated areas where supply and demand are geographically close, resulting in shorter transport distances than for the supply of primary materials, such as in the case of aggregates. Mobile recycling plants are specific to inert C&DW, contributing the advantages of reduced transportation costs as well as direct on-site access to the recycled materials (EU Commision, 2016).

While in theory several ways to validate the quality of recycled materials are possible, harmonized European standards that apply to primary materials also apply to recycled materials, however. Products that are not fully covered by those can still be CE-marked with the use of European Technical Assessments issued according to European Assessment Documents. This voluntary tool enables manufactures to place recycled or re-used products on the EU market and allows them to declare specific information about the performance of their products. Examples of using these tools for processed C&DW covers mainly recycled aggregates (EU Commision 2016). Proper regulation of C&DW management requires that the ownership of the waste is clear in line with existing national legal frameworks and contractual terms between initial building owners, the demolition contractor, the intermediate holder, the final recycling operator and the user of the recycled products. Local authorities are charged with issuing demolition and renovation permits allowing them to promote and enforce the development of high-quality waste management plans based on pre-demolition audits. A post-demolition follow-up and evaluation process is also important as it allows local governments to monitor whether such plans are being implemented effectively (EU commision, 2016).

1.2.2 C&DW management in DK

In Denmark the statuary order on waste sets the obligation to make an inventory of the waste expected to be generated before demolition. The inclusion of the results from the inventory in the tender is crucial to obtain a higher percentage or reuse or recycling when carrying out the demolition, but resource inventories are not mandatory, however. In addition, there is no national guideline on how to carry out waste audits and what to include in terms of hazardous substances. It is the responsibility of the environmental consultant carrying out the audits to ensure representative sampling and to decide on what hazardous substances to include in the pre-demolition audit. These estimations are thus to be based on experience regarding what type of hazardous substances to be expected in buildings and constructions of a certain age and in the different use types (Wahlström *et al.* 2018).

Still, an array of different regulations and laws exist in the legislation regarding how to handle construction and demolition waste in Denmark and the overall aim is to prevent and oppose contamination of soil and groundwater, to limit refuse of raw materials and other resources and to improve recycling. Overall, the waste hierarchy applies, stating that reuse is to be chosen in preference to recycling, recycling in preference to incineration and incineration in preference to landfilling. In parallel to this, materials containing harmful substances should be sorted out and destroyed or disposed off comprising incineration and landfilling to avoid contamination of the surrounding environment. Especially applying to waste containing Polychlorinated Biphenyls (PCB) regulated according to the POP regulation (Persistent Organic Pollutants), it should always be sorted out and destroyed. However, if the PCB-concentration in the waste is below 50 mg/kg utilization or depositing might be allowed, but above this concentration the waste is to be classified as hazardous waste. Below 0,1 mg PCB/kg the waste is regarded as uncontaminated. It is always mandatory to conduct an examination of buildings (environmental mapping) in order to uncover materials contained in the building including PCB, asbestos, chlorinated paraffins and lead etc. before demolition. An obligation to notify applies to the building owner regarding demolition projects concerning areas of more than 10 m^2 or generating more than one ton of waste. Regarding buildings built, renovated or maintained within the period of PCB utilization (1950-1977) special regulations apply in terms of examination and notification (Environmental protection agency, 2018a).

As stated earlier, legislation in Denmark does not require a full pre-demolition audit, only the inventory of PCB is mandatory, and the requirement is limited to the period 1950-1977. However, there are requirements on the removal of hazardous waste from construction waste which in practice means that contaminants other than PCB have to be included in the inventory in order to fulfill this obligation and as a principle the contaminants must be removed at the source. Legislation also requires that the expected waste amounts are declared to the municipality two weeks before the demolition takes place (Wahlström *et al.* 2018.).

The producer of the waste, in general the building owner, is the one responsible for correct sorting of C&DW. Waste generating enterprises must sort C&DW at source, e.g. at the place generating the waste, into fractions of recyclable waste, waste suitable for incineration or landfilling and based on type of material and application. Dangerous waste, including waste containing PCB, should always be identified and sorted out. The producer of the waste might forward C&DW, suitable for material recovery, to a sorting plant for further sorting into different fractions, provided the mixture does not affect the material recovery of individual materials. Fractions suitable for incineration or deposit should however always be sorted at source. The municipalities are responsible for handling all waste from private persons, as well as waste from industry suited for incineration of depositing. Regarding this kind of waste, the municipalities have the right and duty to assign and the general public as well as enterprises are obliged to use those solutions. Regarding recyclable industrial waste however, this fraction is out to competition and not in the hands of the municipality.

The claims regarding sorting of C&DW is stated in the waste announcement and following from this, waste producing companies at demolition sites are required to sort out C&DW into the following fractions:

- PVC
- Impregnated wood
- Natural stones
- Unglazed tiles
- Concrete
- Mixes of natural stones, unglazed tiles and concrete
- Iron and metal
- Gypsum
- Rockwool
- Soil
- Asphalt
- Mixes of concrete and asphalt
- Hazardous waste
- PCB Containing waste
- Double glazed windows

The following fractions of waste might be prepared for reuse for the same or similar purposes performed previously, without specific permissions according to the environmental protection act:

- Natural stones
- Unglazed tiles
- Concrete
- Mixes of the above
- Iron and metal
- Gypsum
- Rockwool

Recycling of C&DW, on the other hand, require environmental permission according to the environmental protection act, however. Companies are free to choose among reuse, recycling or material recovery inconsistent with the priority formulated in the waste hierarchy but they are not allowed to forward waste suitable for material recovery to incineration with energy recovery (Environmental protection agency, 2014).

1.2.3 Selective demolition

The term selective demolition refers to the practice of taking down buildings in a way ensuring correctly sorting of the materials and allowing the materials to be utilized in the best way, while materials containing harmful substances is sorted out for disposal. Utilizing materials in the best way, denote applying them as close to their original purpose and as high in the waste hierarchy as possible, considering overall expenses and environmental effects. As a prerequisite for conducting selective demolition, it is necessary to conduct a mapping of the resources as well as the problematic substances contained in the building, prior to the demolition process. Included here are:

- an estimation of the type of materials
- technical issues regarding their separation
- associated sales opportunities
- economic and environmental opportunities representing the different handling operations
- location of environmental harmful substances and how to sort those out in the best way and finally
- how to comply with the requirements for sorting of different material fractions

All these considerations being well in keeping with the guidelines formulated for pre-demolition audits.

The Danish Demolishing section signed an agreement with the Danish Environmental Protection Agency, regarding the implementation of selective demolition as a fixed quality standard for demolition projects in 1996, the Environmental Control System of the Demolition Business (NMK 1996). Members of the demolition section as a subsection to “Dansk Byggeri”, is required to comply with this inter-industry agreement and carry out selective demolition thus promoting recycling of C&DW (Danish Environmental Protection Agency 2017). As stated, it is mandatory to conduct an environmental mapping in Denmark, but no requirements exist regarding mapping of resources. Furthermore, it is required to announce the generation of C&DW, but it is not required to make a specific plan of the project which could potentially serve as an active planning tool during selective demolition including the results from the Pre-Demolition audits (Wahlström *et al.* 2018.).

The deal, NMK 1996, obligates the members to conduct selective demolition in order to promote recycling of construction and demolition waste, and thus introduces a new standard for environmentally sound demolition practice. The agreement comprise demolition, handling and disposal of decomposition products associated with every kind of demolition within Denmark generating more than 10 tons of waste and involving members of the section. Selective demolition includes removal and sorting of material fractions of appropriate purity enabling the highest possible level of recycling. Before initiating the project, the contractor must carry out an estimation of the expected quantities of waste distributed among material fractions. In connection to the hand-over he must as well document how the decomposition products are transported and which recipients received the waste also in terms of quantities (NMK 1996). NMK96 requires as a minimum 80 % reuse/recycling and maximum 5 % landfilling.

A mapping of the resources might be used as a tool, unveiling the possibilities for recycling of the materials as well as the marketing potential following the demolition. The procedure should always be viewed in relation to the environmental mapping and they might advantageously be carried out contemporary. The mapping of the resources constitutes the basis to reapply the resources at the highest possible level of the waste hierarchy as well as sorting of the waste at source. The mappings should ideally be carried out at an early state, to enable the inclusion of the results in the invitation to tender and thus elucidating the estimation of the amounts. The mapping of the resources might also be involved actively in the demolition work as a basis for planning and afterwards in the final listing of the waste amounts. It is assumed possible to form a general picture of the kind of materials applied as well as the construction techniques expected in a building by evaluating the building style and year of construction. In addition, the building could have been renovated several times, and extraction of BBR information, inspection and examination of drawings are appraised to provide the most valuable information regarding specific buildings (Environmental Protection Agency 2018b).

Public building owners must offer demolition projects as selective demolition according to NMK96 and it is also common practice among private building owners. The overall benefit in recovery of C&DW involve the economic and environmental gains experienced by the building owner who must get rid of the waste and a building owner in search for resources, especially raw materials and to achieve a matching, those needs must be identified. Experiences from different project unveils how an early recognition of opportunities for symbiosis like these as well as dialog among the stakeholders can achieve significant advantages economically as well as in terms of resource savings by matching demolition projects and construction works.

According to the announcement of waste, it is required to notify the local municipality of demolition works regarding the expected types of waste as well as the amounts. As mentioned, within the line of business a specific requirement for mapping of resources could possibly encourage recycling and reuse at higher levels of the waste hierarchy. And a required mapping of resources including considerations of sales opportunities prior to demolition, would provide better opportunities to introduce increased traceability of the waste stream. Enhanced economic incentives for exploring the opportunities of matchmaking between demolition and construction should be demonstrated. Thorough preparation of demolition work should focus on larger projects as great amounts of uniform materials provide the best sales opportunities and in addition, the larger the amounts of waste the more incentives exists to reduce the disposal costs (Environmental Protection Agency, 2017).

1.3 Circular economy

As evident from the different papers addressing C&DW, circular economy stand out as an area receiving more attention in recent years, comprising a central aspect in strategies defining best management practices (Styles *et al.* 2018). In overall terms, a circular economy strives for maximizing the circulation of products and materials and the value embedded within them, and thus production and consumption should happen with the lowest amount of refuse and waste (Styles *et al.* 2018)

A broadly accepted and precise definition of a CE is still lacking, and the concept is applied in different ways by stakeholders, depending on their specific interest. And furthermore, while the basic idea of the CE is intuitive and convincing and the notion is widely used in policy documents, the assessment of progress towards a CE is an issue of ongoing debate. Appropriate monitoring tools need to able to capture different critical issues related to CE strategies. Not all recycling activities are necessarily reducing overall resource demand, but they can result in problem shifting as recycling indirectly may require more material and energy than direct use of primary materials under certain circumstances. In-use stocks of manufactured capital are growing in most countries requiring an increased share of overall resource use. Only if in-use stocks are steady does a substantial closing of loops become possible because then end-of-life flows from demolition and discards can equal materials used for maintenance and replacements of in-use stocks (Mayer *et al*. 2018).

The term “circular buildings” is used to define a building that is designed, planned, built, operated, maintained and deconstructed in a manner consistent with CE principles. When framing building research from a CE perspective, it is important to consider that the useful life phases of a building extend over a significant time span. In northern hemisphere countries, average lifespans of buildings might on average reach 60 – 90 years at least and therefore focusing solely on new buildings will not suffice if we are to bring circularity into buildings. Furthermore, buildings are constructed of standard manufactured products, but when these are assembled, they create a unique, complex, long-lived and ever transforming entity. The main innovation within the idea of a CE consists in decoupling resource depletion and growth, allowing that an ever-growing economic development and profitability can happen without an ever-growing pressure on the environment (Pomponi and Moncaster 2017).

In line with the CE being a central aspect in C&DW management, the circular economy framework and its basic principles “Reduce”, “Reuse” and “Recycle” have been proposed for evaluating and addressing more effectively the construction and demolition waste materials. It has been employed in suggesting appropriate policies as well, in so making CE a current political goal in many countries worldwide. Waste in the CE are part of a continuous material loop that should not be blocked, and circular economy strategies identify the best final treatment opportunities for waste materials, reducing their generation at source and keeping their amount to a minimum by means of increased efficiency, recycling and appropriate design. Ghisellini et al. reviewed and organized the existing literature with the main purpose of exploring the different cases of implementation of CE principles (Reduce, Reuse and Recycle) for the C&DW management with the final goal to evaluate if the adoption of a circular approach for the C&DW management is environmentally and economically sustainable. In the end-of-life phase, reuse and recycling contributes to close the buildings life cycle and to reintroduce materials into future life cycles. The use phase is widely recognized as the most impacting phase in the life cycle of a building but with the reduction of energy consumption in the “use stage” relative importance of “indirect impacts” from the end-of-life cycle of a building becomes more important. Furthermore, it increases the importance of adapting a “cradle to cradle” life cycle approach including the impacts of the precedent levels of an extensive reuse and recycling of the waste (Ghisellini *et al.* 2018).

Circular economy is in essence a cradle to cradle concept and framework where materials, components and products at the end of their life are processed into closed loops, becoming resources for future life cycles. As a result, in the case of buildings the preferred LCA model to evaluate and enhance the implementation of CE principles should necessarily include all processes from cradle to cradle. This model allows evaluating how circular an approach actually is and how environmentally sustainable, at micro (building material), meso (building) and macro levels (urban agglomerates) according to the framework. The analysis of the different cases of implementing the CE approach shows that the recovery of C&DW provides environmental benefits in most of the cases and the reuse/recycling of C&DW in the whole lifecycle of a building contributes to slightly reduce its negative impacts of the construction phase. Generally, the recycling of metals such as aluminum and steel show a high environmental and energy saving potential and the recycling of these materials require low additional energy investments as well. Recent studies comparing recycled aggregates to the conventional products further confirm the environmental advantage of the recycled products. The production of recycled aggregates is affected by transport distances and consideration and embodied energy of the elements in the mixes, in particular the cement level, seems to reduce the influence of transport distances for recycled products. Among the basic principles of the CE, recycling compared to reduce and reuse is the most investigated in the literature. The scarce attention paid to reduction might arise from the fact that the studies mainly focuses on the management of C&DW in the building life cycle where the adoption of the reduction principle is limited. The comparison of reuse and recycling scenarios for C&DW management also evidences the different potential capacity of reuse and recycling options in the life cycle of a building to the environmental or energy impacts. And as a result, the hierarchical importance is not predefined as in the waste management hierarchy, and the desirability of reuse over recycling changes according to the material of interest. (Ghisellini *et al.* 2018).

Within EU, the European commission in 2015 passed a plan of action helping to force the transition towards a circular economy and one of the areas of priority within this plan is exactly the building and construction sector. As an initiative, the European commission has formulated guidelines regarding "Pre-demolition audits" for demolition projects, as described previously, and these might become a necessity when conducting selective demolition. Valuable waste streams as well as those constituting a potential risk, would be identified early in the project and handled optimally (Danish Environmental Protection Agency 2017).

In a Danish context, the government has launched its strategy for circular economy and in this context a special focus also points towards increasing the circularity within the built environment. It is stated that as the building and construction sector accounts for approximately 1/3 of the total amount of waste generated in Denmark, the potential within this sector is of particular interest, both in economic as well as in environmental terms. Significant shares of this fraction are currently recycled at a low value but the market for reused materials could be boosted by sorting out materials containing problematic substances as well as better caretaking of valuable materials during demolishing (Strategi for cirkulær økonomi). C&DW potentially holds an array of problematic substances and materials including polychlorinated biphenyles (PCB), lead, cadmium and asbestos with the associated risk to diffuse these harmful substances into the environment together with fractured C&DW if not identified and sorted out before recycling the material. It is therefore required to increase the quality of recycled C&DW to avoid this diffusive loss of harmful substances to the environment and this action might require increasing fractions of C&DW to be sorted out as unsuitable for recycling (Environmental Protection Agency, 2014).

In conclusion, circular economy roughly eliminates C&D wastes by preserving the added value in building materials as long as possible through recirculating them to close their loops and manufacture new products. It is a steppingstone to an optimal C&D waste management as it reduces resources escaping from the loops and simultaneously maintains their quality. Amirreza Mahpour and collegeas identified ineffective C&DW dismantling, sorting, transportation and recovery processes as well as agency and ownership issues in C&DW waste management as some of the main barriers which should be removed before transforming current linear economy into circular economy in C&D waste management (Mahpour 2018).

1.4 Urban mining

Contradictory to circular economy just elaborated on, the traditional linear approach is based on extraction of raw materials, production, use, wasting and landfilling leaving no options for the raw materials except to be used and then discarded. However, with the constantly expanding populations, there is a shortage of raw materials to continuously supporting this linear approach. The circular approach primarily arises from this increasing need for raw materials and attention is currently moving from the limited and fixed stocks of raw materials to the increasing anthropogenic stock of materials and this creates the base for the development of the Urban mining concept. (Bonifazi and Cossu, 2013).

Urban mining is known as an integrated and interdisciplinary management of anthropogenic material stocks in order to recover secondary raw materials from a part of the stock no longer in use (Schiller *et al.* 2017). The concept of urban mining can help understanding buildings as repositories of material resources whose intelligent management has potentials for conserving natural resources (Ostermeyer et al. 2018). The stocked materials may represent a significant source of resources, with concentrations of elements often comparable to or exceeding natural stocks. As for natural ores, extraction and processing of anthropogenic stocks is necessary and the generation of economic benefit is essential. Given that the storage time of a material cannot really be accurately estimated the difference between a “stock” and a “flow” resource is very difficult to establish (Cossu and Williams, 2015).

To facilitate effective urban mining require comprehensive information about materials and substances. For the exploitation of primary ores, intrinsic properties, such as element concentration, abundance, availability, speciation and partner minerals, determine whether a particular substance can be economically mined. The same applies to recovery of substances from urban material flows and stocks. Data about use during the product lifetime are important such as location, flows, stocks, density, speciation, partner elements and dissipative losses. This information – a cadaster of secondary resources – forms the basis for priorities for recovery, for design of effective reclamation systems with advanced logistics and recycling technologies and for environmentally sound final disposal of nonrecyclables. Locating urban mining processes close to the source of secondary materials has significant advantages. Transportation of wastes and recyclables requires energy, and so does recycling and processing. Hence, short transport distances and processes with high efficiency are important and the concept of urban mining performs best from a sustainability point of view when recycling facilities are located within the city. Data about flows and stocks of materials and substances will play a major role in urban mining and when broken down on the city level with information about the possibility to recover these resources, such data will be of high value for this concept. And finally economic modeling is needed to clarify which potentials of secondary resources promise an economic benefit and which pose marginal of even negative assets (Brunner 2011).

The reuse and recycling of resources from the building stock is coherent, since the buildings “accumulate” a vital contingent of resources. The use of secondary resources from the building stock is of interest since it is likely to improve the reduction of the emission of carbon dioxide but is however poor due to limited information of kind, quantity and spatial distribution of materials. Planning authorities could benefit from this information however, since the strategic waste management could be based on the data, improving the sustainable development of a region and of the building stock (Schnitzer 2014).

2. Background of aggregate supply

2.1 Primary supply of aggregates

The concept of urban mining could in principle be applied to all kinds of materials contained in the building stock, an example being aggregate materials constituting a significant share of C&DW worldwide. In Denmark approximately 8,7 million tons of concrete was produced in 2015 corresponding to a consumption of 1,5 tons of concrete per Dane a year. Supporting this consumption prerequisites adequate supply of aggregates fulfilling the technical criteria applying to concrete. The use of concrete as a building material is widespread, due to its unique characteristics such as high flexibility, great strength and long durability and nothing points toward substituting concrete for other building materials in the nearest future. The aggregates required to produce concrete is available throughout the globe and concrete can thus be produced locally based on local supplies. However technical requirements of the aggregates as well as other interests in using the land areas limits the amount of aggregates available for production of concrete and likewise might force the aggregates to travel long distances. The geographical availability and the resulting transport distances therefore constitutes an important environmental aspect regarding aggregates (Rosholm 2016).

According to the plans for raw materials from the Danish regions it is estimated that materials suffices to cover the demand between 14 and 43 years ahead depending on the specific region. The consumption of raw materials varies from year to year depending on the economy and projections for future consumptions is based on economic as well as demographic conditions. Consumption of raw materials in general can be defined as the sum of extraction on land, extraction from marine areas piloted to Danish harbors, import and reclaimed material. Products of concrete encompasses European norms as well as a few Danish additional standards. According to the regulation on construction products, products of concrete must be CE-marked thereby guaranteeing fulfillment of the claims stated in Danish and European standards. The standards put up some key parameters ensuring durable concrete related to the exposure expected for the material and concrete is categorized into different environmental classes according to the expected utilization of the product.

Concrete aggregates constitute the main part of the concrete, normally between 60 and 75 % of the volume and is a mix of sand and stone materials in different sizes. Aggregates for concrete are normally differentiated by:

- Fine aggregate/concreting sand, 0-4 mm
- Small pebbles, 2-8 mm
- Pea gravel, 8-16 mm
- Fine pebble gravel, 16-32 mm

Compiling of the concrete is done according to the different grain sizes allowing the smaller particles to be compressed within the cavities of the larger ones. Concrete aggregates are thus described according to the distribution of different grain sizes and a close packaging of the aggregates reduces the demand for cement, thereby minimizing the overall costs. The size distribution of the aggregates depends upon different material types, concrete prescriptions and environmental classes, but normally the sand fraction constitutes 20 – 30 % while the stone fraction accounts for 30 – 45 %.

The classification of the aggregates is decisive regarding the quality of the concrete which is categorized according to the environmental classes:

- Passive (P)

- Moderate (M)
- Aggressive (A)
- Extra Aggressive (E)

The cement is the component binding the aggregates together to form concrete and consists of mainly quicklime and clay, which in correlation with water hydrates, generating a strong binding material. As cement is the one component requiring the most energy to produce the environmental profile of the concrete is to a large extent determined by the content of cement and in addition it is also the most expensive component. Cement is a composite product, consisting mainly of pulverized cement clinker as well as gypsum and additions of different rest products from industry including fly ash, micro silica and slag. Water is the other main component of concrete which together with cement bind the aggregates together, and as soon as the concrete is mixed a hydration process between cement and water initiates. The ratio between water and cement is thus decisive for the characteristics of concrete, the lower the ratio the higher the strength.

Aggregates for production of concrete in form of sand and stone are available in large amounts throughout the world and this is also the case for Denmark, where aggregates are extracted from gravel pits on land and from marine areas in certain parts of Danish waters. The extraction from land have been relatively stable between 20 – 30 mill m^3 $year^{-1}$ within the last 40 years and in 2014, 86 % of the total amount of raw materials was extracted on land, the remaining part coming from the seabed. Due to the increasing demand for raw materials a Raw Materials Act was prepared in 1972 and has been revised since then. The aim of this law is to ensure the supply on a longer term and to pursue utilization of the raw materials according to their quality and furthermore it strives for the replacement of natural raw materials by waste products. The Regions are required to carry out a mapping of the resources on land and must perform a plan regarding the extraction and supply of raw materials, based on expected demands 12 years ahead. Changes in the landscape are the main environmental impact related with extraction on land, while influences on the local flora and fauna in the top layers of the seabed are the main concern when extracting on the sea. This practice is also associated with significantly larger investments and operating expenses. The degree of self-sufficiency is around 95 % for sand, stone and gravel for Denmark which mainly imports crushed aggregates required for the highest environmental classes.

The supply of aggregates is to a large extend determined by the existence of contractors of certified materials within a given area as the transport distances constitutes an important factor applying to aggregates. Those materials are characterized by being cheap, heavy and with a high volume making longer transportation uneconomical. The extraction of aggregates is minimum on Zealand and almost non-existent within the capital region and as these areas experiences shortcomings, entrance from shipping are required. A significant share of the resources is unavailable for extraction as they are placed within areas of other interests often prioritized in favor of raw material extraction. These factors, among others, make reliable estimations of residual quantities and supply horizons hard to complete. A significant share of the environmental impact of concrete is related to transport of raw materials, and shortages of supply in different areas might entail increasing transport distances and associated environmental consequences. Local supplies are thus essential for environmental as well as economic reasons.

There might be a significant potential for recycling and recovery of C&DW within Denmark. Through sorting, cleaning and reprocessing and array of recycled products could be generated and utilized within the construction sector as a replacement of natural raw materials. No reliable estimates of the amount of waste concrete generated within Denmark exists as a certain fraction remain unregistered. In addition, only limited information regarding the origin of the concrete waste is obtained and no systematical separation or classification of the waste happens, which could however improve the possibilities for recycling. Limited incitements to explore the opportunities for using recycled aggregates in new construction originate from the already existing demand for using the aggregates as soil stabilization related to road construction. Besides, the potential is only as large as the amount available for recycling (Rosholm 2016).

The region has the authority regarding supply of raw material and extraction on land and is responsible for preparing a plan for the extraction of raw materials to supply for construction work within the region. The plan is to be completed based on the mapping of raw materials and is valid for a period of 12 years within which the supply of raw materials should be ensured. Extraction of raw materials is to be carried out considering environmental protection, interests of water supply, protection of geological interests, protection of nature, city development and infrastructure facilities (Plan for raw materials, Capital region 2016).

Making up a raw material deposit include containing materials of a requested quality, the availability of sufficient amounts and being accessible for extraction. Digging areas comprise clearly defined areas pointed out in the plan for raw material extraction where the amount of materials of high quality leaves them interesting from a business perspective. Extraction should as a starting point happen within these areas and the consideration of raw material extraction come before other interests within these areas. The quality of the extracted materials is decisive regarding the subsequent employment of the material as well as the extent to which they are demanded. Materials of high quality encompasses coarse materials like stones and gravel applicable for concrete production (Plan for raw materials, Capital region 2016).

As stated above, the supply of raw materials should to the largest extent possible be based locally to limit the transport and climate impact. Regarding the region of Zealand, the raw materials are unevenly distributed in the underground and decentralized digging areas in Kalundborg, Sorø and Roskilde remain decisive. These three regional digging areas should contribute the whole region with raw materials for larger construction projects and support the Capital region with raw materials as well. In 2007, The National Road Directorate estimated that the region of Zealand, is the region with the average longest travel distance of raw materials, reaching 44 km and the main reason is that Northern Zealand as well as the Capital region is undersupplied with raw materials. Market forces, including quality, supply, price and transport costs determines where the raw are utilized and according to the line of business the price is doubled if the transport distance increases with 40 km. It is estimated that around 50 % of the raw materials extracted in the region of Zealand is exported to the Capital region, mainly from the area around Roskilde and Kalundborg. Ongoing work focuses on ensuring a higher degree of self-sufficiency within the Capital region. The amount of resources extracted depends to a high extend upon investments within the construction sector. During the period from 1989 – 2011 the average extraction on land in the region of Zealand amounted to 5,1 mill m^3 $year^{-1}$. Based on these numbers and projections for economic development, the extraction from 2012 – 2037 is expected to reach 7,9 mill m^3 $year^{-1}$ and with a total resource of 149 mill m^3 in existing digging areas this corresponds to a supply horizon of 19 years. In the period from 2006 – 2011, the three regional digging areas accounted for 85 % of the total extraction and are thus highly important for the resource supply within the region. The search for raw materials in the region unveils that easily available sand, gravel and stone materials is either already consumed or part of existing digging areas and where maximal production is already obtained additional costs might be required for further production. In the future it might thus be harder to find deposits of raw material containing sufficient amounts and broadness of quality and where the level in conflict of interests are on an acceptable level. In some cases, transport might be cheaper than the opening of new digging areas (Plan for Raw Materials, Region of Zealand, 2012 – 2023).

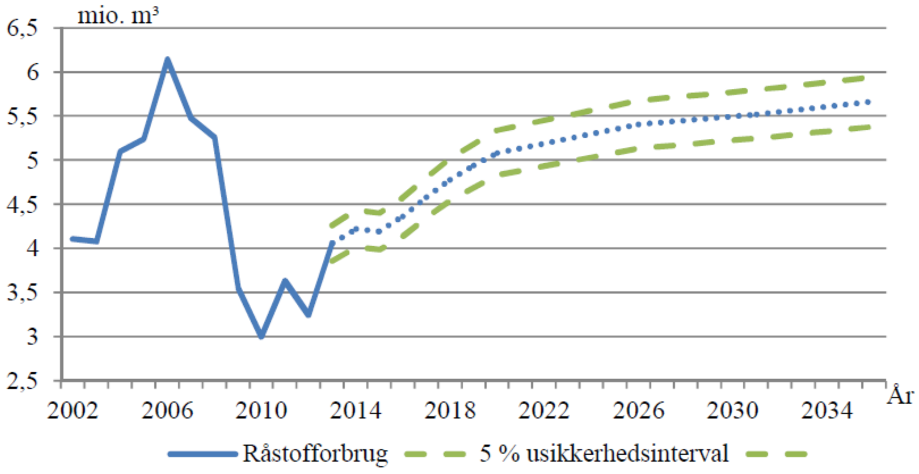


Figure 3 Projection raw material consumption, Region of Zealand 2013 – 2036.

Throughout the period from 1997 – 2012 an overproduction of raw materials was apparent for the region of Zealand and this is probably a result of export to the capital region, solely. When including the consumption of both regions within the same period a deficit in the consumption of raw material is apparent which is to be covered by import from other regions. The amount is estimated around 1-2 mill m^3 a year and as acknowledged within the sector the import of raw material from Jutland to Zealand is expected to increase in future. The consumption of raw materials generally follows the same trend in both regions, but the capital region accounts for the largest share (Plan for Raw Materials, Region of Zealand (2012 – 2023).

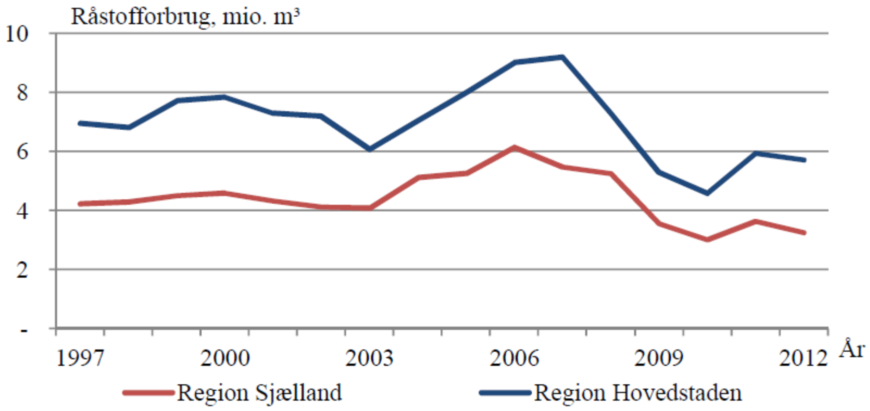


Figure 4 Consumption of raw materials in the Capital region and the Region of Zealand, respectively.

By December 2014, the Capital region compiled an estimation of extraction and consumption of raw materials within the region, unveiling a resource base of 70 million m^3 corresponding to 13 years of consumption. In the capital region the consumption of raw materials is approximately 5 times larger than the extraction and is therefore depending on supply from the region of Zeeland as well as from sea. The extraction of sand, gravel and stones amounted to 800.000 m^3 – 1.200.000 m^3 in the period of 2009 – 2015, the oscillations resulting from general economic fluctuations influencing the construction sector and thereby the market for raw materials. The total consumption would thus be somewhere between 4 million m^3 and 6 million m^3 throughout this period. All together the supply and demand as well as the quality and price of raw materials determine where extraction of raw materials happen (Plan for Raw Materials, Capital Region, 2016).

The consumption of raw materials within the capital region, added up to 7,2 mill m^3 by 2015 while the extraction within the region itself amounted to 2 mill m^3 or 27 % of the total consumption. A smaller share is covered by recycling, around 19 %, but the remaining part is mainly covered by import from other regions or areas outside Denmark. The projections show an increasing trend from 2016 – 2040, jumping from 7,2 mill m^3 in 2015 to 11,4 mill m^3 in 2040 with the increase until 2022 being the most pronounced and an average throughout the whole period of 10,3 mill m^3. The municipality of Copenhagen is assumed responsible for the largest share of the consumption of raw materials expected to demand 42,9 m^3 from 2016 – 2040 or 17 % of the total demand in the capital region (Niras 2018).

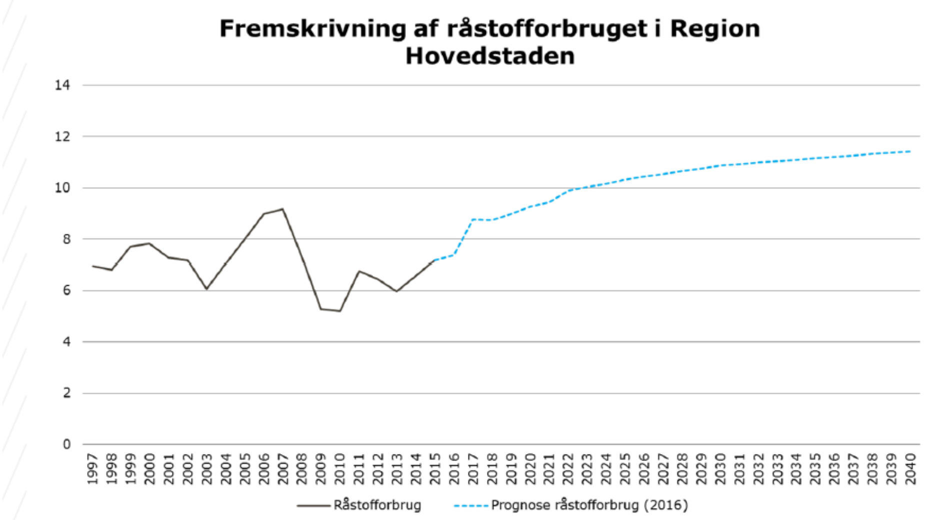


Figure 5 Projections of Raw material consumption in the Capital region, 2016 – 2040.

Waste materials and recycling, as an area of focus in the plan and treated under the headline of circular economy, supports the necessity of viewing C&D waste as a secondary resource substituting extraction form deposits of raw materials (Plan for Raw Materials, Capital Region, 2016). Within the Capital region, an older building will often be demolished before building a new building generating recyclable material, and sorting and recycling of C&DW is more profitable when tearing down larger buildings.

2.2 Secondary supply of aggregates

With the current situation regarding supply of primary aggregates just elaborated on, employment of secondary aggregates to a larger extent might be encouraging, getting even more relevance in the future. In order to make quantitative estimations of the potentials regarding secondary aggregate supply, a characterization of the aggregate waste has to conducted as a first step. Aggregate waste constitutes around 2/3 of the total amount of C&DW but is however comprised by several different fractions including primarily concrete, but also significant amounts of bricks and tiles as well as mixes of these fractions. In addition, concrete waste is not just one specific material type but covers an array of different types containing additional different substances and giving them their specific characteristics. These aspects are decisive to consider when planning C&DW management aimed to increase the recovery of recycled aggregates.

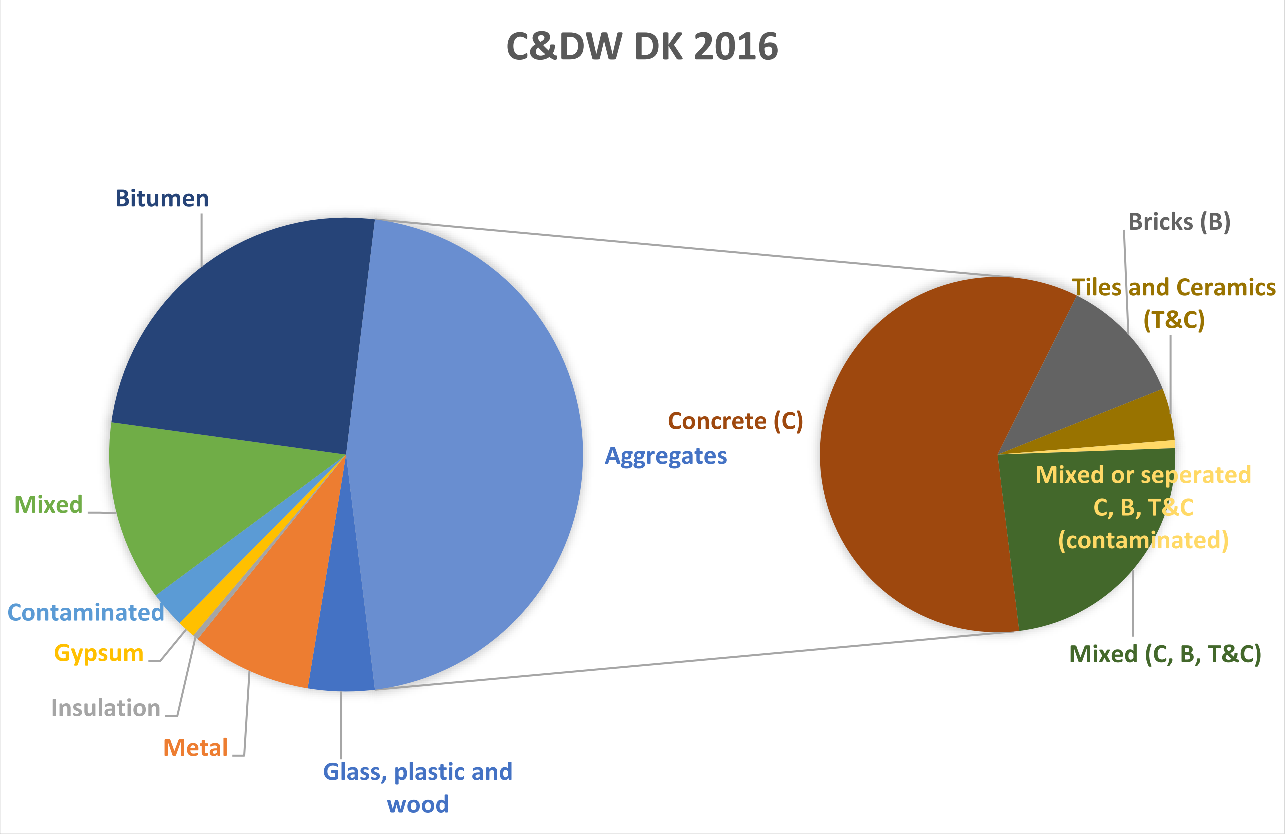


Figure 6 The aggregate fraction of C&DW in Denmark, 2016.

According to the waste hierarchy reuse is a preferred option in reference to recycling and in this regard, it would be interesting to examine the potential to utilize concrete one step higher in the hierarchy (Environmental Protection Agency 2015).

Even though concrete waste constitutes a significant share of C&DW, except for some elements such as beams or blocks which can be dismantled from a building, “clean” crushed concrete waste is barely reusable. (Styles *et al.* 2018).

Currently, re-use of elements is very limited worldwide as well as in Denmark, the main reasons being lack of knowledge and information on the concrete elements that arises as waste, the updated regulation around concrete elements that old concrete does not fulfil and the costs of processing. Some of these problems might be solved once the design-for-disassembly efforts become more common (Environmental Protection Agency 2015).

However, recycled concrete aggregates (RCA), are usable for the so-called unbound applications or as secondary materials in the manufacture of new concrete as the highest quality use of RCA. There are no technical barriers for a virtual 100 % recycling of the main constituents of C&DW, concrete and ceramics waste, but barriers derived from their commercialization, the market of virgin materials or their logistics. The profit margin on recycled aggregates depends on the localization of the resource, which must be closer than conventional quarries, and the respective taxes applied to landfill and natural aggregate extraction. Researchers have shown that, with proper waste separation, recycled concrete aggregates can substitute 100 % natural aggregates in quality applications of concrete (Styles, Schoenberger, and Zeschmar-lahl 2018). From well sorted waste, high quality aggregates can thus be produced, since clean crushed aggregates have a much higher applicability than mixed crushed masonry-concrete aggregates. The final destination of RCA is the substitution of virgin materials. Although main substitution rates are achieved in low grade applications as sub-base materials for roads and backfilling, higher grade applications as aggregates for new structural and non-structural aggregate have a high potential. The use of RCA would thus help to reduce the use of virgin materials from quarries, which usually have a high environmental impact at local level (Styles *et al.* 2018).

According to concrete norms DS/EN1992-1-1 crushed concrete in new concrete must meet DS/EN206 and be divided in a sand fraction (< 4 mm) and a coarse fraction (4 mm – 32 mm). If the source is known for the RCA, the new concrete can be used in an exposure class to which the original concrete was designed with a maximum replacement of 30 % RCA. Otherwise the new concrete has to be in exposure class X0 or XC1 as a dry environment without corrosion and can be used up to strength class C30/37. In Denmark it is allowed to apply crushed concrete for loadbearing structures within the passive environmental class implying that the concrete is not exposed to frost, but the recycled aggregates can only make up 20 % of the stone fraction and 10 % of the sand fraction. For non-bearing constructions, 100 % of the stone fraction and 30 % of the sand fraction can be substituted by recycled aggregates (Environmental Protection Agency 2015).

When fractured concrete is applied as a road material it is classified according to the technical quality, as roads are dimensioned according to different classes of traffic. Roads exposed to heavy traffic requires RA of the highest quality whereas RA of lower quality can be applied to roads experiencing less traffic. In general, the higher the ratio of concrete compared to tiles, the greater the stability and pure concrete waste might therefore be applied to all classes of traffic while utilization of mixed concrete/tiles and concrete/asphalt is limited. Economic advantages might be obtained when using RA for road construction compared to NA as the quality is equal while the price for RA is significantly lower. Reasons for this could comprise lacking security of supply for RA as well doubt about the environmental quality of the RA. The process of fracturing concrete into RA emits more CO_2 compared to extraction of NA and the distances aggregates are travelling therefore determine the complete CO_2 footprint, highlighting the importance of optimized resource logistics when recycling aggregates. Savings on natural resources are another significant aspect in the situation of limited resource supply (Environmental Protection Agency 2015).

In order to estimate the potential for substituting natural aggregates by recycled aggregates, both qualitative and quantitative aspects of the resource would have to be evaluated. Quantitative perspectives consider the amount of aggregate waste available for recycling.

Concrete is one of the largest fractions in C&DW, generating approximately 1 million tons of concrete waste each year in Denmark based on the official register Affalds Data Systemet (ADS) and more than 95 %

of this amount was recovered. However, there are large quantities of concrete waste that are not registered, and stakeholders place the unregistered quantities to at least one million tons. Concrete waste is normally produced by demolition and renovation and only to a lesser extent by new construction and is source separated from other waste materials. Use of crushed concrete as aggregate does not occur in large scale in Denmark for technological, economic and environmental reasons. Concrete based recycled aggregates is currently more expensive than concrete based on virgin materials, so there is no economic incentive for waste operators to divert waste into that route. Moreover, for most concrete applications, legislative requirements on hazardous substances and quality standards discourage manufacturers from utilizing crushed concrete in their concrete products. Overall, the demand for crushed concrete for use as filling material and especially sub-base material is high, mainly because of the lower price of crushed concrete compared to the alternatives. In contrast, stricter regulations, variability in quality and uncertainty of supply limit the possibilities for crushed concrete to be used as aggregate in new concrete (Environmental Protection Agency, 2015).

Sorted concrete and tiles might be recovered according to regulation stated in the announcement of residual products without special permission in line with Environmental Protection Act, implying the materials are uncontaminated. Until now, concrete containing recycled aggregates has not been valued as suited for load-bearing constructions due to properties like high drying shrinkage and high and uncontrollable creeping compared to conventional concrete. Against that, recycled aggregates are considered equally suitable as primary resources for application in slabstone paving, concrete floors, indoor non-load-bearing partition walls etc. The most pronounced barrier regarding optimal recycling of fractured concrete from buildings comprise lacking knowledge and surveys about the scope of application achieving economical, technical and environmental sustainability (Environmental protection agency 2017).

2.2.1 Characteristics of recycled aggregates

Regarding the quality of recycled aggregates, the roughness as well as the angular shape of aggregates influences the workability of the concrete, and additional water must be added as well as a corresponding amount of cement to maintain a proper water-cement ratio. As cement is the expensive component of concrete and decisive regarding the environmental profile, an evaluation of the benefits connected to recycling of aggregates must therefore be conducted (Environmental Protection Agency 2015).

Silva and colleges carried out a systematic review of the literature on the physical and chemical characteristics of RA to unveil how these affected the concrete produced. Properties comprising size, shape, density, water absorption, mechanical properties, mineralogical composition and contaminants were examined. After crushing and undergoing beneficiation in certified recycling plants, the resulting aggregates may be assigned to different classes. Recycled Concrete Aggregates, comprise a minimum of 90 % by mass of Portland cement-based fragments and NA where the quality is determined by the recycled brick content. Recycled Masonry Aggregate (RMA) includes aerated and lightweight concrete blocks, ceramic bricks and sand-lime bricks often also containing mortar rendering and burnt clay materials. And finally, the Mixed Recycled Aggregates (MRA) are composed of crushed and graded concrete and masonry rubble. The variety of contaminants that can be found in RA from the demolition of existing structures can severely degrade the strength of concrete made with it. Since mortar is less dense that concrete, the more adhered cement paste in RCA the lower the density of the aggregates and the number of processing stages often determines this amount. When mixing RCA and RMA resulting in MRA, the density of the resulting aggregates is expected to increase with the RCA content while decreasing with the RMA content. Regarding water absorption RA will almost always exhibit higher values than NA and is directly related to its porosity. The porous nature of clay bricks means that aggregates derived from them have higher WA values than NA and RCA do. After various processing stages, coarse RCA have lower WA than the corresponding fine fraction due to the increasing amount of crushed cement paste accumulating in the fine aggregate fraction. The mechanical performance of RA was found to be mainly influenced by the recycling procedure used and the quality of the original materials. Generally, the use of lower-density aggregates blends resulted in concrete specimens with poorer performance and therefore the performance of concrete will often decline as a result of increasing water absorption. As a good correlation was found between the properties of an aggregate and those of the resulting concrete, it might be suggested to classify aggregates partly on their composition but mostly on their physical properties. Overall, coarse RCA are often considered as the most suitable RA for use in concrete production, but specifications limits the application of coarse aggregate for use in concrete to a maximum ranging from 25 % - 55 %, depending on the future use (Silva *et al.* 2014).

RA derived from C&DW generally consists of natural coarse aggregate and adhered mortar. The quality of RA mostly depends on the methods of recycling process to be adopted while the properties of RA mainly depend on the water/cement ratio of the original concrete from which it is obtained. The most distinguishing feature of RA is its adhered mortar which makes it porous due to the high mortar content, inhomogeneous and less dense. The volume of old mortar in RA varies from 25 % - 60 %. The amount of adhered mortar signifies the effectiveness of the crushing procedure and the particle size of RA is greatly responsible for its anomalously high water absorption capacity (2 – 3 times higher compared to natural aggregate). In addition, recycled aggregates might have inferior mechanical properties such as lower crushing strength, impact resistance and abrasion resistance compared to natural aggregates and might as well be contaminated with organic and inorganic impurities. Altogether these factors might affect the concrete in terms of workability, strength and durability. Even though the potential for the use of RA has been acknowledged, some salient properties such as particle size distribution, shape and size of aggregate, porosity, absorption, toughness, hardness, strength and the impurity level are necessarily to be assessed before its use in the concrete. Being more porous in nature RA requires more water than conventional concrete to obtain the same workability. The water absorption capacity of RA increases with increasing strength of the parent concrete they are derived from as higher strength corresponds to larger quantities of adhered mortar. RA are less resistant to mechanical action due to its poor bond between old mortar and the RA, presence of transverse cracks and fissures resulting from the recycling process and the presence of weak porous mortar around RA. Most importantly, cement mortar adhered to the aggregate surface influences the performance of RAC, basically the strength characteristics. The compressive strength of RAC depends among other factors on the combination of w/c ratio of the original concrete as well w/c ratio of RAC and typically decreases with increasing w/c ratio. The reduction in compressive strength is op to 30 % as compared to natural aggregate concrete at 100 % replacement. It depends partly upon the age of the parent concrete from which the RA has been derived as the residual cementing capacity of un-hydrated cement present in old matrix governs the strength properties. However, the reduction in compressive strength might not be prominent when RA replacement is up to 30 %. It has been acknowledged that the desired compressive strength can be achieved by using more cement content than normal concrete, by incorporating some alternative cementitious material such as fly ash or silica fumes or with the aid of some super plasticizers (Silva *et al.* 2014).

Split tensile strength exhibits similar behavior as compressive strength with the increase in RA quality but the effect of RA on this parameter might be less pronounced, however. It has been found that the split tensile strength and flexural strength of RAC mainly depends on the quality and surface characteristics of RA regardless the replacement level of RA. Concrete with RA which is derived from high strength concrete shows better split tensile performance than RA derived from normal strength concrete and flexural strength might decrease with increasing content of RA. Drying shrinkage is a very prominent feature of RAC related with decrease in volume or contraction of hardened concrete and the total amount of water in fresh concrete and drying shrinkage is directly related to each other. Concrete made with RAC exhibits significantly higher drying shrinkage compared to conventional concrete which can be explained by the higher water absorption characteristics and highly porous nature of RA due to attached mortar. However, it has been shown than with a replacement level of up to 30 %, RA has no major effect on the drying shrinkage. Another parameter influencing the performance of concrete is that of creep, which has been shown to increase with increasing content of RA in concrete and is directly proportional to the content of mortar present. Creep of RAC can be increased of up to 50 % compared to conventional concrete. Modulus elasticity is another important mechanical property which signifies the stiffness of concrete and is affected by factors such as porosity and density of the aggregates. Like compressive strength, similar trends have been observed for modulus of elasticity decreasing with an increasing substitution of RA. It might be lowered up to 45 % and 15 % with a substitution of RA by 100 % and 30 % respectively. As a result, RAC might behave in a more brittle manner with reduction in stiffness compared to conventional concrete. It can be concluded that the influence of the content of RA on shrinkage, creep and especially on the modulus of elasticity is significantly higher than that of other strength properties, showing an inverse relationship with RA content. On the other hand, RA content does not have much influence on the bonding between concrete and reinforcing bars whereas the bar profile has more influence on the bond strength than the RA replacement. It has been noticed that the negative effects can be mitigated to a certain extent by adding different ingredients, including fly ash, silica and superplasticizer to the concrete in a modified manner. Durability performance of concrete is a measure of the permeation characteristics of the concrete as well the integrity against aggressive agents in the environment and investigations have shown durability performance of RAC to be poorer than conventional concrete. The poor durability of performance of RAC is associated with the inferior quality of RA due to the numerous cracks, fissures and pores present inside the aggregate making it more susceptible towards permeation. Modification of the porous nature has been one of the great concerns to improve the durability properties of RAC and can also be helped out by incorporating mineral admixtures as mentioned above (Silva *et al.* 2014).

2.2.2 Contaminants

Beside the qualitative characteristics elaborated on above, contents of environmental harmful substances might reduce the feasibility of utilizing RCA and making people more reluctant regarding employment of RCA in structures. A characterization of the potential contaminants expected to emerge from old concrete structures would thus be decisive to propagate recycling of concrete to a larger extent. For the period from the 1950's until toady some of the most prominent substances to expect from concrete waste arising today and in the future include polychlorinated biphenyls (PCBs), chlorinated paraffins, polychlorinated hydrocarbons (PAH's) and heavy metals and asbestos fibers in addition, which might be hard to separate from the concrete.

Polychlorinated biphenyls are a group of organic substances, applied as softening agents from 1950 to 1977 in Denmark, mainly within soft fillers, paintings and adhesives and are covered by the list of the Stockholm convention on persistent organic pollutants (POPS). PCBs might contaminate concrete secondary by migrations into concrete exposed to PCB containing paintings or tertiary by transmission via air. Chlorinated paraffins are a group of organic chlorides, especially applied as fire retardants and softening agents in fillers and paintings, substituting PCB's from end 1970's and they are also covered by the POP statutory instrument. Polyaromatic hydrocarbons (PAH's) are found in tar and are applied as a lubricating agent for sealing of foundation walls with the aim of preventing moisture to penetrate and it has been utilized until the 1970's. Heavy metals have been employed in paintings indoor and outdoor and as base coatings etc. and they are typically found in old layers emerging during demolitions. Heavy metals encountered in concrete waste today include lead, cadmium, chromium, copper, zinc, selenium and mercury. Except for mercury, heavy metals in general are not fugitive but might comprise a problem for the operating environment during renovation or demolition. Applying recycled aggregates in new concrete comprise the risk of vaporizing fugitive substances as PCB and PAH into the indoor climate or accumulation in the new concrete if not cleansed beforehand. Waste concrete from recycling stations might not immediately be characterized as uncontaminated, as it in some cases exceed the thresholds limits for utilization of soil and residual products. Testing from receiving installations in Denmark have shown low concentrations in clean fractions of concrete and tiles, however, while the mixed fractions in general unveiled higher concentrations of hydrocarbons, PAH's and metals compared to the clean fractions (Environmental Protection Agency 2015).

2.2.3 Processing waste concrete

Waste concrete is generated during demolition of buildings, plant constructions as well as private residences. The demolished material is sorted in order to remove visible metal- and plastic fractions. The concrete is fractured outright or is transported to larger receiving installations where a waste handling company carry out the fracturing. The waste concrete is typically fractured into a grain size of 0-32 mm. When buying recycled aggregates, it consists of either pure concrete, a mixture of concrete and tiles or a mixture of concrete and asphalt. All three categories might be employed as uncombined road base in road constructions or open places, substituting base coarse aggregates (Environmental Protection Agency 2015).

Bricks and ceramic waste can be processed in the same recycling facilities as those designed for concrete recycling, which can threat all mineral waste coming from construction and demolition. The main processing recycling facilities for CBC waste are stationary plants, which can process large amounts of waste, and mobile plants which are designated for processing lower quantities of waste. The later are very suitable for building demolition as they enable CBC waste to be processed on-site and the recycled aggregates to be reused directly on the same site.

In general, CBC recycling procedures undergo the following stages:

- Sorting concrete waste
- Preliminary sieving to remove fine-grained fraction, including soil
- Manual or mechanical sorting to remove contaminants or unwanted materials such as wood, paper, plastics etc.
- Removing ferrous metals using a magnet
- Reducing the size of materials with a crusher
- Sieving, shredding and mixing

The use of recycled aggregates cannot fully replace natural aggregates when concrete is used for structural purposes in construction and at present around 30 % of recycled aggregate substitution is recommended in concrete used for structural applications. Recycled aggregates resulting from bricks and ceramics waste are suitable for different low-quality applications such as road sub-base construction and filling works rather than as aggregate substitutes in concrete. In general, the presence of masonry and mortar in a concrete recycled aggregate can be detrimental in terms of physical, mechanical and chemical properties (Sáez and Osmani 2020).

Classification of RA into easily understandable categories, alongside proper certification, also helps facilitate further client purchases since they will be buying an item appropriate to future application. Depending on the type of concrete structure, different support structures and demolition methods are required. C&DW recycling plants are not significantly different from plants that produce crushed NA from other sources and might employ various crushers, screens, transfer equipment and devices for removing contaminants with the objective of manufacturing a specific-sized granular material. The degree of processing depends on the initial C&DW's level of contamination as well as the intended future application. Normally, a mobile plant consists of one crusher or more rarely two crushers and some sorting devices with lower contamination removal effectiveness. A stationary recycling plant usually consists of a large primary crusher working in conjunction with a secondary or tertiary crusher and in addition various cleaning and sieving devices to produce high quality RA. The choice of whether CDW processing should be done in mobile of stationary plants is complex and needs to be evaluated based on a case by case basis, considering several technical, financial and environmental aspects. Owing to their varying nature, C&DW are difficult to process and the existence of contaminants affect the handling as well as the properties of the final product the quality of which being inferior to that of NA, is one of the biggest barriers to their wider use in construction. But nevertheless, stationary recycling plants have progressed to a point that minimizes the quantity of contaminants to an acceptable minimum thereby allowing the production of high-quality RA for higher grade applications. And furthermore, owing to their large size, stationary plants have the potential of building up stocks of different quality materials for immediate supply to larger contractors. Mobile recycling plants, on the other hand, have a considerable advantage over stationary facilities in terms of the short transport distances between demolition site and the processing equipment. When the end use application has low requirements and there is an abundance of inert materials on the demolition site, it is thus better to employ a mobile facility thereby reducing transportation costs and CO_2 emissions. The C&DW gate fee charged by recycling plants have been shown, having a strong influence on the profitability of the plants and special attention must therefore be paid to ensure this gate fee is managed as efficiently as possible.

Upon arrival at the recycling plant, C&DW may either enter directly into the processing operation or need to be broken down to obtain materials with workable particle sizes. Jaw crushers were found to produce RA with the most suitable grain-size distribution for concrete production while impact crushers are more suited if the RA are intended for road application and they are less sensitive to material that cannot be crushed. Both types of crushers have large reduction factors, defined as the relationship between the input's particle size and that of the output. In order to produce RA with a predictable grading curve, it is better to process debris in two crushing stages, at least, but more crushing stages would yield products with decreasing particle sizes, contradicting the mainstream use of RA. Coarser RA fractions are namely preferred regardless of the application. After the primary crushing stage, self-cleaning magnets separate bits of steel reinforcements and other ferromagnetic metals but electromagnets might also be employed having the advantage of not accumulating the metals in the magnet. Regarding non-ferrous metals including aluminum, copper, brass, lead and zinc, being non-magnetic they have to be separated from C&DW using an eddy current separator and as this technology might be damaged by ferromagnetic metals, these have to be removed at an earlier stage in the process. At later stages, contaminants such as dirt, gypsum, plaster and other fine impurities might be eliminated by passing the crushed aggregates over a set of scalping screens separating the materials based on size and shape. In the final contamination removal stages, either air sifting or wet separation can be used. Air sifting may be as effective as wet sifting separation in terms of the removal of lightweight contaminants like wood, hardboards, plastic, straw, roofing felts and asbestos fibers and in addition avoid the use of large quantities of water. Wet separation on the other hand allows leaching of water-soluble chlorides and sulphates and despite its potentially lower economic and ecological advantages, aggregate washing is a better contaminant removal method to produce RA, meant for the production of cementitious materials, than air sifting.

Dust, noise and vibration are generated by processing operations and are likely to be of greater concern if the recycling facilities is close to sensitive receptors and although these issues are normally not sufficiently strong to cause property damage or injuries to people, they might be quite uncomfortable. The main sources of dust, noise and vibration are the working engines that power on-site crushing and screening equipment plant, as well as vehicles (Silva *et al.* 2017).

3. Hypothesis and aim of research

The hypothesis of this project is that closing the loop of material recycling of aggregates is possible to a larger extent compared to the current situation of today and in this regard sparing the extraction of natural aggregates.

By improving the data within this field, covering more specifically certain materials expressed by material intensity coefficients (MICs), would assign resources locked up in the existing building stock more value. By combining this knowledge with data about the spatial distribution of buildings of different types and age, predictions about future waste flows arising from the building stock would be more precise. Both in terms of quantity and quality of materials but also regarding spatial and temporal distribution of these flow of waste.

The objective of this project is to further improve data about the existing building stock in a regional context of Zealand. Focusing on a smaller scale, data on the building stock will be gathered, more specifically covering different kind of materials used in the buildings. One part of the project focuses on the region of Zealand and the Capital region trying to balance supply and demand of primary vs. secondary aggregates. The other part of the project is more focused towards C&DW management in a national context and comparing its performance to other nations on an overall level.

This model structure comprises the combination between the bottom up method of MICs designating the amounts of different materials employed and top-down approach for the building stock in terms of the number of square meters. Application of this model should help identifying the concrete contained in the existing building stock in both qualitative as well as quantitative terms. This knowledge would assist the End of Life (EoL) management of construction and demolition waste (C&DW) and potentially support the transition towards a more circular economy. As a result, ideally more aggregate waste could be recycled and employed in new structural construction works instead of the current practice, applying it as filling for road construction.

Based on the characterization of the existing building stock, in terms of different building types constructed in specific time cohorts (archetypes), a prospective building stock model will be developed to predict the share of the building stock remaining in the future. The demand for new construction materials will take its offset in the need to maintain this building stock combined with scenarios designating the future need of square meters as the drivers for the development of the stock. The potential for secondary aggregate supply in terms of the existing building stock becoming obsolete in future as well as the demand for new construction aggregates as driven by the development of the stock will be obtained. And finally, based on the characteristics of the different aggregates applied in the construction sector, estimations of the possibilities for substituting primary aggregates would be attempted, considering the supply horizon of primary aggregates in a regional context.

3 Litterature review

3.1 MFA

Different modelling approaches can be used to quantify environmental flows and stocks in the built environment.

Material flow analysis (MFA) is a technique used to quantify the inputs, outputs and stocks of materials in order to determine the material metabolism of a precinct, city or country [1]. In general MFA begins with the definition of the problem and of adequate goals. Then relevant substances, goods, processes and appropriate system boundaries are selected. These steps comprise the system definition and lead to the qualitative model. Next, mass flows and stocks are then determined and balanced based on the principle of mass conservation for each process as well as for the entire system. Uncertainties might be considered and the result is a quantitative model. Often, the only possibility is to define system boundaries as administrative regions such as nations, states and cities because information is systematically collected on these levels. An advantage of using these system boundaries is that political and administrative stakeholders are within them and results of the MFA can thus be implemented more easily. One of the main purposes of MFA is to develop simple and reliable models to picture reality. Two different ways of assessing the amount of materials in stocks exists. The total mass of the stock can be determined either by direct measurement of the mass or by assessing the volume and the density of the stock. The second approach involves calculating the difference between inputs and outputs over an appropriate time span.

Static versus dynamic MFA is another characteristic, distinguishing different kind of MFA analyzes. While static MFA is rather concerned with generating a better understanding of a material system based on material accounting principles like mass balances, dynamic MFA is primarily used to investigate the stock buildup of materials in society as secondary resources as well as in the environment as dissipative losses based on the material flow over time.

An MFA is thus static if it describes a “snapshot” of a system in time whereas a dynamic MFA describes the behavior of a system over a time interval (Hilty *et al.* 2014).

As an advantage of dynamic MFA, it is able to identify trends over time and enables extrapolation of system behavior into the future. By dynamic MFA it is thus possible to understand consequences of changes in a time dependent system temporarily and to analyze alternative scenarios in terms of future material management. Analyzes of MFA can furthermore be distinguished based upon whether they apply a top-down or a bottom-up approach. For the top-down estimate a time series of input-output balances is used to calculate the total stock, while the bottom-up estimate is based on deriving the total stock from the material intensities in all relevant products. Output of obsolete products is often calculated based on lifetime functions with outputs being calculated by accumulation of all former inputs becoming obsolete in the respective year. As an alternative, using leaching coefficients determines the fraction leaving the stock in a specific year meaning that all the material in the stock has an equal change of exiting the stock.

As mentioned, the top down approach is to quantify the sum of annual additions to the stock over a long period and stocks are thus derived from the difference between inflows and outflows calculated from year to year. These flows are known from statistical data or are estimated based on average lifetime or survival functions. If a dynamic approach is applied, the change in flows over a long period is studied by assuming removal from the stock of materials contained in built works which reached the end of their lifetime. An average lifetime or a mathematical survival function (probability for a built work to be demolished after a given number of years) is used. Dynamic analysis can be based on input flows, e.g. by extrapolating their recent yearly average, and this method is termed a flow-driven model (Augiseau and Barles 2017). Flow driven models assume the material stock to be driven by its inflow and outflow, where the inflow is predicted as a function of socioeconomic factors, whereas the outflow is determined by either a leaching or a delay process. On the other hand, a stock driven model assumes the stock as the driver of the material flows and can be considered as a service unit driven by population and its lifestyle. The outflow of materials, coupled with the obsolete service units, is determined by a delay process, whereas the inflow of materials, coupled with the new add-in service units, is introduced to maintain the stock in use. The bottom up approach is based on a division of the stock into categories and then by the application of material ratios or material intensities. This approach, also known as the coefficient-based method, provides a good knowledge of the "inner structure" of the stock and allows both the quantity and the quality of materials to be taken into account (Augiseau and Barles 2017).

Top down approaches provide almost no classification by type of materials and are unable to distinguish between different forms of buildings. On the other hand, bottom-up approaches supply much more detailed information on the constitution of the building stock and is able to describe the stock accumulation through time and space. This method combines indicators that describe characteristic material compositions of typical buildings with indicators estimating the physical size of the building stock (Ostermeyer *et al.* 2018). However, there is a need for a bottom-up approach that models the city at a high spatial resolution and includes construction aspects assemblies and materials including their spatial organization (Ortlepp *et al.* 2016). Two major databases are required when applying the bottom-up approach: the physical size of the built-environment components and the material intensity coefficients (MIC) specific to each component (Österbring *et al.* 2017).

Bottom up studies generally shares the assumption that built works can be divided into groups or types which have the same material intensity by using criteria such as construction period or use of a building. Dynamic flow analysis methods also assume that each group of built works has an average lifetime and they express the probability of a building to be demolished with survival functions. Dynamic prospective flow analysis using a flow driven model generally assume that future construction and demolition are correlated to factors such as national or local demographic forecasts or economic activity and GDP forecasts (Augiseau and Barles 2017).

The assumptions and data used by bottom-up approaches raises questions. Firstly, the assumption of homogeneity within different types of built works is problematic when buildings grouped within the same type according to their use can vary a lot, especially applying to the non-residential building sector. Besides, material intensities rely on case studies, expert opinion or modelling and significant differences can be observed according to the source. This especially applies to trace materials but also for non-metallic mineral waste. Average lifetimes are also problematic as there according to, Kohler and Hassler, is no relation between the age or the condition of a building and the probability that it will be demolished. As a consequence, local case studies should be pursued to produce more accurate estimates of material intensities and lifetime and relevant crossing of top-down and bottom-up data approaches can also enhance the reliability of the estimates.

The bottom-up approach offers a high degree of flexibility, whether for the description of flows or the analysis of material stock. Schiller et al. developed a hybrid approach combining a top-down analysis to determine the extent to which material flows and estimates of stock size can be derived from general economy-wide statistics, while on the other hand a bottom up analysis considered individual objects using a coefficient-based MFA approach. Quantities of stock of goods and flows, expressed as functional units such as m^2, are linked to goods-based material contents (MC). (Schiller *et al.* 2017).

Several studies considering quantification of C&DW have been conducted applying an MFA analysis to the existing building stock. They differ in terms of the spatial scale covering large areas like all of Europe or large countries like China down to regional level or even individual cities. They also differ in terms of time scale ranging from retrospective and prospective studies covering a century to an assessment for a single reference year. Materials which are most studied are those with most mass, especially non-metallic minerals including aggregates, sand and concrete but trace elements like non-ferrous metals, iron and steel are also the subject of several studies (Augiseau and Barles 2017).

A dynamic stock model was first developed by Müller (Müller 2005), to analyze the Dutch dwelling stock and later on the model was modified and applied to the Norwegian dwelling stock by Bergsdal and colleges (Bergsdal *et al*. 2007). Similar dynamic dwelling stock models have also been used for studies of the Chinese dwelling stock, (Hu *et al.* 2010) and further advances in the modelling consisted in segmenting the building stock in cohorts (Holck *et al.* 2014).

In a study conducted by (Müller 2005) considering the Dutch dwelling stock, a stock dynamic approach was introduced as a method for simultaneously forecasting resource demand and waste generation. The population and its lifestyle as manifested in service providing stocks of products in use were applied as the central driving force where the input of new service units determines how much material is needed. This material input was used, together with a lifetime, to calculate the material stock accumulation and output. Using this method, they estimated the floor area stock and flows of construction and demolition waste, as well as the corresponding stocks and flows of concrete in the period 1900 – 2100. This approach can be classified as a stock driven approach, as opposed to the flow driven approach assuming stocks to be driven by flows. The question as to whether stocks drive flows or vise versa is not always easy to answer and might also depend on whether the focus of the question is short- or long-term. As precise estimations of the development of stocks are impossible, this model approach has significant shortcomings with respect to determining short-term changes. In the long-term, however, there are indications that stocks of service units follow certain patterns. The same general approach to dynamic long-term modelling of stocks and flows was applied by (Bergsdal et al., n.d.) to the Norwegian residential dwelling stock. The main objective was to investigate the dynamics of the stock, measured by units of useful floor area, and its influence on the corresponding stocks and flows of concrete. The study presents results from simulations for 1900 – 2100 and subsequent results for concrete, emphasizing the relationship between historic C&D activity and future projections. The residential dwelling stock is comprised is a variety of building types and vintage cohorts, both differing with respect to material composition and the cohort approach allows one to account for the long-term effects of changing building stock size and composition with respect to material demand and waste scrap generation. This study unveils how estimates of past activity levels contains inherent uncertainties in the input parameters, in particular for the lifetime parameter of buildings which was the most influential one in the scenarios of this study. Mingming Hu and collages also applied the same approach to Beijing's residential building stock for the floor area and the construction material, concrete (Hu *et al.* 2010). They found the per capita floor area as one of the most important variables determining the material stock dynamics of housing and it showed a powerful correlation with the local GDP.

Projections of waste generation and materials demand from building systems are often performed based on trend analysis which might represent a sufficiently good approximation if limited to a short period of time. However, it may fail to grasp the long-term effects calling for the use of dynamic modelling taking into consideration the activity levels of the past and their interrelations and attempting to explore how these will affect the future activity levels (Sartori *et al.* 2008).

The reusable and recyclable material stock available in residential buildings depends both on their specific structures and on the date of erection. Oezdemir and colleges (Oezdemir *et al.* 2017), conducted a study with the aim of showing a detailed and site specific approach for identifying quantities of material stocks, available in specific residential buildings and thus to provide a foundation for using anthropogenic stock as secondary material in the building sector. The authors argue that only after a regional cadaster exists that provides a relatively exact quantification of the composition of available material, concepts can be created to reuse material from demolished buildings in another regional building site. They used georeferenced vector polygon data fitting the built environment and attributes in form of floor count, roof type, function and year of construction to account for the building structure in the study area. A building's material stock is highly dependent on its year of construction and this information is therefore required. In this case a catalogue defining twelve age classes over the time span from 1859 until today was applied distinguishing between single-family houses (SFH), terraced houses (TH), multi-family houses (MFH) and apartment blocks (AB). To make the stock accessible, they first estimated the material quantities with their individual composition and then extrapolated the results to a regional level providing a resource cadaster with a spatial visualization of the quantities of available material stocks. Mapping potential regional storage provides orientation for meeting and coordinating future emerging demands for secondary materials as the appearance of a secondary material stream can be estimated by using this method. The developed methodical procedure in this paper could provide the foundation for the identification of future reuse from the building stock and to analyze the recycling potential in any region. However, information about toxic substances detected through construction period analysis needs to be included in the process of information collection.

(Schebek *et al.* 2017) identified the special characteristics of the non-residential building sector as differing much more in function and technical components as compared to residential buildings. Non-residential buildings might contain a higher share of metals and other high value materials and in addition the temporal variations of the nonresidential sector are driven by the dynamics of economy, making in-use time of buildings significantly shorter. These factors leave the residential building sector of specific interest in terms of recovery of secondary resources. For the non-residential building typology two characteristics of function and age was applied and the combination of function and age-class gives a 12 x 8 matrix yielding 96 theoretically possible types of NRBs. The stock-taking-process was executed by first identifying the material stock based on obtained documents and drawings while in the second step, the verification of materials and their quantities was done “on-site”. As a result, from evaluations and analysis of spatial data, the frequency of building types within the total stock of a selected area can be identified. By incorporating information of age-classes derived from other sources, a database was compiled which assembles information from single buildings to the total stock within a regional boundary. As argued by the authors, a metropolitan region like the Rhine-Main can be considered a suitable level for planning and strategy making for resource recovery. On the one hand due to the existing administrative structures of planning organizations and on the other hand it can be stated that construction waste management require a regional perspective in order to conceive strategies for recovery of and optimization of material flows. Especially applying to mineral construction waste, it is known that longer transport distances reduces recycling rates due to economic reasons with an upper limit around 50 – 70 km and in addition supply and demand of mineral waste is focused on urbanized areas. Regarding metal resources however, sites of metal production have far larger catchment areas of secondary resources, e.g. steel scrap. The findings of a study like this might be useful for companies as well as well as for strategic planning in the waste management sector and contribute optimization of secondary value chains as a prerequisite for substituting primary materials. As companies within this sector base their capacities as well as investments in novel technologies on expected demolition activities and related waste amounts and qualities, they might benefit from regional information as a basis for their business planning. Finally, due to the information on function and age-classes and the allocation to individual buildings, a detailed picture of the future dynamics of regional material stocks can be derived. This will yield information on the change and amount of flows in time and will also gain further insights on the quality of feedstock materials coming from the stock.

As stated in (Ortlepp *et al.* 2016), little is known about non-domestic buildings although they account for approximately half of the total building stock. Non-domestic buildings are heterogeneous in terms of types of construction, materials and morphologies making a systematic description more difficult. In their study they developed a new method to quantify indirectly the material stock of non-domestic building, comprising three steps. First material composition indicators were calculated in t/m^2 floor space, then the total floor space of non-domestic was estimated and broken down according to the defined building types and finally, the total material stock was determined by combining the results of the previous steps. Floor space was used as the indicator to quantify the building stock. They found the most striking difference between non-domestic and domestic buildings to be the proportion of metals (primarily steel used for structural frames and reinforcing steel), which was much higher for non-domestic buildings, 8 %, compared to 1-4 % for domestic buildings. Recycling paths are however already well organized for materials like metals due to the financial savings that can be made by reusing such valuable materials. The options for reuse, recycling and recovery of mineral building materials are considerably more limited and should be used much more extensively in line with policy goals. In this regard greater knowledge is required of the quantity and quality of materials within the built environment in order to calculate output flows accurately and thereby supporting waste management strategies. Reliable data can be used to improve the strategic planning of governmental authorities, to monitor resource flows and deployment, to ensure efficient resource use and to avoid shortages. In addition, it might help the creation of specific policy instruments to promote a more circular economy and to inform the business plans of companies in the construction and waste management sector.

Based on the experiences gained from applications of MFAs it can be derived that the top-down and bottom up approach hold different benefits and drawbacks respectively. The top-down approach might be easy to employ as the information required for its application are immediately available in statistics, but this method is unable to analyze building stocks on a more refined level, however. The bottom-up method, on the other hand supply much more detailed information on the constitution of the building stock and is able to describe the stock accumulation through time and space. But in general bottom up studies shares the assumption that built works can be divided into groups or types which have the same material intensity by using criteria such as construction period or use of a building which might not be reflected in reality, however. The need for a bottom-up approach that models the city at a high spatial resolution is acknowledged and local case studies should be pursued to produce more accurate estimates of material intensities and lifetimes. In addition, relevant crossing of top-down and bottom-up data approaches could also enhance the reliability of the estimates. Finally, the non-residential sector was found to differ much more in terms of construction materials and function compared to the residential sector. As it constitutes close to half of the total building stock and might contain a higher share of metals and other high value materials and in addition experience significantly shorter lifespans, it might be interesting from a secondary resource perspective.

3.2 Environmental impacts of C&DW

Life cycle assessment (LCA) is in general a widely accepted methodology to assess environmental impacts of products and services along their life cycle [3], and the methodology is increasingly being used to identify strategies that will improve the environmental performance of waste management systems (Bovea and Powell 2016)

Reduction in greenhouse gases from the build environment has typically been focused on the buildings in-use even though embodied emissions originating from extraction, processing, manufacturing and transport of materials also are significant (Densley *et al.* 2017). The environmental impacts originating from the energy use have traditionally been the major contributor to LCA results conducted on buildings. But as future buildings are expected to become more energy efficient in terms of energy use for operation, the embedded impacts derived from building materials would become more significant regarding LCA results for buildings in future.

In a review paper conducted by Bovea and Powel, the overall results showed that on-site recycling was always preferred to landfill, but results for offsite recycling are highly dependent on haulage distance. However, it is highlighted that if avoided burdens are taken into account, the quality of the recycled material obtained need to be considered when the substitution ratio is estimated. In all cases recycled material generates lower environmental impact than its equivalent primary material. The need for on-site separate collection to ensure “clean” materials and the efficiency of the recycling process as well as transport distances and transport type are considered as important parameters to maintain environmental advantages. It is also important to make a note of the need to specify the composition of the C&DW since the End of Life strategies used largely depend on the composition of the waste (Bovea and Powell 2016).

Environmental issues associated with CO_2 emissions play a leading role in the sustainable development of the concrete industry in this century. Due to the high demand on concrete production, the construction industry is responsible for about 7 % of global CO_2 emissions. Besides, it is estimated that about 37,5 billion tons of aggregate are consumed annually around the world. In order to pursue sustainable development in construction the consumption of raw materials and energy should be decreased and, in this regard, recycled coarse aggregates could play an important role. Researchers have been engaged in many investigations on both mechanical and structural behavior of RAC but in addition to technical objectives environmental issues should also be addressed and balanced. In the area of sustainable evaluation on RAC utilization, LCA has been an effective tool in meeting municipal decision makers’ interest, as results from LCA can be used as indicators for environmental effects of source separation, waste treatment and concrete recycling technologies.

Concrete is the most heavily consumed material in the construction sector and the second most heavily consumed substance on Earth after water. In addition, construction and demolition waste has become the largest and increasing waste fraction in industrialized countries. Environmental benefits of high-grade RC applications have been in doubt. As cement is the main contributor to many environmental impacts of concrete, additional cement use for RC due to larger grain size surface area of recycled aggregates might outweigh potential benefits of natural aggregates substitution. In addition, transport distances and types could significantly affect the balance of RC. Knoeri and colleges established a comparative LCA of conventional concrete and recycled concrete to analyze the effect of cement content and transport distances. The production of recycled aggregates for RC requires additional treatment of the C&D waste compared to building dismantling. Therefore, environmental benefits from co-products of the recycling operation including steel scrap were considered as avoided impacts. Three different concrete qualities were investigated since different applications require different technical standards and exhibit different acceptance of RC materials and three cement content scenarios were defined for the structural RC options to assess the sensitivity of environmental performance. They found cement and transport to be the main contributors to environmental impacts of concrete corresponding to previous studies. In addition they found the main difference between RC and CC stemming from the avoided impacts of C&D waste landfilling and recovering of steel scrap from RC, demonstrating the importance of considering the coproducts in the recycling processes (Knoeri *et al.* 2013).

The main motivation for using RCA in concrete is to reduce construction cost and environmental impacts. By using RCA, less non-renewable natural resources like rocks and gravel are mined and depleted particularly near urban areas where construction volume is high. This also reduces the number of quarries further from the cities leading to a reduction in the aggregate transportation distance. If quantitative assessments, such as LCA show that the use of recycled aggregate in concrete can reduce the environmental impact of concrete production, it could provide incentives to the industry to build specialized CDW recycling plants that produce RCA, usable in concrete. As the first study if its kind, Yazdanbakhsk and colleges conducted a comparative LCA study to determine whether the environmental impacts caused by concrete production in the New York City area are significantly affected if RCA is used as coarse aggregate in all the ready-mix plants of the region. The functional unit was defined as 1 m^3 of concrete with a specified compressive strength as the main property used to design most types of concrete. Some types of RCA can affect concrete durability and therefore reduce the lifetime, however. The RCA concrete mix used in this study has 8 % more cement than the NA concrete, but even if no additional cement was required for RCA concrete, the environmental benefits of producing RCA concrete in New York City are not significant. When prevented landfilling is not accounted for, the environmental impacts of producing NA and RCA concretes are thus similar since the impacts caused by the demand for additional cement for RCA concrete is offset by the shorter transportation distance between RCA sources and concrete ready-mix plants. The results of this study are thus in agreement with most of the studies comparing environmental impacts of producing NA and RCA concretes:

- The environmental impacts are sensitive to the demand for cement and aggregate transportation distances
- Replacing NA with RCA in concrete does not have a major impact on the environment

The authors underline however the importance to perform project-specific analyses to determine in what types of construction projects the use of RCA can lead to maximum environmental benefits. It is expected that the benefits are the highest for the projects in which old concrete is recycled in the demolition site by mobile facilities and used for construction at the same site (Yazdanbakhsh *et al.* 2018).

Ding and colleges draw up a regional LCI for NAC and RAC production in China and established a comparative LCA study on the environmental impact. RAC with 50 % and 100 % replacement percentages were both conducted in the analysis. Due to the existence of adhered old mortar, mechanical properties of RCA are decreased to some extent resulting in lower density parameters, higher crushing value index and higher water absorption. The higher water absorption may impact the net water to cement ratio of RAC requiring extra water as well as extra cement in addition. In general, RAC structures have a lower durability performance than that of NAC structures and the comparative analysis of this study was limited to non-aggressive environment conditions. However, mixing RCA in concrete has the environmental advantages of saving primary mineral resources and avoiding possible landfilling. Apparent from the results, under the assumed transport distances, RAC mixtures have limited environmental benefits compared to NAC on the aspects of global warming potential and cumulative energy demand. The results also demonstrate that the cement proportion always presents the highest environmental credit and is the largest contributor to all impact categories due to the huge CO_2 emission and energy consumption during the calcination process and fossil fuel consumption. The transport phase acts as the second most important contributor to the result of GWP and CED impacts and these was reduced because shorter transportation distances apply to

RCA compared to NCA as a result of short distances between concrete production facilities, aggregate recycling plants and demolishing sites. RAC utilization was characterized by smaller primary mineral resources extraction (CMR) compared with NAC, proving the biggest advantage of RAC utilization to be saving of primary resources as expected. The sensitivity analysis carried out regarding transport proved that the transport phase leaves a possible source of lowering environmental impact for RAC compared to NAC (Ding *et al.* 2016).

Recycling has the potential to reduce the amount of C&DW disposed of in landfills and to preserve natural resources and this potential is utilized if aggregates obtained by recycling are used not only in lower quality product applications but for structural applications too. When demolished concrete is crushed, a certain amount of mortar and cement paste from original concrete remains attached to some particles in the recycled aggregate and this is the main reason for the lower quality of RAC compared to NA. The density of RCA is lower while the water absorption capacity is higher compared to NA. Marinkovic´ and colleges determined the potential of recycled aggregate concrete to be used as structural concrete and compared the environmental impact of the production of two types of ready-mixed concrete. Natural aggregate concrete (NAC) made entirely with primary sand and gravel and recycled aggregate concrete (RAC) made with natural fines and recycled coarse aggregates. To compare the environmental impact of different concrete types, it is necessary that both concrete types fulfil the same similar functional requirements e.g. that both have the same strength, mechanical properties and durability. The mix proportion of NAC and RAC is determined so that both types have the same compressive strength and workability. However, it is likely that RAC will have a lower durability performance than NAC and as a result the analysis is limited to a type of concrete structure for which non-aggressive environment conditions apply. The quality depends mostly on the quality of the demolished concrete used for recycling and utilization of fine recycled aggregate in RAC for structural use is generally not recommended. In this case study the impact of the aggregate and cement production phase is slightly larger for RAC than for NAC and that leaves the transport phase as a possible source of lowering the environmental impact of RAC compared to NAC. Natural aggregate sources are becoming scarcer and more away from urban areas where most of the construction activities are located, while recycling plants usually are located near big urban areas. Keeping all other parameters constant and varying only the aggregate transport distance, it is possible to determine the “limit” transport distance of natural aggregates defined as natural aggregate transport distance below which environmental impact of RAC is larger than for NAC regardless of recycled aggregate transport distance. The limit distance for natural aggregates was found to be around 75 km in this study (Marinković *et al.* 2010).

To sum up, the results gained from previous LCA studies of C&DW in general confirm recycling of C&DW to be superior to landfilling in line with the priorities appearing from the waste hierarchy, but it might depend on transport distances, however making on-site recycling attractive. As the operational energy for buildings are expected to decrease in future, embodied energy in construction materials might gain increasing importance in future especially applying to energy intensive materials such as steel. Regarding the aggregate fraction of C&DW, even though constituting the major share of the waste in terms of mass, the environmental savings in terms of carbon emission reductions are negligible. Other environmental impacts might be worth considering however, and as it appears from the studies the benefits achieved by recycling of aggregates depends to a large extent upon extra additions of cement as well as transport distances required. Another environmental benefit is related to savings of natural aggregates and as a result, gaining a general view of the environmental performance of C&DW management practice applied to aggregates needs to consider supply and demand of primary vs. secondary aggregates in a regional context.

4. Methodology

4.1 Developing material intensities for residential buildings

One of several methods developed to estimate material stock is bottom-up accounting also known as a coefficient-based method, discussed earlier. This method is preferred for its ability to describe the stock accumulation through time and space but are however data demanding. Two major databases are required including the physical size of the built-environment components (m^2) and the material intensity coefficients (MIC) specific to each component (kg/m^2). While the first database can be collected from statistical offices or geographical information centers, MIC databases are site specific and not available in many countries.

One part of this thesis builds on a bottom up approach to characterize the existing stock of materials, contained within the buildings of Odense as a case study. Different types of buildings, single family houses, terraced houses and apartment blocks were analyzed using architectural drawings and floor plans retrieved from:

- www.weblager.dk

Measurements of dimensions (length, height, width) of different components were performed by using the tool, ImageJ. In combination with scales apparent from the drawings this tool was used to quantify the dimensions of different components. Qualitatively, the types of materials employed are often evident from the drawings either using symbols or directly designating the type of materials employed. In some cases, detailed description of material usage was lacking and under these circumstances, assumptions were made according to typical construction methods and construction materials employed during certain periods of time. Further, differentiation of buildings according to different cohorts and use types was also conducted in order to identify historical trends of material use in the building sector. In this way, material intensity coefficients (MICs) was assigned to archetypes of buildings. Three sample buildings were analyzed per archetype and all these data were gathered as a database showing material types and intensities of different buildings assigned to different cohorts.

Data extracted from Bygnings- og Boligregistret (BBR) covers building codes assigning the building to either single family house (120), terraced house (130) or apartment blocks (140). Additional information includes number of floors, year of construction, eventually year of renovation, footprint area, external wall material type and roof material. BBR contains information about all buildings and housings in Denmark. The owner of the property is the person responsible regarding accurate information in the register and large cash flows depends upon the information appearing from it. Under public management it covers taxes on real estate and block grants for housing subsidies while it within the private sector includes loan-taking and property transaction in real estate offices.

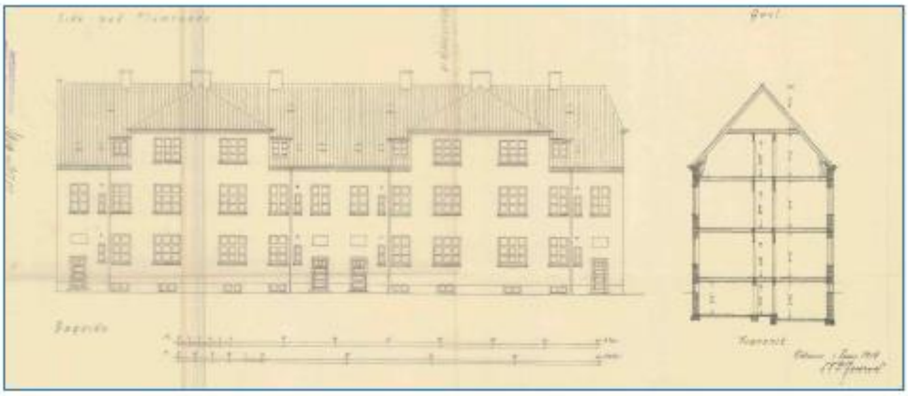


***Figure 8** Example of* Architectual drawing

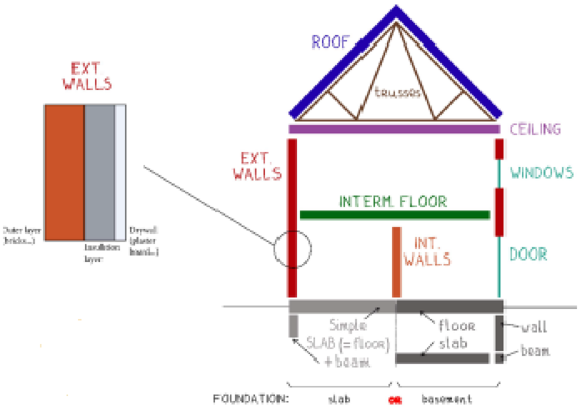
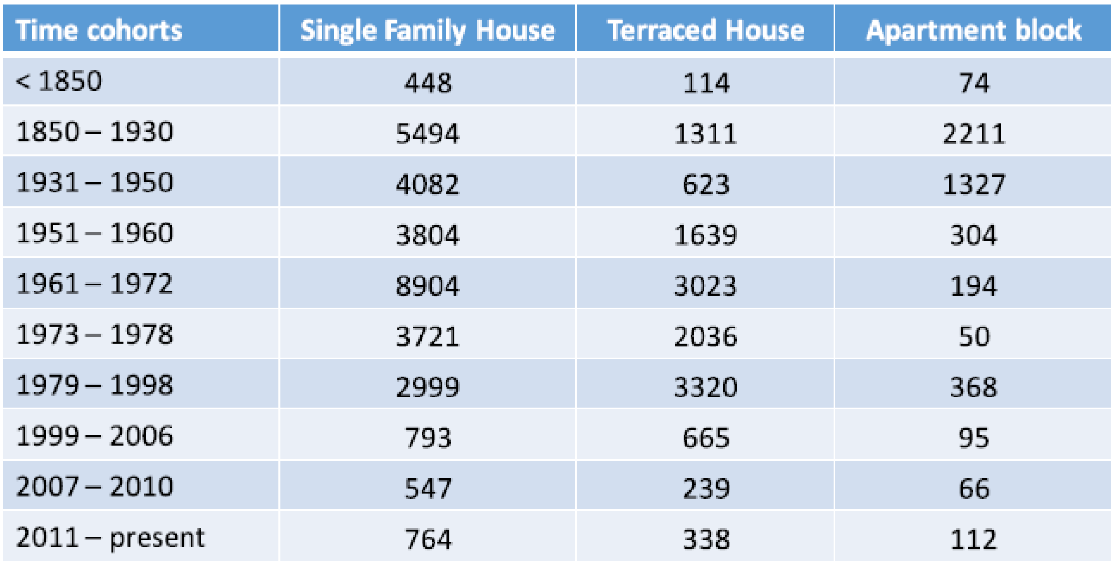


Figure 7 Building model (By Maud Lanau)

Each sample building will be analyzed based on architectural drawings visualized in **Figure 8** and the material intensity assigned to each individual component of the building according to **Figure 7**. In the end the material intensities was aggregated on building levels, obtaining MIs for each material per archetype.

Regarding the Odense case study, the different buildings and year of construction (archetypes) appears from **Table 1**. The material intensities retrieved previously will be assigned to the respective archetypes. The archetypes were not determined by the author of this project but have been developed as a part of the TABULA project. These archetypes have been used to evaluate the energy performance and possible energy savings obtainable through refurbishment interventions.

Table 1 Residential building stock in Odense



Time cohorts	Single Family House	Terraced House	Apartment block
< 1850	448	114	74
1850 – 1930	5494	1311	2211
1931 – 1950	4082	623	1327
1951 – 1960	3804	1639	304
1961 – 1972	8904	3023	194
1973 – 1978	3721	2036	50
1979 – 1998	2999	3320	368
1999 – 2006	793	665	95
2007 – 2010	547	239	66
2011 – present	764	338	112

The input for the archetypes have been derived from three randomly selected buildings per archetype and the available data for Odense was gathered by the PhD student and co-supervisor Maud Lanau. She altered the gathered datasets to make them useful and randomization was achieved through the following steps.

First of all, the data derived from BBR was classified based on their end-use code into Single Family Houses (SFH), Terraced Houses (TH) and Apartment Blocks (AB) and assigned to three spreadsheets. To ensure random selection of buildings a new column was added to the spreadsheet used to apply a random number via the random function of excel to each line representing a building or dwelling. Afterwards the spreadsheets are sorted by the random numbers from the smallest to the largest. To select a building sample e.g. SFH 1961 – 1972 the SFH spreadsheet are selected and the time cohort 1961 – 1972. Going from the smallest to the largest of the randomized numbers and accordingly scrutinizing weblager.dk for available documents, the building sample is taken as a sample if the levels of details are deemed satisfying. Through a joint effort by the PHD-students Zhi Cao and Maud Lanau and the master Students Julija Capuletti, Luca Herb, Sven Müller and myself a number of 90 residential buildings and dwellings have been evaluated in total and assigned to 30 different archetypes respectively.

Different databases have been examined in order to obtain information covering building types built within different cohorts. In connection to this, the websites:

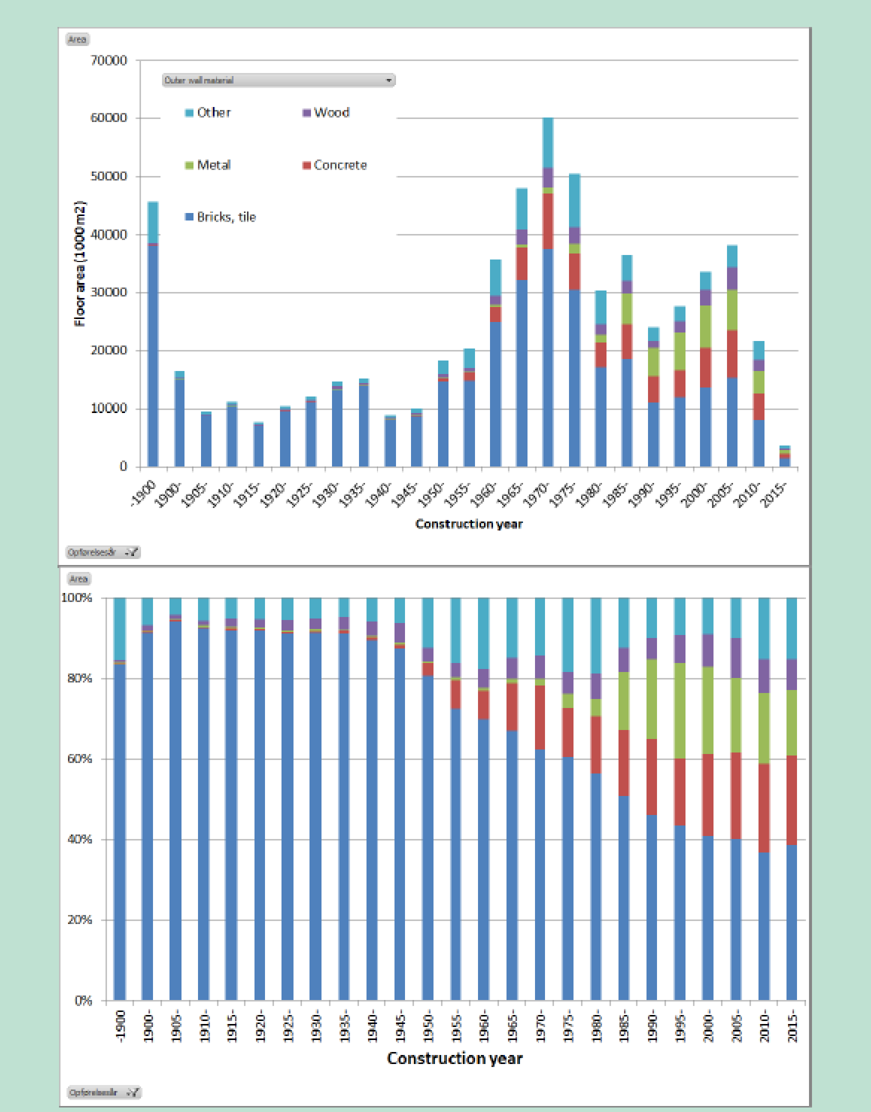
- http://huseftersyninfo.dk/hustypebeskrivelser

- http://www.danskebygningsmodeller.dk/

should be mentioned. Each of these websites contain information regarding different types of buildings build within different periods stating the material composition of different components typical for each of the archetypes as prevailing construction methods.

In the end, material intensities (MIs) corresponding to each of the archetypes have been obtained, following from this workflow. These material intensities should thus be quite representative for a Danish building stock, as they have been derived from the current building stock of Odense. Because of using Odense as a case study, the results generated might be more representative for this specific area but is this study they will be applied to the total building stock of Denmark. These considerations represent a major generalization which might subject the results of the study to some uncertainty but is however a consequence of the limited time available when conducting the study.

Construction of new buildings classified by type of exterior material, measured by dwelling or office area and by fraction of total area appears from **Figure 9**. As it appears, concrete exteriors did not start to become prevalent until 1960's and before that, brick was the predominant material. However, since the 1990's concrete has constituted about 20 % of new buildings.



Source: Statistics Denmark, Table BYGB60

Figure 9 New structures, by outer material and year of construction, in m^2 of dwelling area and share of total dwelling area.

4.2.1 Material intensities for nonresidential buildings

The data collected as a part of this thesis covered only the residential housing stock, whereas the non-residential stock also constitutes a significant share of the total building stock. As this project would also consider the non-residential part of the building stock, MIs applying the building stock comprised by non-residential buildings and distributed by commercial, industrial and public, would have to be derived.

(Ortlepp, Gruhler, and Schiller 2016), have proposed a new method to produce an MIC database for non-residential buildings in Germany including 252 building samples separated by construction period (7 time periods between 1975 and 2010) and building type (institutional, office, agricultural etc.). (Kleemann, Lederer, Rechberger, et al. 2016) in another similar study developed a MIC database used to estimate the material stock of buildings in Vienna, Austria. This database included data on 66 sample buildings collected from on-site material analysis, construction files and lifecycle inventories and grouped into 15 building categories, classified by 3 building types (residential, commercial, and industrial) and 5 construction periods (from before 1918 until 1997). Finally, in a study conducted by (Österbring et al. 2017), a MIC database of residential buildings in Sweden was created and the database was based on specialized architectural data including descriptive texts, cross-sections and architectural plans of 12 typical single-family and 34 multi-family buildings, constructed in Sweden during the time period 1880 – 2010 (Österbring et al. 2017).

For this project, the MIs derived for Apartment Blocks from the Odense case study have been applied to all non-residential buildings however, including commercial, industrial and public buildings respectively.

4.2 Quantification of the building stock

Later on, the MI retrieved will be combined with a mere top down approach, based on statistics on different kind of buildings build during different cohorts. This activity will take its offset in data from the Danish Statistics more specifically, the dataset BYGB34: AREAS OF THE BUILDING STOCK BY REGION; USE, AREA TYPE AND YEAR OF CONSTRUCTION. The regions are delimited by the administrative regions of Denmark (5), as well as by the individual municipalities (98). The year of construction is assigned to periods before 1900 and then subsequent years delimited by intervals of four years and the use types are assigned to single family houses, terraced houses, apartment blocks etc. This step was performed in order to give a more thorough view of materials locked up in the existing building stock on a larger scale at a regional level.

In addition the dataset also distinguish between different area types including Floorspace above basement, Floorspace in basement, Industrial/Commercial and Dwelling. Upon the correspondence with Paul Lubson, the one responsible for this data set, it was clarified how the total building stock can be derived by summing up Floorspace above basement and Floorspace below basement and therefore therefore these area types was used for this project.

In the end these datasets will be used to make predictions of future waste flows. These flows should consider different types of materials or components (quality) but also the amount of materials associated with these flows (quantities). Finally, the estimations on quality and quantity of materials contained in the existing building stock as well as predictions on when and where these materials become available, can be generated.

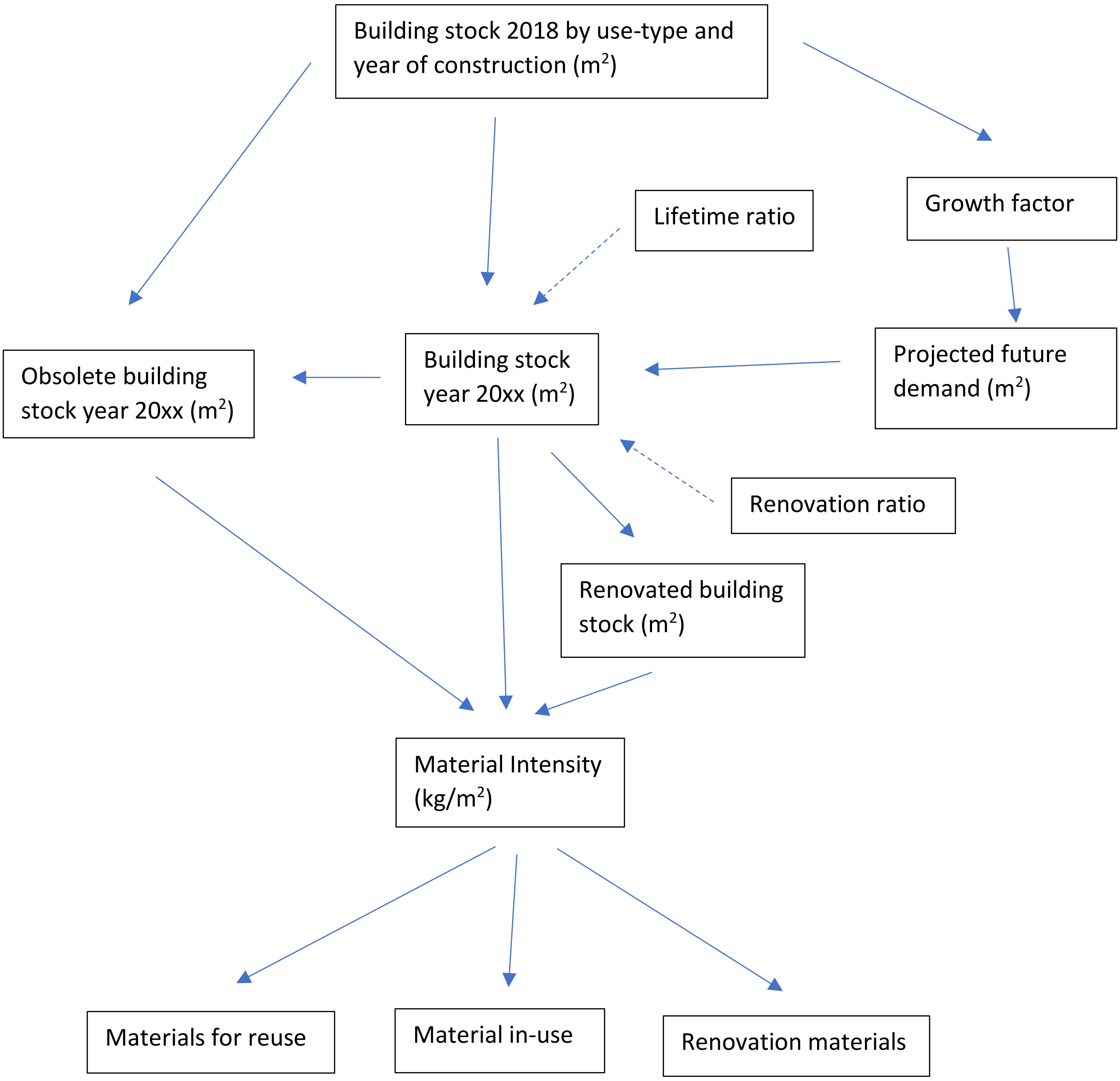


Figure 10 Dynamic building stock model.

4.3 Characteristics of the building stock

On a national level, the total number of buildings in Denmark increased by 42.500 buildings or 1 % from 2018 – 2019 while the building area increased by 4,9 million m^2 or 0,6 %. Year-round residences constitute the largest share of buildings in terms area, accounting for 46,9 % of the total floor area and the area increased by 30 % from 1986 – 2019. Farm buildings also constitute a significant share, accounting for 16,5 % but this area only increased by approximately 10 % since 1986. Floor areas holding offices, trade and administration only accounts for 11 % approximately but the floor area has increased by more than 100 % since 1986. The categories institutions and cultural buildings and factories and workshops account for 5,5 % of the floor area each but while the first category experienced an increase of almost 35 % during the period the second category only increased by 7,5 %.

Taking a look on the longer term of employment in Denmark in a retro perspective manner, unveils how the number of people employed in the sector of “general government” and “public administration education and health” has increased significantly during the last 32 years. The number of employees in the industrial sectors of “trade and transport” and “other business service” are on a relatively high level and have been increasing in the last 32 years as well. Other industry sectors have experienced different development, however. Earlier on, a significant number of people were employed in manufacturing, but the number have decreased considerably throughout the last 32 years. The number of people in the agricultural, fishing and forestry sector has decreased as well but the number of people employed in this sector is on a considerably lower level, though. Throughout the whole period, the number of people employed within construction remained on a relatively stable level. This trend is also reflected in the development of new enterprises. During 2015, 29.911 new enterprises were created among which 44 % happened within the sectors Business service and Trade and transport while only 5 % emerged within the sectors Manufacturing, mining and quarrying and public utilities. From 2000 – 2017, employment in the manufacturing sector was reduced by 27 % and in the same period, employment in agriculture, fisheries and forestry has fallen by 25 %.

On a regional level, evaluation of the current building stock, reveals significant differences between the Zealand Region and the Capital Region, respectively. Whereas the Capital Region are dominated by residential houses, comprising around 70 % of the total building stock the split between residential and non-residential buildings are more equal considering the region of Zealand. Also within the category residential buildings, essential differences are evident. In the Capital region, multi-dwelling houses constitutes almost half of the residential building stock, whereas detached house only accounts for one third, approximately. Moving to the region of Zealand, a larger share of the residential building stock is composed of detached houses, accounting for twice as much compared to multi-dwelling houses and terraced houses, together. In addition, farmhouses also account for a significant share amounting to 9 % compared to 2 % in the capital region. The nonresidential sector of the capital region is dominated by trade and public administration comprising over half of the building stock and education and research also accounts for a significant share. Regarding the non-residential building stock in the region of Zealand, farm buildings comprise almost half of this building stock and factories and work-shops also constitutes a significant share. Buildings assigned to offices, trade and public administration only represents around 18 % while buildings for education and research make up approximately half the of the share compared to the Capital region.

The building stock are distinguished by six different types for this project. The residential building stock covers single-family houses (SFH), multi-family houses and apartment blocks while the non-residential stock encounters industrial, public and commercial buildings, respectively. According to the BBR and the statbank data, the categories include the following building codes:

SFH:

- Farmhouses (110)
- Detached houses (120)
- Weekend cottages (510)
- Unspecified holiday purposes (520)
- Allotment garden houses (540)
- Garages with room for one or two vehicles (910)
- Carports (920)
- Outhouses (930)

MFH:

- Terraced, linked or semidetached houses (130)

AB:

- Multi-dwelling houses (140)
- Student hostels (150)
- Residential buildings for communities (160)
- Other residential buildings (190)

Industrial:

- Non-residential farm buildings (210)
- Factories, workshops, etc. (220)
- Power stations, gaswork, etc. (230)
- Other building used for production (290)

Public:

- Transportation or garage (310)
- Office, trade, inventory, incl. public administration (320)
- Unspecified transport and trade (320)
- Library, church, museum etc. (410)
- Buildings for education and research (schools, laboratory etc.) (420)
- Building for hospital, home, maternity home etc. (430)
- Daycare institutions (440)
- Non-specified welfare institutions (490)
- Sport centres, club houses (530)

Commercial:

- Hotel, restaurant, hairdresser and other services (330)
- Unspecified recreational purposes (590)

4.4 Drivers for future building stock demand

In order to estimate the future demand for floor space it is necessary to evaluate which purpose the different building types fulfil as well as the expectations to be meet by available floor space, in other words the drivers behind the development of the stock. The total stock per use type is calculated by summing up all the m^2 within each use type in the starting year. The future scenarios are affecting the size of the total stock per use type and based on the total stock in the starting year, the building stock will be multiplied with a specific factor indicating the expected development. The outcome is thus the demand in the following year which must be satisfied. By deducting the future stock from the sum of the left-over stock, both from the same year, the difference equals the demand of new floor space needed that year.

4.4.1 Residential buildings

Regarding residential buildings, future demand for construction is based on projections for population development and here the statbank dataset, FRKM118: POPULATION PROJECTIONS 2018 BY MUNICIPALITY, SEX AND AGE will be used. The regions are delimited by the administrative regions of Denmark, age classes by each individual age and above 100 years and the projection run towards 2045 for men and women respectively. As it appears from figure X, the population increases in general within the capital region, although remarkably differences exist among different age classes. The number of inhabitants is already significantly higher in this region as compared to the region of Zealand while this picture is going to be even more pronounced in the future. The general trend is also increasing for the region of Zealand, but again large differences exists in the different age classes with declining trends more abundant. Another remarkable difference is the smaller share of younger people and larger share of elderly people as compared to the capital region. These observations support the trend of urbanization where people are moving from the countryside towards urban areas.

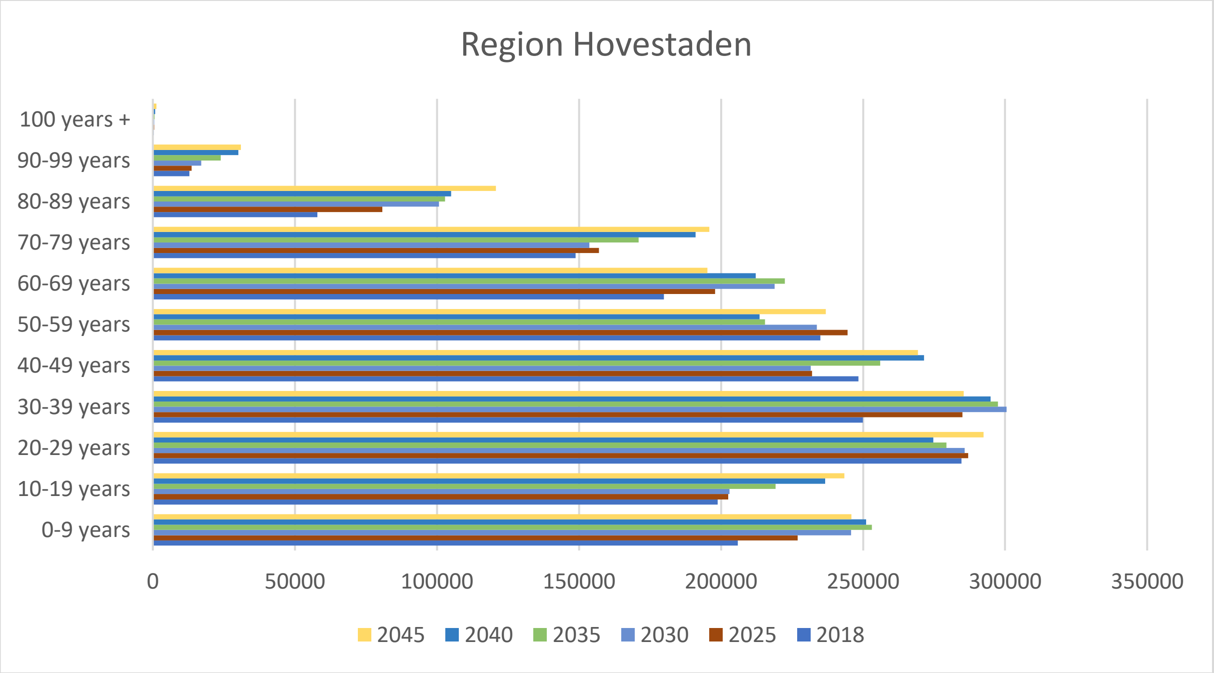


Figure 11 Population projections, Capital Region

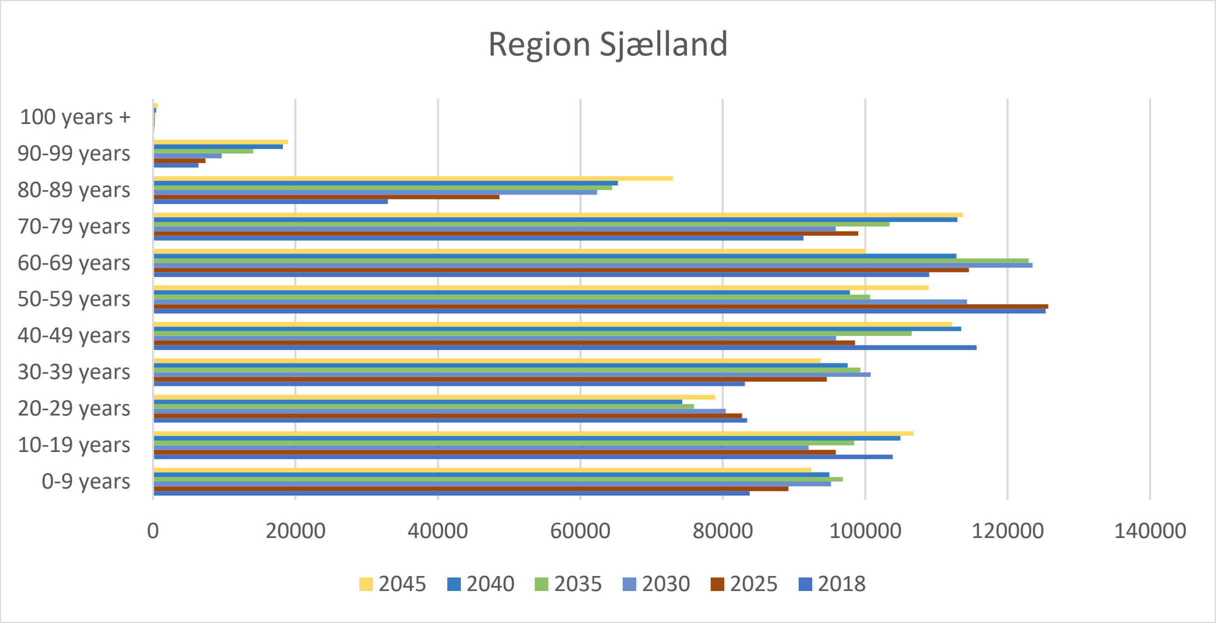


Figure 12 Population projections, Region of Zealand

As a factor for change the ratio between 2018 and 2045, evenly distributed over all 27 years has been chosen:

$$population\ growth\ ratio = f(PGR) = \sqrt[27]{\frac{Population\ 2045}{Population\ 2018}}$$

Population 2045 = population projected by 2045

Population 2018 = population by 2018

This dataset will be combined with another dataset BOL106: DWELLINGS WITH REGISTERED POPULATION (AVERAGE) BY AREA, UNIT AND USE. From this dataset, the average dwelling area per person appears, delimited by the administrative regions and covering the years from 2010 – 2018 specified by different use types. Thereby a trend for average dwelling area per person can be derived and combined with the former dataset future demands for residential floor space can be estimated. The stock driven model, applied in this case thus considers the building stock as a service unit driven by the population and its lifestyle, a distinctive characteristic of stock driven MFA models.

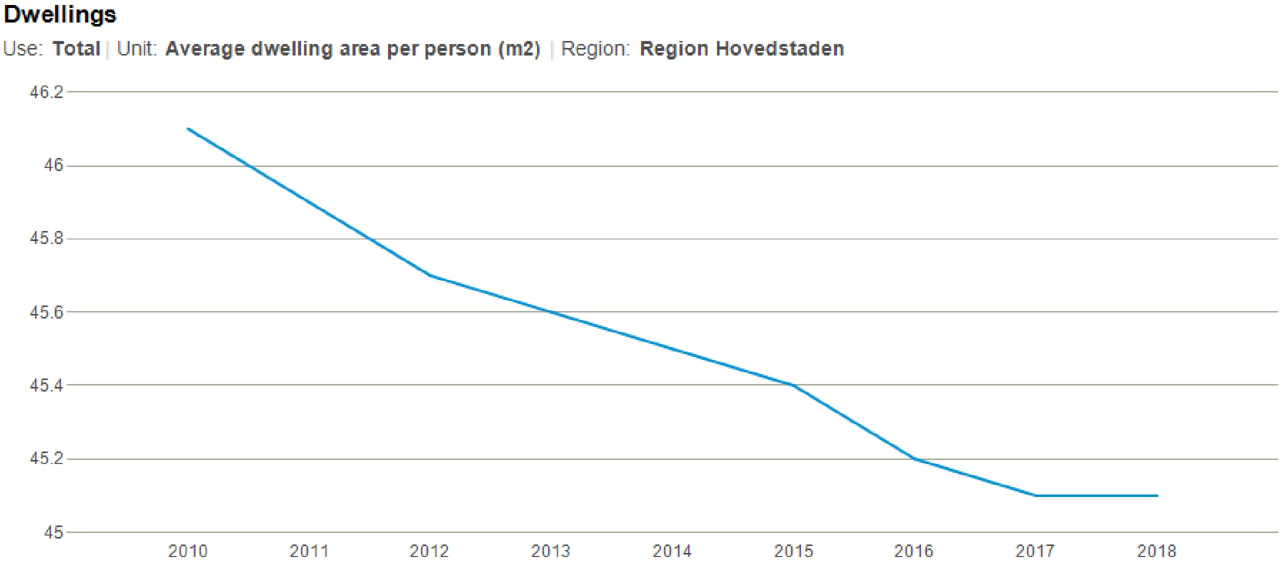


Figure 13 Floorspace per capita, Capital region

As visible from **Figure 13**, the average floor space per person within the Capital Region has been shrinking slightly during previous years. Within more densely populated areas of the region, the trend is even more pronounced. The average floor space in the municipality of Copenhagen experience the lowest level and the average floor space decreased from above 42 m^2 per person in 2010 to around 40 m^2 per person in 2018. Also other municipalities around Copenhagen confirms this trend with the municipalities of Gladsaxe, Hvidovre, Albertslund and Rødovre also having less than 42 m^2/person.

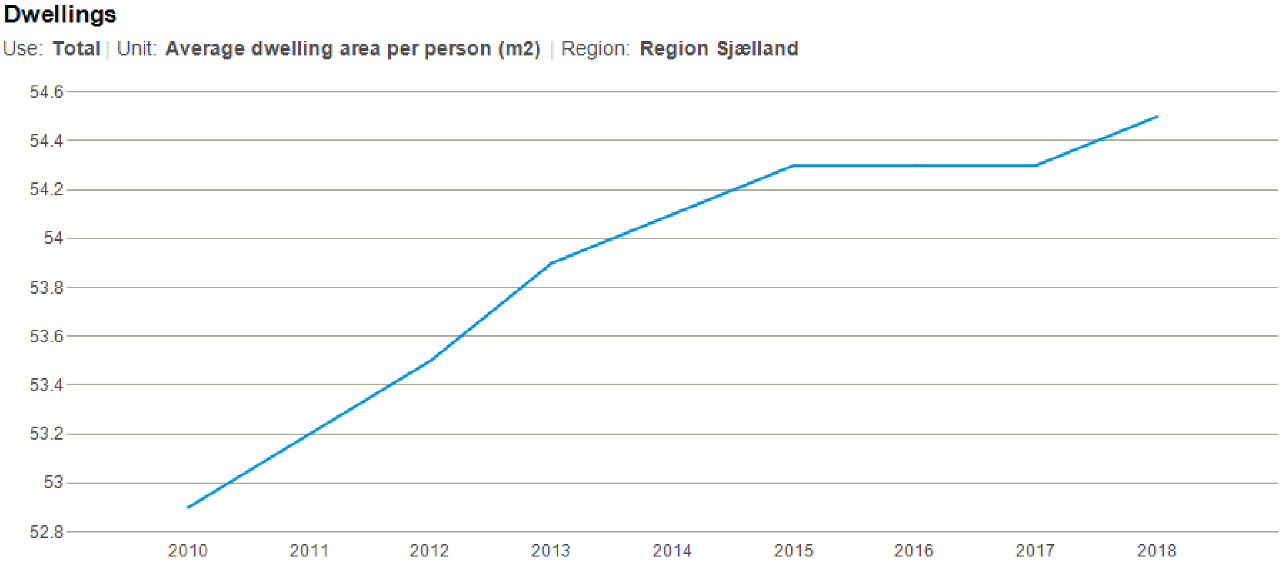


Figure 14 Floor space per capita, Region of Zealand

Moving further away from the urban area of Copenhagen, the picture changes a bit, and as it appears from **Figure 14**, the housing area of Region Zealand have experienced the opposite trend where the average m^2/person has increased by almost 2 m^2 in recent years. In general, inhabitants in this area have almost 10 m^2 more available floor space compared to the inhabitants of the Capital region.

These observations will also be considered when developing the model based on the formula below concerning m^2/cap:

$$development\ of\ \left(\frac{m^2}{cap}\right) = f\left(\frac{m^2}{cap}\right) = \sqrt[27]{\frac{(m^2/cap)2045}{(m^2/cap)2018}}$$

Based on these two factors, a total growth factor can be derived, which will then be used to predict the future building stock growth per year:

$$f(GfR) = \sqrt[27]{\frac{Population\ 2045}{Population\ 2018}} * f\left(\frac{m^2}{cap}\right)$$

Regarding the calculations for the population growth the calculations result in factors of 1,00418 and 1.00219 for the Capital region and the region of Zealand, respectively and the numbers for average floorspace, 0,997262 and 1,00373 correspondingly. In the end, the growth factors add up to 1,00143 for the Capital region and 1,00593 for the Zealand region.

4.4.2 Non-residential buildings

While the evolution in residential houses are likely to be driven by population development, other factors are at play regarding the commercial, industrial and public building stocks.

Apparent from the appendix several infrastructural projects are planned during the forthcoming decade and especially within the capital region, large projects are expected be commenced. That applies to the health care sector among others, where large projects are in the pipeline. The investments in the health care sector happens in line with the projections for the age structure development, predicting an increasing share of elderly people with higher frequencies of hospital visits. The increasing share of elderly people among the population would thus increase the demand for capacity at the hospitals. Also the share of the age-groups of younger people are expected to increase in future and this development might drive the expansion of the building stock related to education and research already comprising a significant share of the current building stock. This is probably also related to the fact that Denmark focus extensively on research and development, only surpassed by Sweden, Germany and Austria regarding the share of GDP spend within this sector.

The growth factor for the public sector are based on the development of the population within the age cohorts over 65 and below 25 as the development of this building stock are assumed to be driven by the demand for elderly homes, hospitals, schools and other educational institutions.

$$PGR = \sqrt[27]{\frac{Pop\ (\ 65 < +\ 20 >)\ 2045}{Pop\ (\ 65 < +\ 20 >)\ 2019}}$$

Where:

PGR = Public building stock growth factor

$Pop\ (\ 65 < +\ 20 >)\ 2045$ = Population over 65 and under 25 in the year 2045

$Pop\ (\ 65 < +\ 20 >)\ 2019$ = Population over 65 and under 25 in the year 2019

The results point towards increases in both regions with growth factors of 1,0092 and 1,00752 for the Capital region and the region of Zealand respectively.

The growth rate for the commercial building stock will be based on numbers from the table NABB10/LBESK31 from statbank. The number of people employed within the sectors "Trade and transport", "Information and communication", "Financial and insurance", "Real estate activities" and "Other business service" will be applied as the driver of stock development within this sector.

$$CGR = \sqrt[10]{\frac{Employes\ Q1\ 2018}{Employes\ Q1\ 2008}}$$

CGR = Commercial building stock development

Employes 2008 Q1 = number of employes in quarter one by 2008

Employes 2018 Q1 = number of employes in quarter one by 2018

The growth factor for the capital region amounts to 1,00981, while the corresponding number for the region of Zeeland is 0,9948.

Regarding the industrial building stock, the floorspace taken up by this sector are not expected to increase in future in the modelling for this project. On a national level, the floor space of this sector only increased by 7,5 % from 1986 – 2018, with decreasing trends in recent years and in the same period, the number people employed in manufacturing and agriculture have decreased significantly. Due to these considerations, the growth factor for the industrial building stock are will assumed be one or stated differently the floorspace demanded by this sector will stay at the level of 2018. Calculating growth factors by the same method applied to the commercial sector confirms this as the numbers adds up to 0,992719 and 0,975482 for the Capital region and the Zealand region, respectively, predicting steady or slightly decreasing trends.

4.5 Dynamic Building stock modelling

Based on historical trends, predictions of future developments will be attempted in order to evaluate future flows of construction and demolition waste. For this purpose, a building stock model will be developed. To find the percentage of the initial building stock still being in use in the future a ratio of the observed year in the future against the initial stock is build. This ratio is then multiplied with the initial building stock to obtain the m^2 of building stock in the year of observation.

$$S_n = R_{Lt} * S_i$$

S_n = Remaining building stock in year n [m^2]

S_i = Initial building stock [m^2]

R_{LT} = Lifetime Ratio, percentage of building stock still in-use [%]

To obtain the stock changes over the years which represents the obsolete building stock, a Probability Density Function (PDF) of the normal distribution as the lifetime profile will be applied:

$$\frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{[(x_2-x_1)-y]^2}{2\sigma^2}}$$

x_1 = year of the time cohort we want to evaluate

x_2 = year in the future to which the time cohort is evaluated against

y = Mean of the distribution

σ = Standard deviation of the mean

σ^2 = variance

The complementary of its Cumulative Distribution function (1-CDF) gives the lifetime profile (L), which is the probability of a dwelling built in one year to be still in use in the future years. The share of the building stock still being in use in future can then be calculated:

$$f(x_1, x_2, y, \sigma) = 1 - CDF = 1 - \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{[(x_2-x_1)-y]^2}{2\sigma^2}}$$

f = Percentage of building stock left in the specific year

$$R_{LT} = \frac{f_1(x_1, x_2\,, y, \sigma)}{f_2(x_1, x_i\,, y, \sigma)} = \frac{1 - CDF}{1 - CDFi} = \frac{1 - (\frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{[(x_2-x_1)-y]^2}{2\sigma^2}})}{1 - (\frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{[(x_i-x_1)-y]^2}{2\sigma^2}})}$$

f1 = Percentage of building stock left in a specific year

f2 = Percentage of building stock left in the starting year (stock from 2018)

x_1 = year of the time cohort to be evaluated

x_2 = year in the future to which the time cohort is evaluated against

x_i = Initial year of observation

y = Mean of the distribution

σ = Standard deviation of the mean

R_{LT} = Lifetime Ratio, percentage of building stock still in-use [%]

In the end, the building stock becoming obsolete each year can be derived:

$$\Delta S_{obs} = f(S_1, S_2) = S_1 - S_2$$

S_1 = Stock in the previous year

S_2 = Stock in year of observation

ΔS_{obs} = Obsolete building stock per year [m^2]

For this project the lifetime of the buildings has been derived from the study by Bohne et al. investigating the service life of residential buildings and key building components in Norway, based on available statistics and standard methods for the estimation of lifetime distribution. As stated by the authors, the service lifetime distribution of buildings is expected to follow a sigmoid curve, first with a period of no demolition, then a period of increasing demolition activity before a long period of decreasing demolition activity. In their study they employ statistics on two complete counting's, in 1980 and 2001 respectively, of buildings erected in different time intervals. And assuming that the buildings are following a standard decay function, a constant decay factor, k, can be calculated for the various age spans. The reliability function R(t) for the residential buildings was calculated using the standard decay function, $N = N_0 * e^{k*t}$ but by changing the decay factor for the different time spans. In order to reduce the noise from the series of decay functions, the result was fitted into a sigmoid curve. This curve describes the probability for that a building still in use at time (t) and both the average lifetime and the standard deviation to this can be found from this semi empirical data. Based on the results from this study, an expected lifetime of 126 was found, but as stated by the authors the main outputs from the building stock is expected to arise from renovation and refurbishing in the near future and not from demolition.

To distinguish between the Capital Region and the region of Zealand another study have been evaluated. In the study by Østergaard et al. (Østergaard et al. 2018) the developed a lifespan quantification model based on a data set comprising 26320 observations of buildings in Denmark demolished between 2009 and 2015 collected by the Danish Building and Residence Register (BBR). A multiple linear regression model was used to derive quantitative lifespans models including five building characteristics as categorical variables. The categorical variables comprise region, refurbishment, use type, wall material and roof material. The building location may contain information on the regional characteristics while the building function is determined by the intended classification of use. Information relating to whether the building was refurbished or not may reflect the building condition and the materials applied for the building envelopes are considered as fundamental factors influencing the LS of buildings. The regions are defined as the Capital Region (RH) and the rest of Denmark/other regions (OR) and the use types distinguish residential, commercial, agricultural, recreational, institutional and other use. The mean LS of buildings in OR varies between 71 and 74 years compared to a 60 years LS mean for RH. According to the different use types, the lifespan varies from 44 years for institutional buildings to 103 years for agricultural buildings. It was also observed that wall material/cladding is the only independent variable related moderately to LS, followed by the fairly weak correlation with use type. A limitation of the model proposed here is that no information on the reason for demolishment is provided by BBR (Østergaard et al. 2018). Based on this study, different mean lifetime and standard deviation have been applied to the building stock of the Zealand Region and the Capital region respectively.

Taking the form of a dynamic MFA this analysis thus tries to assess the buildup of materials within the building stock through time based on historical trends to make projections into the future. Outputs of obsolete products in terms of demolition of buildings is calculated based on accumulation of former constructed buildings becoming obsolete in the respective year. Using the existing stock, the building stock constructed during different time periods still standing toady, as a predicter for future material flows, is termed a stock driven model within the terms of MFA. It is characterized by assuming the stock as the driver of material flows.

The future demand for building floor space would thus be covered partly by the building stock build in previous time-cohorts while the remaining part must be covered by new construction. The future demand for construction materials depends on the demand of building floor space disaggregated by the different use types. It can be expressed as the difference between the demanded floor space in year n and the remaining building stock of the specific type in year n. The starting point for the future scenarios will be the building stock by 2018 (BS_i) and the future demand will impact the size of the total building stock per archetype. The building stock per year (BS_n) and archetype is calculated by summing up the m^2 of all time cohorts in the chosen year. The current building stock will then be multiplied with the ratio still in use to obtain the building stock per time cohort and year in the future. To obtain the building stock demand (BS_{dem}) the initial building stock is multiplied with the stock growth factors per archetype and region. The outcome is then the projected building stock in year n (BSp_n) and the demand for additions to the building stock (BS_{dem}) can then be derived by subtracting the building stock per year (BS_n) and archetype from the projected building stock in year n (BSp_n). In the end a prospective building stock model should have been obtained.

$$BS_n = m^2_{until\ 1905} + m^2_{until\ 1910} + \ldots + m^2_{until\ 2019}$$

where:

BS_n = remaining building stock in year n [m^2]

$$BSp_n = BSi * (growth\ factor)^{(n_x - n_i)}$$

where:

BSp_n = projected building stock in year n [m^2]

BS_i = Initial building stock year 2019 [m^2]

n_x = year of observation

n_i = initial year

$$BS_{dem} = BSp_n - BS_n$$

where:

BS_{dem} = Building stock demand, amount of building m^2 required to fulfill the demand

BSp_n = Projected building stock in year n

BS_n = Remaining building stock in year n

To distinguish the different materials included in the building stock, the floorspace of the existing, obsolete and renovated building stock as well as the future demand will be multiplied, according to their time cohorts and archetypes per region with the respective material intensities. In the end, the materials per archetype are gathered to get the weight of the material per region.

$$MIA_n = BS_n * MI_n$$

where:

MI_n = Material intensity data per archetype and time cohort [kg/m^2]

BS_n = Building stock per archetype and time cohort [m^2]

MIA_n = Material per archetype and time cohort [kg]

n = time cohort

$$MA = \Sigma MIA_n$$

where:

MA = Material per archetype [kg]

MIA_n = Material per archetype and time cohort [kg]

4.5.1 Renovatoin waste

Renovations and refurbishments will be implemented through a fixed ratio which will be renovated per year of the left-over buildig stock. The renovatoin rate is assumed to be one % of the floor space above ground of building stock within each use types. The underground structures will be negleted for renovation, since they mainly concist of heavy concrete structures which will not be replaced in case of refurbishment. The renovation ratio is applied to the total building stock in use per year, archetype and time-cohort and the spuaremeters assigned to obselote material and material demand. The amount of waste generated equals the one % share of the stock, reflecting the different kind of materials and a demand of materials equal to the amonut removed by renovation is added to the stock accordingly.

$$RBS_n = BS_n * R_{ratio}$$

where:

RBS_n = renovated building stock in year n [m^2]

BS_n = Building stock (per archetype) in 2018 [m^2]

The gained results might in the end be helpful for authorities responsible for regional development in terms of waste management and resource supply, as well as for companies operating within this sector. Knowing the amount of waste expected to arise in the future and how the different influencing factors would affect the trend would help highlighting the areas most appropriate for intervention. Furthermore, it would assist the planning of future waste management plans and improving their quality as these could be designed based on the amount of C&DW expected to arise in the future in terms of quantity as well as quality of different materials. The different scenarios applied to the existing building stock will consider increasing/decreasing developments of the building stock and the lifetime respectively.

5. Results

Before digging into the future scenarios regarding the development of the building stock, the amount of C&DW generated in previous years in the area of Zealand will be evaluated focusing on the aggregate fraction. As it appears from **Figure 15**, the concrete waste generated in the capital region outcompete the number from the region of Zealand in terms of amounts. By 2016, the amount of concrete waste reached around 365.0000 tons, more than double the amounts generated in the region of Zealand (approximately 174.000 tons). Regarding the other fractions, the amounts generated within each region are more similar with considerable variations from year to year, however. Since 2010 the amount of concrete waste has been on an increasing trend in both regions.

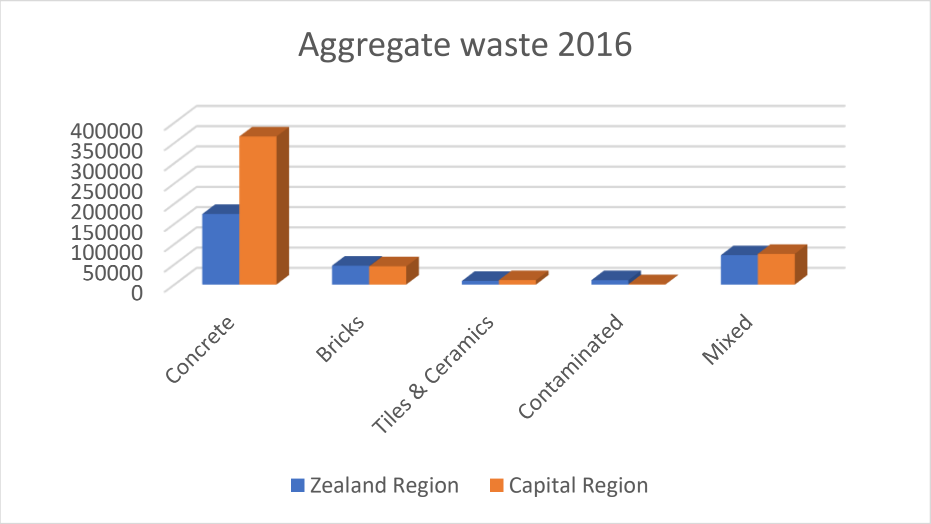


Figure 15 Aggregate waste in the Region of Zealand and the Capital region by 2016, respectively.

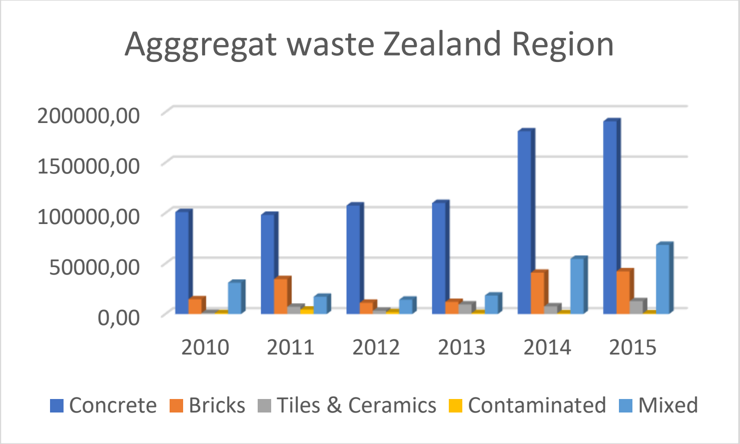


Figure 16 Aggregate waste in the region of Zealand, 2010 – 2015.

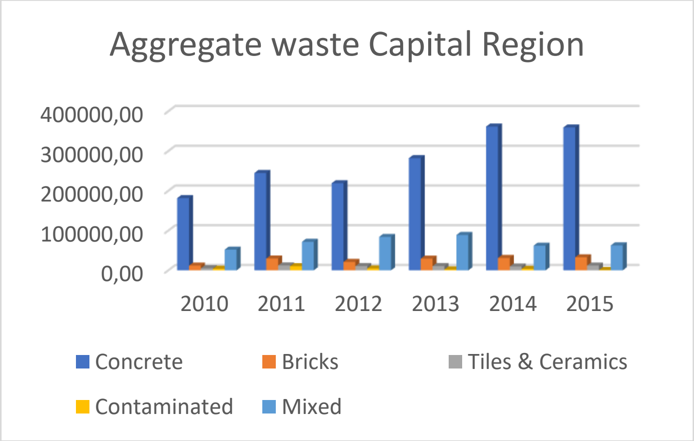


Figure 17 Aggregate waste in the Capital region, 2010 – 2015.

5.1 Capital Region

The development of the building stock in terms of total floor space, total obsolete floor space and demand for new floor space are depicted in **Figure 18**.

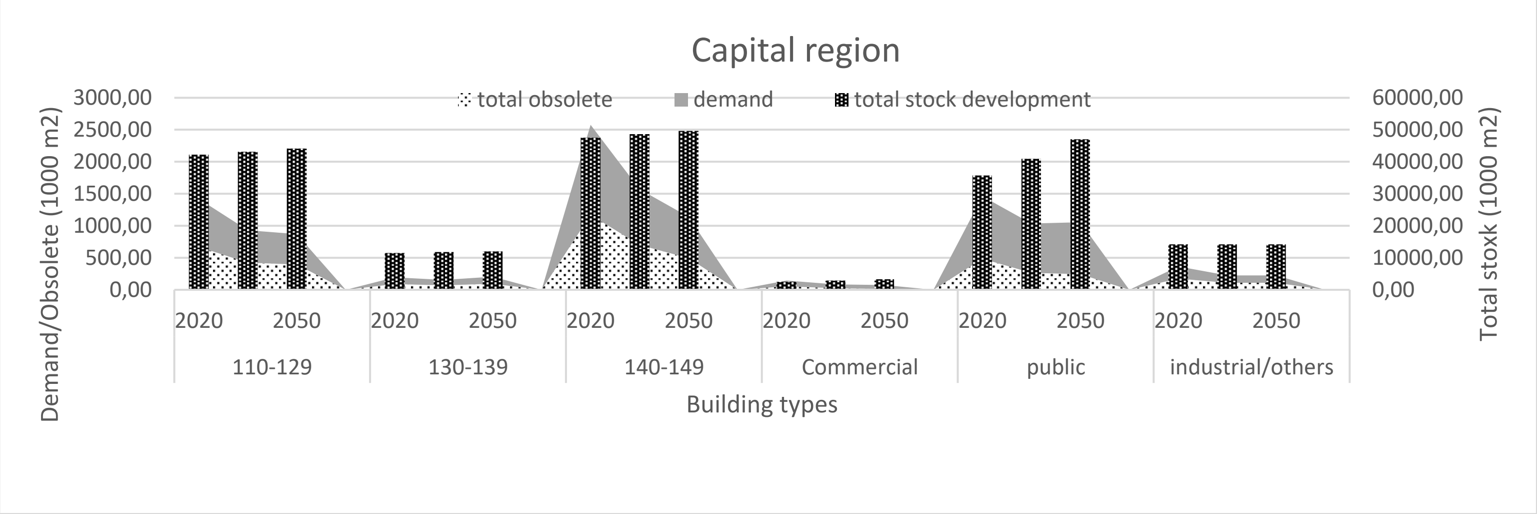


Figure 18 Building stock development in the Capital Region by 2020, 2035 and 2050 respectively.

As it appears, growth is expected within all sectors of the building stock with the exception of industrial floor space. The growth is most pronounced within the public sector increasing from 35,7 million m^2 in 2020 to almost 47 million m^2 by 2050. Other sectors, despite limited increases in the gross floor area, still require significant inflow of materials to maintain the existing stock most visible for the large sectors as apartment building blocks and singe family houses. A considerable share of this demand might potentially be covered by the outflow of obsolete stock.

While the amount of concrete becoming obsolete are expected to increase slightly towards 2050, the fraction of obsolete brick is expected to decrease significantly. The share of obsolete tiles remains relatively low throughout the period.

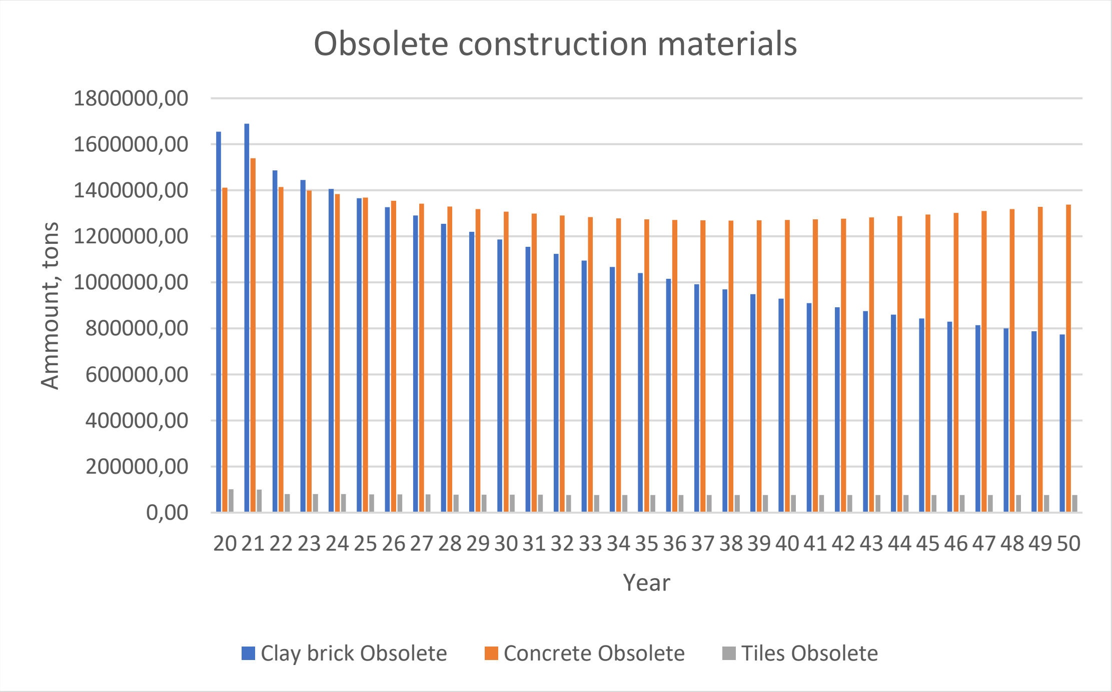


Figure 19 Obsolete Clay Brick, Concrete and Tiles in the Capital Region towards 2050 by columns.

Visualized in **Figure 19** the outflow of concrete is apparently unable to fully cover the amount required by demanded floor space. By 2020, the demanded floorspace requires apparently over double the amount released by demolition, but the gap between obsolete and demanded concrete appears to lessen during time.

Having a look at the fraction of bricks, the picture is the opposite as it appears from **Figure 20**. For this case, the amount of obsolete material seems to cover more than double the amount of additional material demanded by 2020. Even though the gap between demanded and obsolete bricks diminish by time, the outflow of obsolete amounts exceeds the demand until 2050.

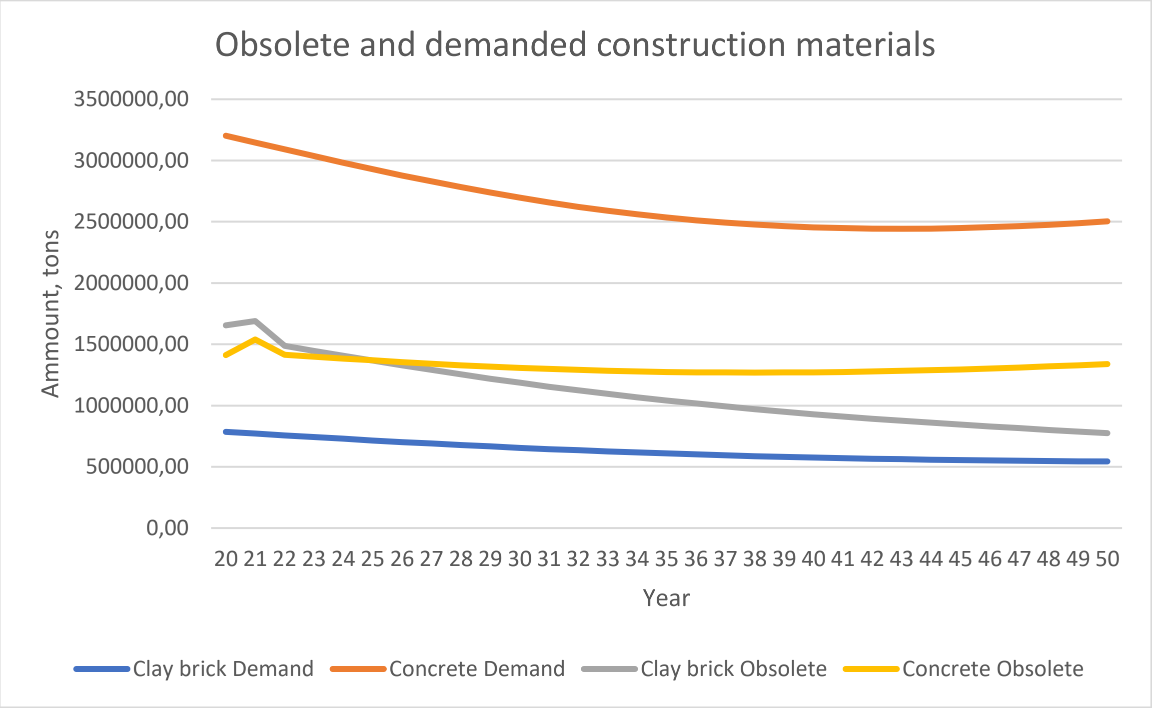


Figure 20 Obsolete and demanded Clay Brick, Concrete and Tiles in the Capital Region towards 2050 by lines.

Regarding characteristics of C&DW and focusing on aggregate waste, a prominent change in the composition appears when comparing the years 2020 and 2050. Apparently, the fraction comprised by bricks are going to diminish in favor of a larger fraction of concrete arising towards 2050 see figure **Figure 21** and **Figure 22**.

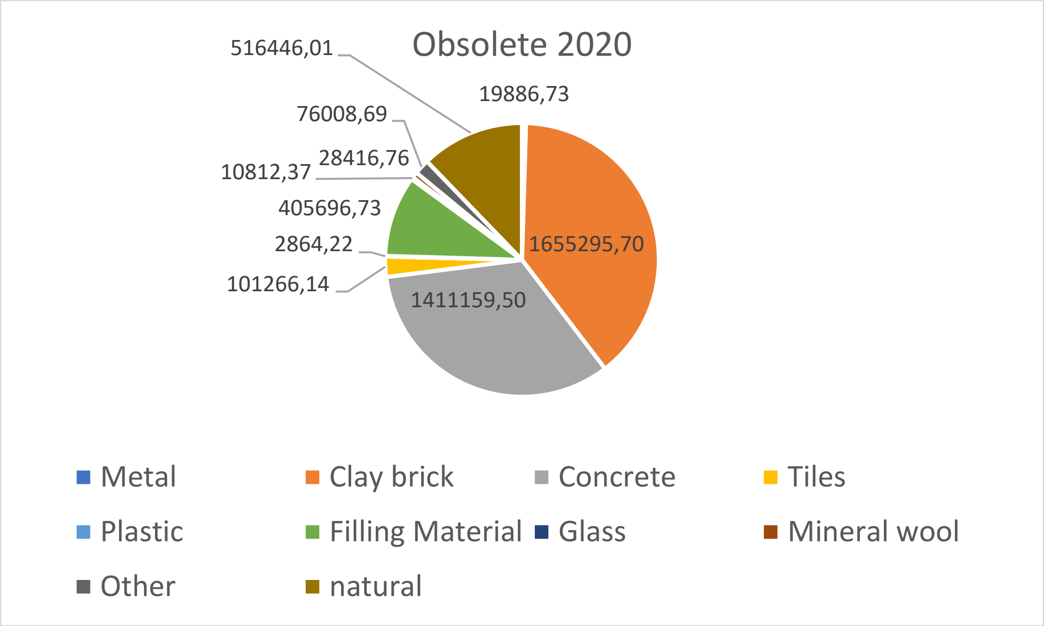


Figure 21 Characteristics of C&DW by 2020 in the Capital Region.

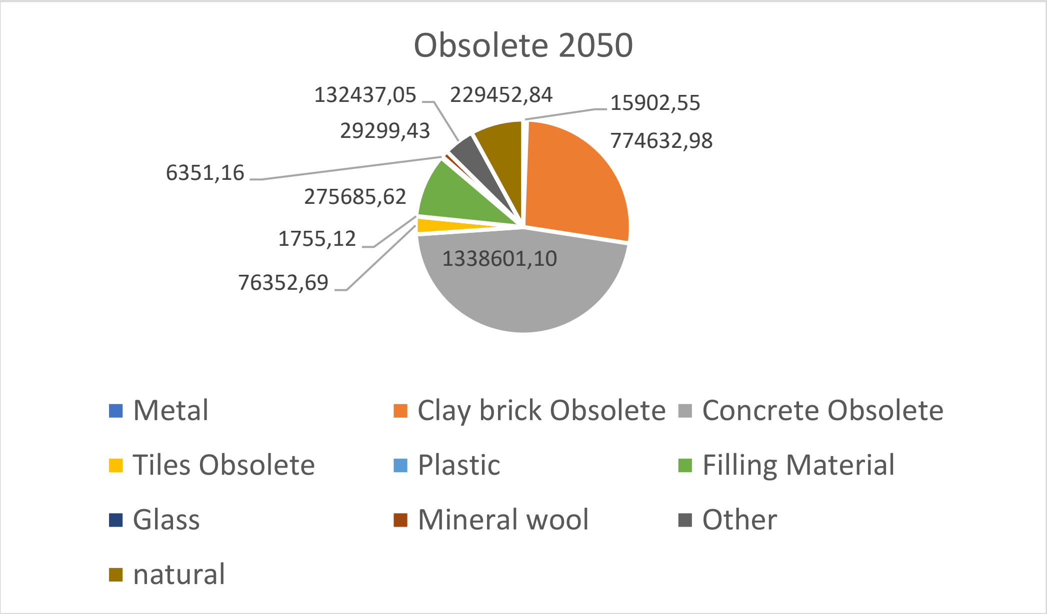


Figure 22 Characteristics of C&DW by 2050 in the Region of Zealand.

The share of C&DW originating from demolition activities and renovation activities respectively will change significantly until 2050 according to the model. Whereas in 2020 the amount of waste coming from demolition was more than twice the amount related to renovation activities. By 2035 the difference would only be one third more waste coming from demolition compared to renovation and by 2050, the shares would be almost equal.

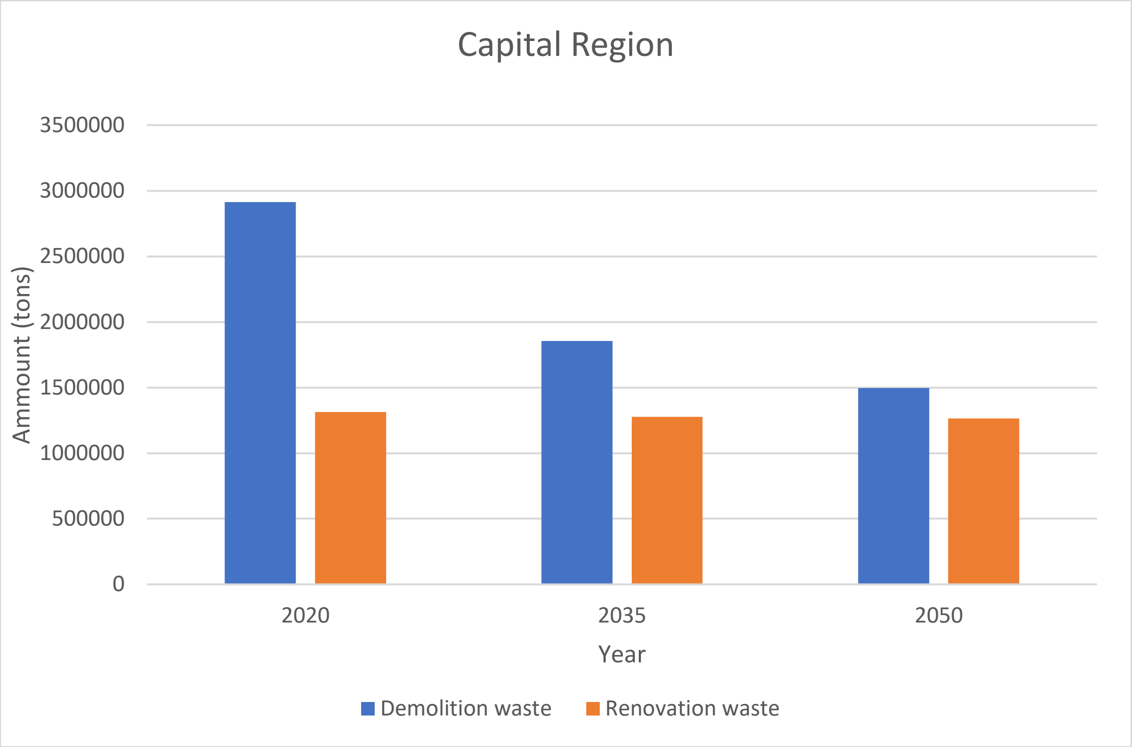


Figure 23 Demolition waste vs. Renovation waste

5.2 The region of Zealand

In the Region of Zealand, the most pronounced increase happens within the building stock of single-family houses growing from 52,56 million m^2 by 2020 towards 62,77 million m^2 by 2050. The growth in the public building stock is also significant with an increase from around 15 million m^2 by 2020 towards 18,7 million m^2 by 2050. Also applying to this region, the demand for new floor space, exceeds the area of floor space becoming obsolete, see **Figure 24**.

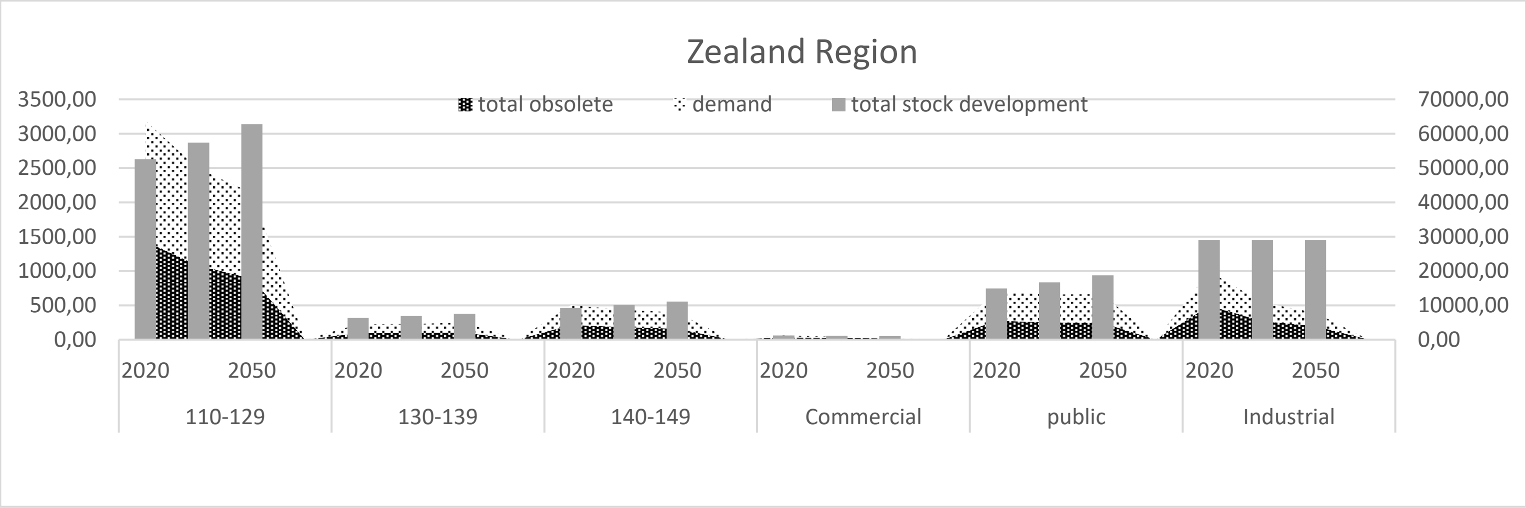


Figure 24 Building stock development in the region of Zealand by 2020, 2035 and 2050 respectively.

The amount of concrete becoming obsolete steadily increases by time towards 2050, while the fraction of brick waste are expected to decline evenly. Also in this region the share of tiles play a minor role, see **Figure 25**.

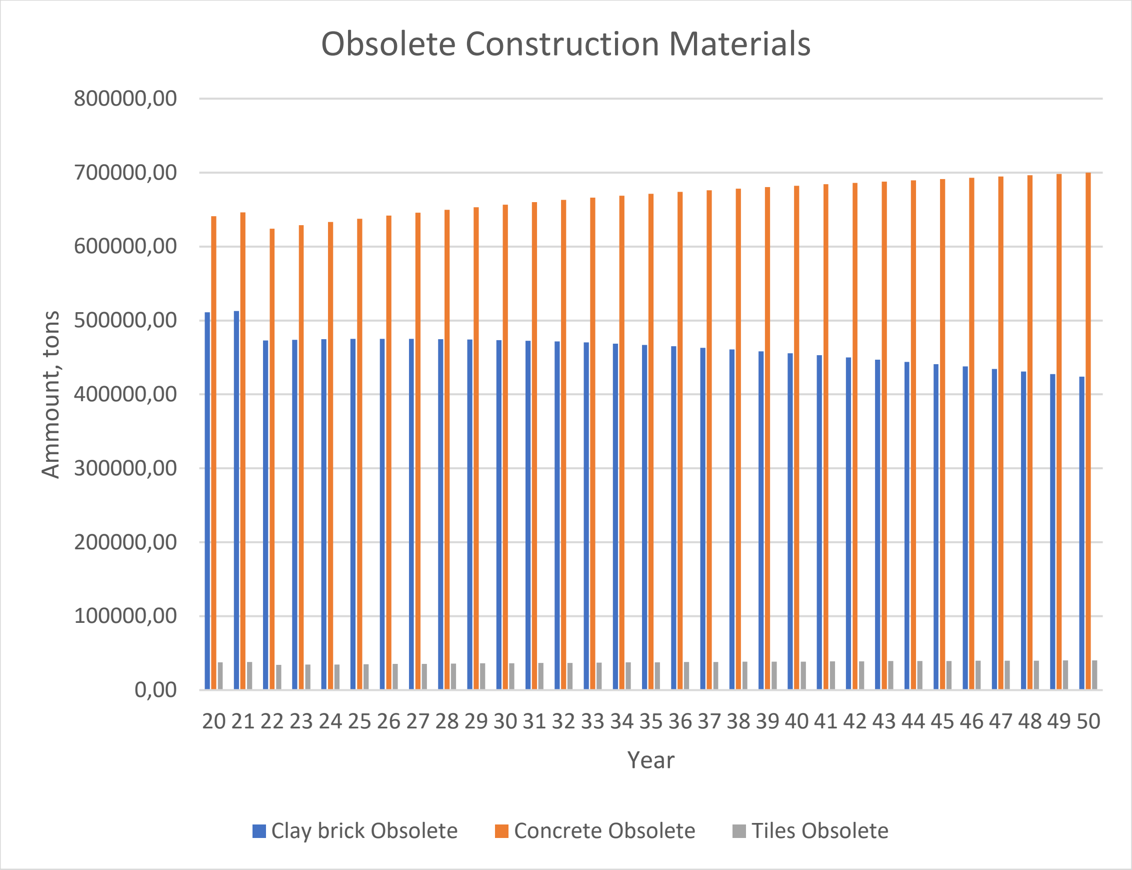


Figure 25 Obsolete Clay Brick, Concrete and Tiles in the Region of Zealand towards 2050 by columns.

In the region of Zealand, the need for concrete required to satisfy the demand for floorspace are higher than the amount coming from obsolete stocks even though the span is more narrow compared to the Capital Region. Like the Capital Region, the gap diminishes through time. Regarding the fraction of bricks, the amount arising from demolition and renovation exceeds the amount demanded until 2050, both decreasing slightly by time, however. See **Figure 26**.

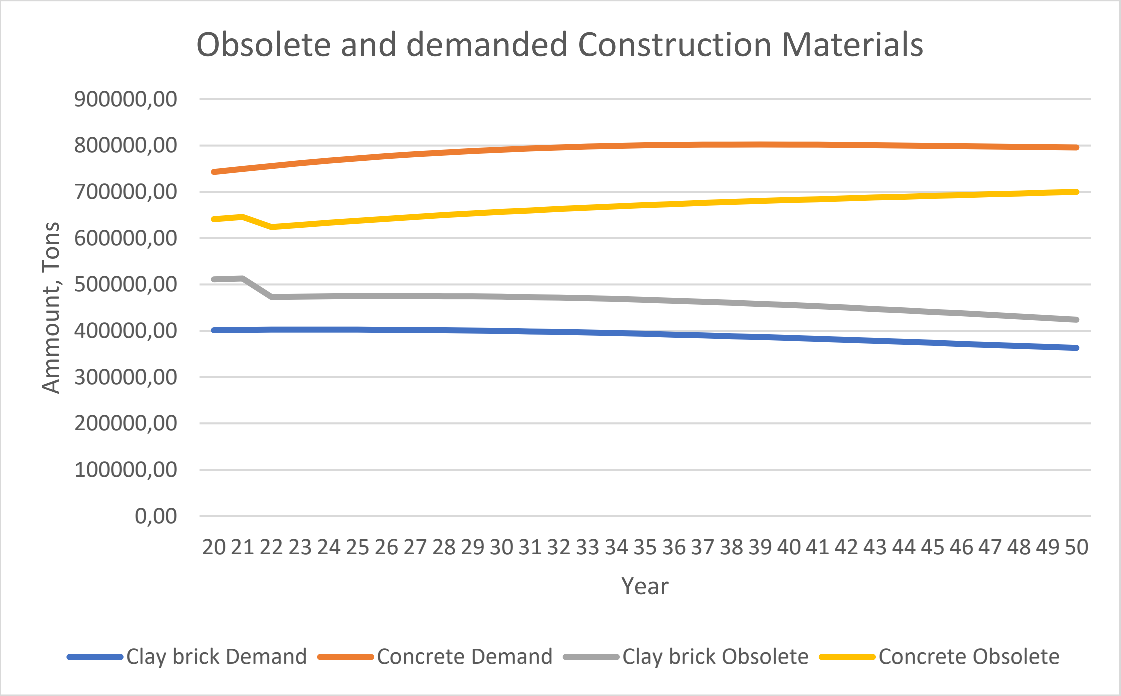


Figure 26 Obsolete and demanded Clay Brick, Concrete and Tiles in the Region of Zealand towards 2050 by lines.

Having a look at the composition of C&DW, the same pattern appears for the region of Zealand in terms of an increasing share of concrete waste at the expense of a decreasing share of brick waste, see the **Figure 27** and **Figure 28**.

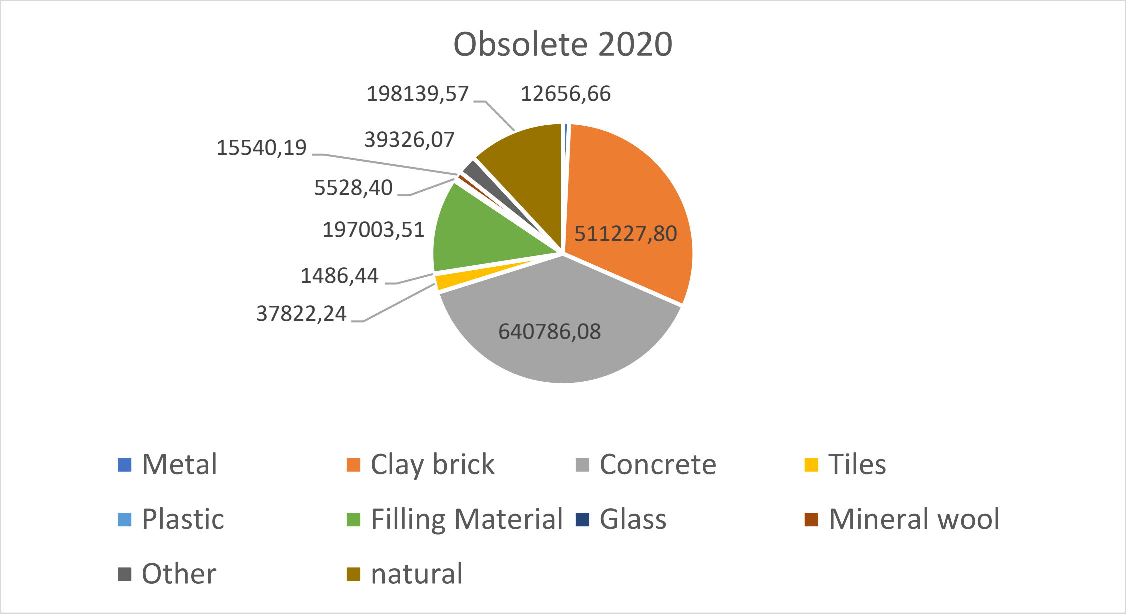


Figure 27 Characteristics of C&DW by 2020 in the region of Zealand.

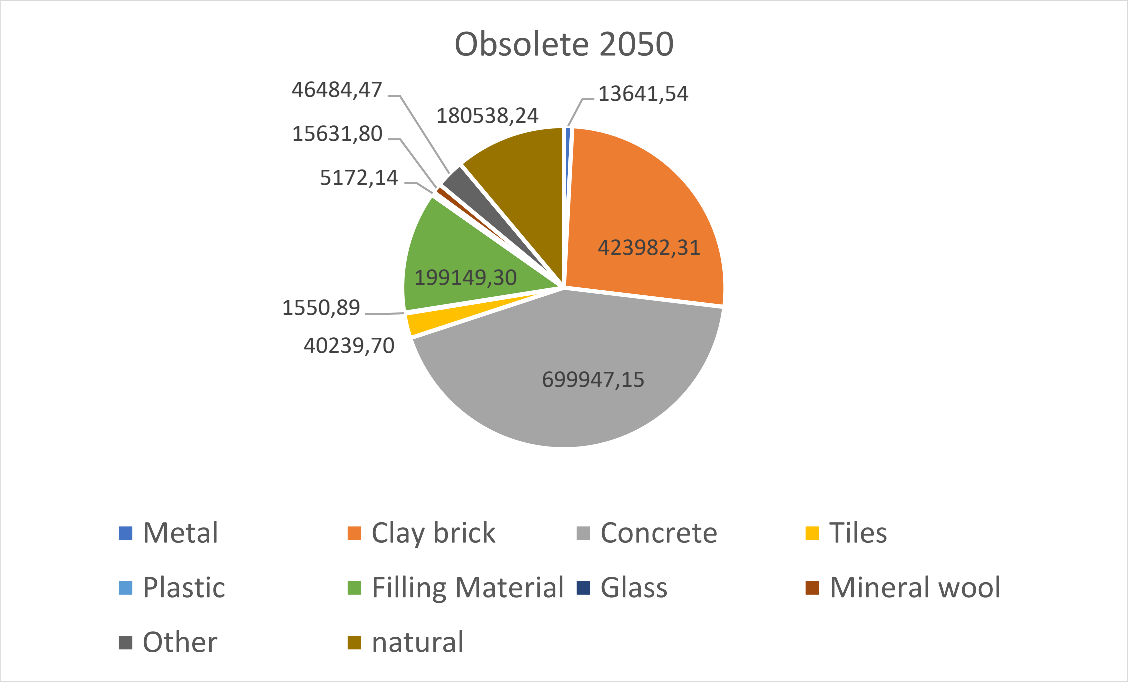


Figure 28 Characteristics of C&DW by 2050 in the region of Zealand.

Finally, the split between waste coming from demolition and renovation respectively shows the same trend for the region of Zealand as compared to the Capital region. In general the amount of C&DW decreases towards 2050 and simultaneously the share associated with renovation activities increases, see **Figure 29**.

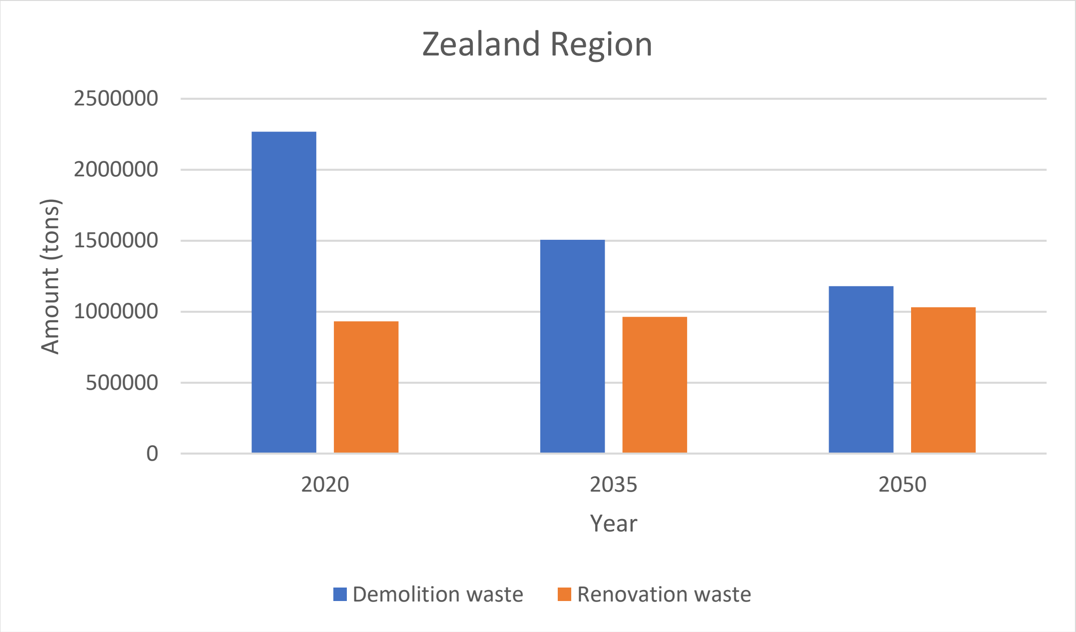


Figure 29 Demolition waste vs. renovation waste.

6. Discussion

6.1 Building stock modeling and lifetime

The main components of all building stock models are the delimitation, the composition and the dynamics of the stock. The existence of a spatial limit influences the growth and demolition when phenomena of saturation appear and when the analyzed stock becomes part of a larger region with a specific dynamic behavior. The stock dynamic is characterized by the construction, renovation and demolition rate respectively. Lifespan assumptions, if based on the present demolition rate, the lifespan is assumed to be inversely proportional to the demolition rate. For a yearly demolition rate of 0,5 % of the stock, the lifespan would reach 200 years and estimations give thus generally very high values. Another method is to base the estimations on average lifespan assumption where an average lifespan is selected and completed by a statistical distribution, typical normal or weibull, of the demolitions. In Europe, underestimations are often made of the real lifespan, which might exceed 100 years. The analytical demolition models developed in mass flow and energy analysis are well adapted and transparent, but their predictive quality relies heavily on the assumed average lifespan and decision between refurbishment and demolition. The necessity to demolish buildings because they cannot be adapted to present user needs or cannot be reasonably energetically improved is heavily biased by the opinions and interest of the planners and the construction industry (Aksözen *et al.* 2017).

No systematic or empirical information regarding buildings or building parts functional average lifespan is available and thus has to be based on a rough estimate including:

- The development of the building stock over time as ageing of existing buildings
- Developments in society including demographic developments
- Demolition rates for existing buildings
- Changes applying to the building stock as demand for energy retrofitting

As of 2012 the average age of the total building stock in Denmark was approximately 56 yrs. Within the period 1994 – 2012 according to numbers from Danish Statistics, 7,9 mill m^2 has been added to the stock each year reaching an amount of 150 mill in total. Within the same period, the building stock increased by 120 mill m^2 indicating demolition of a certain share of building stock existing in 1994, corresponding to a yearly demolition rate of 0,3 %. If all new buildings by 2012 replaced existing buildings, it would correspond to a demolition rate of 0,8 % and a demolition rate larger than this would hardly be realistic in practice.

For this project a simple lifetime with a normal distribution is applied to the existing building stock. The lifetime distribution is applied to the building stock irrespective of the different use types and are based on numbers from literature. This is however a simplification worth mentioning as an array of different factors are at play determining obsolescence of buildings.

Obsolescence of building stocks, defined for domestic as well as for non-domestic, can be approached from different perspectives and can have a wide range of causes comprising categories like physical, economic, financial, functional, location, environmental, political, market, style and control obsolescence. Considering the huge diversities in occurrence of obsolescence between and within buildings and building types, age alone is not a decisive clarification. The subject can be ordered by distinguishing the major characteristics as the nature of causes and effects, different levels of scale, building category and building type and the kind of tenure and control. The most acknowledged and widely applied causal distinction is between physical factors related to material processes and behavioral factors related to human actions as well as the interactions between them. Regarding the scale, obsolescence can appear separately or combined at the level of building materials, parts and elements, building construction systems, separate buildings, blocks, quarters and neighborhoods. Within the building category there are essential differences between residential and non-residential buildings. Apart from differences in purpose, use, funding, management and legislation, housing is a rather stable function with a longer life cycle expectancy whereas non-residential buildings often have a shorter cycle of usage and adaption and consequently different vulnerability for obsolescence. Finally, tenure is decisive for property management and control and there are essential differences between rented and owned property as well as between profit and non-profit. The often-used categorization of obsolescence distinguishes, on the one hand, internal and external factors and on the other, physical and behavioral factors. Internal factors are related to processes typical for the building itself and can be physical like deterioration over time caused by ageing or behavioral like damage by maltreatment. External factors are related to influences from outside and might be physical like the impact of changing conditions in the environment by nearby buildings of infrastructure or by changes in government regulations, rising standards and functional requirements. They can also have behavioral effects like social depreciation processes in the neighborhood and loss of market position and value.

Even if obsolescence is defined as a condition that justifies demolition, there are other solutions like renovation, reuse and transformation to extend the service life of buildings but on the other hand, obsolescence is not a necessary condition for demolition. Knowledge about the decision-making in the final phase of the life cycle of buildings and the underlying motives is scarce and fragmented and regarded as a complex range of interrelated and often conflicting interests and expectations of different parties. Physical quality and market demand can be considered as the main decisive variables, with tenure and asset management as main conditional factors (Flier 2011).

In general, robust and reliable data for outflows from the construction sector, i.e. construction and demolition data, is hard to come by. A possible strategy to overcome data limitation is exactly the creation of models which simulate waste outflows, as attempted in this study. But this obviously poses new challenges in terms of data requirements, modelling assumptions and limitations. It is generally acknowledged that a better understanding of the dynamics that characterize the construction and demolition of buildings is a necessary step towards a more sustainable built environment. Accounts of construction material stocks rely mainly on the normal/log-normal, weibull and gamma distribution but as a main issue up to today, a proper cohort-based dataset is yet to be available especially for non-residential buildings. Among these commonly used distributions, the one which best fit stock accumulation modelling is still unclear but wide variability with considerable effects for the speed of stock accumulation and the forecast of waste production, have been displayed. Common experience suggests that, apart from in cases of catastrophic events or exceptional structural deficiencies, very recently built buildings are very unlikely to get demolished. The peak of demolition likelihood will happen after some time has passed, but those buildings which survive their demolition peak are most likely to represent the best of their cohort, in terms of both architectural design and structural qualities and are probably worth preserving (Miatto *et al.* 2017).

Alessio Miatto and colleagues performed a best fit calculation for the five most commonly used probability distributions and found that the right skewed distributions performed the best (gamma, log-normal, weibull) matching with the theoretical assumption of an initial demolition free period, followed by a spike and a long tail. Unfortunately, up to today a large-scale analysis on the lifespan of buildings is still missing, constraining one to rely on a small set of case studies. Some studies provide yearly demolition rates rather than lifespan, but it is not possible to convert yearly demolition rates to an average lifespan without knowing the composition of each cohort, making it impossible to use this information with the top-down inflow driven stock accumulation model. As the top-down inflow driven stock accumulation model is mainly sensitive to the average lifespan and almost insensitive to the choice of lifespan distribution calculation of realistic lifespan for different building typologies could be a suggested direction for further research.

In general, the housing stock in Europe is ageing as a consequence of relatively low housing production in the last two decades and high production in the first decades after WW 2. As a result, the deliberation between life cycle extension and demolition becomes more important in housing management and the knowledge about demolition, the decisive motives, the pros and cons and its consequences are getting just as necessary as the knowledge about the initial phase. As evidence grows that demolition plus replacement is most likely less sustainable than life cycle extension of the existing building, also the environmental consequences necessitate a careful consideration. Based on previous research about demolition, factors like tenure, building period and building type, might be considered as relevant explanatory variables. Main variables in the decision-making process are the characteristics of the object, the dwelling, and the motives of the decision maker, usually the property owner or proprietor. In western Europe, the final decision about demolition rest at the owner(s) of the property, the proprietor. However, in some specific cases the government can force demolition. The motives for demolition vary by tenure according to their interests and scope of the property owners. While homeowners are mainly motivated by the physical quality of their home, commercial landlords are more motivated by profit related motives. Social landlords will probably have both types of motives while property developers' scope is directed to redevelopment of the land. The decision to demolish may have to do with the motives of housing managers but also with their capacities regarding capabilities and resources (Thomsen 2014).

As it appears from the discussion above, the development of the building stock development is a rather intricate phenomenon affected by several interrelated factors and are thus hard to interpret on a more detailed level. Developments of models might however help getting a better understanding of the different factors at play thereby becoming better to make decisions and interventions in the management of C&DW. As the knowledge within the field gets improved through further research, elements of the model might be changed concurrently, becoming better reflections of reality in the end.

In this project a normal distribution has been applied to the lifetime distribution in order to model the development of the building stock and the lifetimes have been derived from literature. In a first attempt it was however tried out to derive the lifetime from statistical data covering the building stock, disaggregated by different use types and age cohorts. The year of construction run from before 1900, until 2000 divided into intervals of 4 years and after 2000 while the year of observation runs from 1986 – 2006. By analyzing this dataset, it should be possible to derive the lifetime based on the building stock build in different cohorts and the part of this stock remaining in recent years. When evaluating the data, the building stock from remote cohorts was found to increase in recent years, which doesn't make any sense from a logical point of view. The reason for this unnatural behavior of the data probably originates from the way the data have been treated. Another issue was related to the change in the administrative regions of Denmark as data covering the building stock before 2006 are aggregated by the 271 municipalities existing before the structural reform while data after 2006 are aggregated by the resulting 98 municipalities and 5 regions.

6.2 Renovation vs demolition

For this project, the modelling of waste coming from renovations has been carried out by assuming 1 % of the building stock standing in the respective year to get renovated. The outflow of waste resulting from these renovation activities has been calculated based on the assumption that an amount of material corresponding to 1 % of the building stock will be removed and replaced during the renovation. This is however a highly simplistic way of estimating the waste flow from renovations. First of all, the different building types are probably not equally likely to be exposed to renovation. Secondly, renovation activities will more likely behave in a cyclic manner depending on the age-distribution of the building stock. And finally, the different materials will not be exchanged during renovation in a similar fashion but depends on whether they are part of structural components or not. In the case of concrete, most of this material are likely to be part of structural components, not being released until the demolition of the whole building. In terms of concrete, demolition activities would thus probably be more relevant when trying to evaluate the potential for secondary supply of aggregates. The outflow of concrete might thus be overestimated by the model applied for this project, but as the outflow and inflow resulting from renovations are the same, they would equalize each other in the end.

As acknowledged by Sandberg and colleges, understanding and influencing the existing and future dwelling stock is of vital importance as there are significant lock-in risks associated with the long lifespans of buildings and infrastructures. Consequently, a majority of today's dwellings will still exist in 2050 and beyond. Housing stocks are exposed to refurbishment activities during the ageing process, and renovation in the coming decades to a large extent depends on the age composition of the stock and the previous renovation activity. Standard linear dwelling stock models commonly assume fixed rates for construction, renovation and demolition activities whereas in reality these rates are dynamic both in the short and the long term and depend upon external drivers as well as the type and age composition of the building stock. In their study they employ a dynamic dwelling stock model based on the drivers population and numbers of persons per dwelling and apply it to analyze the construction, demolition and renovations activities in the dwelling stock of 11 European countries. For each country the housing stock is modeled with respect to its past evolution and with projections towards 2050. The total number of demolished buildings were estimated each year by applying a demolition probability function on the construction from all previous years. Mass balance principles are used to estimate the construction activity in year i, that is equal to the sum of new dwellings that are needed to replace the demolished ones and meet the change in demand from year i-1 to year i. And finally, the renovation activity in year i, was estimated by applying a renovation probability function to the construction from all previous years allowing for cyclic repetition of the renovation probability function, described by the average time between renovations of a certain dwelling. The cyclic renovation probability function was linked to the lifetime probability function, preventing a dwelling to be demolished shortly after being renovated. The lifetime probability function was assumed to follow a Weibull distribution defined by the parameters, average lifetime per dwelling and the initial period after construction where the probability of demolition is zero while the definition of the renovation activity is case specific and assumed to follow a normal distribution. All the results were normalized against the size of the stock in the respective country in 2015 (Holck *et al.* 2016).

The construction rate simulated by the model was high from 1900 to around 1950/1980. Thereafter there has been a decrease in the construction rate, expected to continue in the future due to slower population growth and saturation of the number of persons per dwelling. The simulated annual demolition rate in most countries has been rather stable at 0,3 – 0,7 % in the past expected to remain at the same level or slightly increasing towards 2050. Similarly, the simulated annual renovation rate has been stable at 1 – 1,5 % and is also expected to remain at the same levels or increase slightly towards 2050. Their simulations suggest that renovation will, in most countries, be the dominant activity in the system in future, in terms of number of dwellings exposed to this activity. The authors conclude that the model seemed to perform reasonably well at simulating the long-term development of changes in the dwelling stock composition and expected annual renovation activities. Short- and medium-term variations in construction activity are not well captured by the model as these depend on drivers not represented in this model such as economic, climate and unemployment. The future development in construction and demolition is sensitive to the population input and the lifetime of dwellings, which are highly uncertain. However, as the authors claim it might be better to include the best available estimates of these important parameters in the study and identify the implications of their uncertainty rather than using traditional models with fixed construction, demolition and renovation rates that are based on recent trends without discussing their realism and applicability for future analyses (Holck *et al.* 2016).

The economic key figures of the construction sector might indicate the activity regarding construction, renovation and demolitions, and the numbers for Denmark appears from the appendix. As appearant, the turnover within the constructoin sector is higher for new buildings and extensions, however the turnover of repair and maintainence is also significant and not far behind. Detached hosues, terraced houses, apartment blocks and office and trade buildgings show the largest potential for the market of renovation. Overall, the trend point towards an inreasing demand for renovations within the housing sector, while demoliton works not are expected to increase significantly on a longer term. Regarding occupational buildign stock, a running demand for renations are likely to prevail while total demolition worrks primarily are exepected to happen to old stables and occupation buildings affected by urban renewal.

In overall terms the renovations of dwellings constitues around 60 % of the market responsible for 3-4 % of all C&DW while renovations of occupational and institutional areas accounts for approximately 40 % generating 6 % of the C&DW. Regular rebuildnig comprises the largest single item, while outer maintainance like renvation of façades and replacement of windows and roofs constitues 40 % approximately. Insualtion and other energyimprovment also accounts for significant shares of the turnover. The technical evaluation of the condition of a building and the cost related to renovation versus demolition determines the decisions regarding demolition to a large extent. In additon, demographical and socioeconomic factors might influence the number of demolitions. Demolitions of occupational buildings depends mainly on estimations by the building owner regarding the functionalty and profitability of the building. These types of buildings have often been furnished based on the functional requirements associatd with a specific producion activity, often making it difficult and costintensive to conduct renovations preparing for other uses.

The economic activty of the construction sector could be applied as an indicator of where most activity are happening, be it new constructions, renovations or demolitions. But how these activities are related to the amount and types of C&DW generated is not straight forward however. As concluded by Sandberg and colleges, renovations will most likely be the most dominant activity exposed to the building stock in Europe in future, and this trend probably also apply to Denmark as well (Holck *et al.* 2014). In another study from Norway, Bergsdahl and colleges developed a method for estimating the amounts of building materials moving from the use phase to the waste management phase, from demolition and renovation activities. Projections of these waste amounts from the C&D industry in Norway were estimated through the development of a simple stocks and flows model for the period 2004 – 2018. The found demolition to produce a very large amount of the heavy fraction concrete and bricks, compared to renovation. These fractions constitued 67 % of the total C&DW ammonut but for demolition alone, the same figure is 85 % much higher than the contribution from construction and renovation.

Efforts targeting waste prevention or better management of waste in general should focus on the waste generating activities, including new constructions, renovations and demolition and building types covering offices, apartment blocks etc. The statistic material within this field is not well-developed however, regarding characterization of C&DW among these activities. A rough estimate could be derived from the PROBA-project carried out by the environmental protection agency, aiming for a detailed estimation of the amounts of C&DW as well as well as projections for future potentials. The results from this study showed around 50 % of C&DW to originate from demolitions of residential and non-residential buildings while the corresponding number for renovations of these buildings where around 10 %. Only around 3 % of C&DW was related to new constructions. It would thus be important to establish age-type-matrixes for each layer of the buildings and their corresponding service life. They estimate 90 % of the concrete to be part of the structural components, having a service life equal to the service life of the building and leaving 10 % of the concrete as subject for renovations and a more frequent turnover (Bergsdal 2007).

Considering these numbers, C&DW related to demolitions are probably the most relevant activity to consider when focusing on the potential for reusing/recycling of aggregates.

6.3 Recycling of concrete

As evident from the regional plans for raw material supply, the digging areas already pointed out by the regions would run empty within a foreseeable future, a little earlier in the Capital region compared to region of Zealand. As of today, the demand for primary aggregate in the Capital region are to a large extent covered by import from the region of Zealand and this practice might become even more significant in future. Transportation of aggregates over longer distances from areas in Zealand to areas within the Capital region are associated with considerable extra cost as well as emission of CO_2. Other areas within both regions might be suitable as new digging areas and as stated by Per Kalvig, resource limitations are not based on geological scarcity, but rather caused by land-use conflicts and absence of political decisions on how to manage and prioritize the resources. An array of different interests apply to the areas of Denmark including more forest, more nature and more energy production (Copenhagen economics).

It might thus still be interesting to evaluate the potential for secondary resource supply, especially around the Capital area where existing buildings often would have to be demolished, clearing the space for new construction. And it would prepare the way for reapplying the secondary aggregates in new construction work nearby the demolition side. Depending on the potential it might help sparing exploitation of primary aggregate resources reducing emissions of CO_2 simultaneously.

Considering economical aspects, a significant share of the cost encountered by primary aggregate supply relates to the transport and are thus depending upon the distances between the extraction site of the aggregates and the construction site.

As contractors get the raw materials delivered directly on the construction site for application, the relevant price encountered by the contractor isn’t just the price of the raw material itself but the total price per ton of material delivered at site. As the raw materials in itself has a relatively limited value compared to the weight and volume, the distance transported by the material quickly affects the total costs to a large extent (Copenhagen Economics). As a rule of thumb, the price for transportation of aggregates can be calculated as 1 DKr. per ton for each kilometer of transport, implying the total price to be doubled when traveling its own value in kilometers. Transportation costs might be even 2 or 3 DKr./ton for each kilometer driven within city areas, increasing the transportation costs even more. These expenses could be reduced to a large extent through secondary aggregate supply if demolition sites and construction sites are localized within a delimited area,

Considering only the material cost, recycled aggregates should be economically attractive as the price adds up to 150 DKr./ton compared to 190 DKr./ton encountered by conventional aggregates and these prices probably reflects uncertainty about quality as well as security of supply. But as stated by Ebbe Naamansen from RGS Nordic, they are currently hardly able to be competitive on secondary aggregate supply, leaving primary supply from natural resources, the preferred option until now.

Considering these numbers delivering 1 ton of naturel aggregates from gravel pits around Roskilde (35 km) and Kalundborg (103 km) to construction sites within the capital region would add up to 225 and 293 respectively. Using recycled aggregates instead directly at the construction site would thus save 75 DKr. and 143 DKr. per ton, compared to supply from Roskilde and Kalundborg respectively. However, these calculations should be interpreted with care as they are related to high uncertainty and an array of other factors might influence the cost and benefits encountered by using recycled aggregates. Even though, they serve the purpose to clarify how transport distances exposed to aggregates are influencing the overall cost to a large extent. This aspect might get even more important in future where the current gravel pits will be emptied, and alternative extraction sites would have to be assigned.

Secondary aggregate supply is however associated with costs related to crushing actions of C&DW. According to Ebbe Naamansen, the aggregate fraction of C&DW currently comprise a negative value by demolition companies as they are charged for delivering this fraction by companies like RGS Nordic, handling construction and demolition waste. The cost witnessed by the demolisher to dispose of the C&DW depends mainly on the purity of waste and in this regard, cost savings might be encountered by the demolisher if selective demolition on site ensure the purity of the aggregate fraction allowing it to reenter the circle of structural concrete.

Regarding the environmental impacts, a larger share of the total emissions of CO_2 might be derived from the production phase in case of secondary resource supply, compared to the primary resource supply were a larger share of the emissions originates from transport. In the study by Wahlström et al. they found CO_2 emissions of 5,87 and 2,86 kg CO_2 equivalents for crushing action of one ton of concrete waste and extraction of one ton of primary aggregates, respectively. The CO_2 emissions related to transport of one ton of aggregate material amounts to 0,185 CO_2 equivalents per kilometer:

$$5{,}87 - 2{,}86 = 3{,}01\ CO_2\ equivalents$$

$$\frac{3{,}01\ CO_2 equivalents}{0{,}185\ CO_2 \frac{equivalents}{km}} = 16{,}27\ km$$

Considering these numbers, the natural aggregates could be transported 16,27 km before crushing down waste concrete equal outs in terms of CO_2. These numbers again have to be interpreted with care however, as the calculation method has been highly simplified, and an array of other factors might influence the environmental performance in the end. But they still serve the purpose of illustrating the importance of transport when weighing out benefits vs. drawbacks related to extraction secondary supply of aggregates as a substitute for primary extraction.

Overall, the environmental and economic benefits depend to a large extent upon the possibilities to reapply the concrete in a local context. The reduction of costs, energy use and CO_2 emissions depends on the relevant logistic conditions and the possibilities of matching new construction projections and demolition works. The ideal solution would be reusing the concrete from demolition works of an existing building and reapply to a new building on the same site. This practice implies however adequate space at the construction site and the possibilities to set up crushing plants and temporary storage of the material (Environmental protection agency 2017). In cases where the source of concrete waste is close to its final use, e.g. reduced transport environmental and economic costs, and the concrete waste is free from hazardous substances e.g. low environmental and economic costs for pre-treatment, crushed concrete in new concrete is preferable. But as these ideal conditions rarely occur in practice, waste operators prefer to use crushed concrete as filling or sub-base material. As both the secondary and the virgin aggregate materials are not based on energy intensive processes, the preference, in environmental terms, for crushed concrete versus natural gravel depends primarily on the transport distances between waste sites and new construction sites or between gravel pits and new construction sites (Environmental protection agency, 2015).

If concrete waste in future are to be reutilized with a greater knowledge about the contents of environmental harmful substances and in a more sustainable way, knowing the origin of the concrete waste is required. Concrete exist is different qualities, determining possible applications of the material and sorting waste concrete at source might facilitate application of the material at higher levels of the waste hierarchy. The quality of the concrete depends upon the age of the demolished buildings and the content of environmental harmful substances is determined by the origin of the concrete. As of today, knowledge generated upstream during identification of harmful substances as well as knowledge of larger homogenous amounts of concrete, is inadequately transmitted through the value chain, preventing its employment during recycling. It is therefore deemed a necessity to distinguish between different technological and environmental classes of concrete to ensure optimal utilization of C&DW calling for better transfer of knowledge throughout all joints in the value chain (Environmental protection agency, 2015).

Existing barriers for utilization of waste concrete comprise several conditions. First, the fact that only a fraction of the total amount is notified, prevents municipalities to obtain a complete picture of the actual potential resources. Secondly, no threshold values or requirements for documentation of uncontaminated C&DW exists in legislation, reducing motives for source separation of different concrete waste streams and resulting in impaired trust in the purity of concrete waste. Finally, lacking planning of logistic conditions might be an important factor as crushed concrete is a heavy material with a relatively low value, making longer transportation distances costly. As a premise of optimal resource logistic a matching between demand and supply of secondary resources in terms of security of supply is required (Environmental protection agency, 2015). The issue of the limited supply security is related to uncertainty regarding the supply of sufficient amounts at the right time during construction projects (Environmental protection agency 2017).

The main codes for structural concrete design lack clauses that can allow a better understanding of the potential structural behavior of RAC and bearing in mind that concrete producers and designers strictly follow these codes, a revision is vital in order for them to fully grasp the implications of incorporating RCA on the performance of concrete. This might contribute to a greater confidence in the material and use of greater amounts of value-added C&DW in construction.

Certification guarantees the quality of the aggregate in meeting recognized standards and is within audited quality assurance schemes and certified RCA conform to the same specifications as those of traditional NA. Despite the potential inconsistency of the final product, this should not hinder the certification of RCA, since the most intrinsic physical properties will remain thereby allowing proper categorization. As observed in the study by Silva and colleges, the basic physical properties of RA followed a predictable relationship, regardless of their size and composition. These results prepare the way for the development of a performance-based classification system easily understandable by professionals in the industry and also facilitating certification of the final product (Silva *et al.* 2014)

The term willingness to consider (WtC) might play an important role regarding market development of recycled aggregates and contractors of recycled aggregates will probably react based on the signals from customers changing the capacity of the supply chain accordingly. Considering the supply side of the market to react in relation to the level of demand before investing it could end up in a situation like the chicken and the egg. The customers might not consider using recycled aggregates to a larger extent due to limited WtC whereas contractors would not invest in the necessary capacity due to limited demand. Increasing the knowledge base about recycled aggregates would require additional experience in its utilization which additionally might result in tipping points turning over the market.

6.3.1 Case studies of recycled concrete

The Danish recycling effort of concrete wastes started in 1980s when methods for recycling into filling material or road sub-base were developed. The Danish Concrete Association established in 1987 a working group with the aim to formulate a methodology for utilizing crushed concrete in new concrete of passive environmental class. A technique was developed in 1989 after a testing period and it was concluded in 1996 that it is possible to build based on recycled materials both technically and financially. It was also concluded that an important prerequisite for recycling of building materials, is to develop standards and to set up criteria for their utilization in practice and there is a need to create a stock and secure supply of recycled material so that the delivery can occur with a reasonable flexibility and in competitive prices. The Danish Environmental protection agency conducted a project aiming at developing a total concept for on-site recycling of heavy material fractions from demolition projects including concrete and tiles. The aim was to recycle 80 – 100 % of the concrete waste applying it to new constructions of concrete in the passive environmental class directly at the construction site. With the construction of Pelican Self Storage the project exemplifies how it might be possible to recycle 100 % of the clean concrete contained in the existing buildings and applying it directly on the construction site in new structures of concrete. As of today, considerable transport is associated with production of concrete from gravel pit and cement plants to ready-mix concrete facilities and along to construction sites consuming large amounts of energy due to transportation of the heavy material. The amount of transport is significantly reduced by introduction of the circular construction site, however. The municipality of Copenhagen granted an exception for producing concrete containing 100 % recycled aggregates in the coarse fraction applying to bearing as well as non-bearing structures. The aggregates were sorted into the fractions: 0-4 mm, 4-22 mm and > 22 mm. They achieved the same strength as corresponding conventional concrete without adding extra amounts of cement. Also from an environmental point of view, the scenario turned out to be preferable, with a saving of 37 kg CO_2 per m^3 of concrete by using recycled aggregates and mixing on the construction site amounted to a saving of 11 % compared to the reference scenario. About half of the savings were related to reduced transport, while the remaining share arise from minimization of refuse resulting from mixing directly on the construction site. In addition, the LCA appoint a potential environmental gain by not using recycled aggregates for road-bed material as this practice might result in environmental harmful effects from leakage of toxic substances, even though this effect is highly uncertain (Environmental protection agency, 2018c).

In the construction of “Sydhavn Genbrugscenter” within the Copenhagen area, recycled aggregates from a demolished chimney was utilized in the new construction work. After crushing, the aggregates were sorted into three size classes: fines, 4-25 mm stones and larger fractions containing scrap reinforcement. The fraction 4-25 mm was applied as aggregates in the concrete. In this project, the recycled aggregates were applied for concrete in the aggressive environmental class and 100 % recycled aggregates was utilized as coarse aggregates. The aggregates were prewetted in addition to the mixing due to the higher absorption of water and the resulting concrete becomes less dense, an issue which has to considered carefully. Less cement was added compared to conventional concrete resulting in slightly reduced strength but still plentiful for the application and the transport was reduced considerably. In depth analysis of the donor concrete is necessary in order to allow 100 % substitution of the stony fraction and the project challenged the existing legislation in the field but was granted an exception from the municipality of Copenhagen. In the newest update of the standard for concrete DS/EN 206 DK, published 6th of September 2018, a few new openings appear regarding the utilization of recycled aggregates in production of concrete. The overall guidelines are European, but the claims applying to recycled aggregates are written in Denmark. It is important to examine and document the quality of the donor concrete and the crushed aggregates must fulfill the standard requirements for aggregates DS/EN 12620 as well as certain claims regarding the purity. Up to the strength class of C30/C70, recycled aggregates can only constitute 10 % of the fines and 20 % of the coarse aggregates. Above this strength class, recycled aggregates can only constitute 10 % of each fraction, but if it is approved structural properly, the share in the coarse fraction might be increased to 30 %. Otherwise you need a grant of exemption of the municipal council, as in the case studies described here. Concrete containing recycled materials can only be used for constructions in the exposure class X0 and XC1, constructions exposed only to passive environmental impact, involving constructions at low moisture levels, heated constructions, constructions permanently in ground without flowing water etc. Concrete in the passive environmental class constitutes around 60 % of the approximately 8 million tons of concrete produced each year in Denmark Recycling of concrete, challenges, projects and politics (2018).

The project of “Sydhavn Genbrugscenter” just received the Sustainable Concrete Price as they took recycling of concrete one step further compared to previous practice. First of all, 100 % recycled concrete have been applied and in addition recycled concrete have been used for external surfaces exposed to frost, water and other environmental stress. In other words, the concrete has been casted in the aggressive environmental class whereas recycled concrete previously has been applied indoor, solely.

The company RGS Nordic together with the concrete manufacturer Danish Concrete and the Environmental Development Demonstration Program (MUDP), have invested 18,8 million in a project aiming to recycle around 300.000 tons of concrete waste as aggregates in new concrete each year. This amount conforms to approximately 1/7 of the total amount of concrete demolished in Denmark each year. It might be possible to challenge the limit of 20 %, as pilot projects substituting 60 % of the coarse have been demonstrated, but exploiting a larger share of the potential would require certification of concrete containing larger shares of recycled aggregates, as certified concrete are what the market ask for. Again this would require technical documentation proving the feasibility of pushing the existing limits for substitution with recycled aggregates and allowing its applying in other environmental classes than the passive. Challenges to be solved include:

- Cleaning of environmental harmful substances
- Documentation of the technical characteristics
- Sorting of waste concrete according to quality
- Improving the methods for crushing of concrete waste making the aggregates more cubical
- Washing the concrete might be required
- Certification and traceability of the concrete fraction

In addition, the dilemma of additional cement would have to be solved as it otherwise might be economically and environmentally inconvenient to make use of recycled aggregates in construction of new concrete. As recycled aggregates compresses itself closer together compared to natural aggregates making it harder to produce and handle and to obtain the required fluidity additional water would be added. But as the characteristics of concrete to a large extent are determined by the ratio between cement and water more water means more cement and thereby additional emissions of CO_2 as well. Right now, additional cement of 5 – 10 % are required to obtain equal strength characteristics. Reducing the emissions of CO_2 is however not the only environmental gain strived for when recycling concrete as savings of virgin materials is another important aspect. The aim of this project it to substitute the entire stony fraction of passive, moderate and aggressive environmental classes.

As an example of a successful case from abroad, the Theo Pouw Group is a Dutch company that receives and processes C&DW and sells secondary products. The company processes crushed concrete into secondary aggregates and produce new concrete with it. Contrary to other European countries, the Netherlands has limited access to naturally occurring sand and gravel and the demand for filling material and aggregates are mainly covered through imports and recycling C&DW. In 2012, around 300.000 tons, or 19 % of generated waste was recycled into the concrete branch. The clean heavy fraction of crushed concrete can be used as aggregate material in new concrete. First, the concrete is crushed typically into grain sizes of 0-32 mm. The metal parts are then removed through magnets and the light fraction such as wood and plastics are blown away. The aggregates are typically separated into a sandy and fraction and one or two stony fractions (Recycling of concrete, challenges, projects and politics 2018).

The case studies of “Sydhavn Genbrugscenter” and the “Pelican Self Storage” both turned out successfully in the end. In both cases, characteristics of the donor concrete was known beforehand and the crushed aggregates was applied directly on site. 100 % of the coarse fractions have been substituted by recycled aggregates and in the first case the resulting concrete was even applied in the aggressive environmental class. Additional cement was not required to achieve the required strength characteristics and environmental savings achieved mainly derive from reduced transport of aggregates as well reduced refuse by accessibility of the new concrete directly on site. And from an economically point of view, the costs of the projects did not increase compared to conventional construction with primary aggregates.

6.3.2 Potential of secondary supply

As it appeared from **Figure 9** applying concrete as a construction material started around the 1950’s and ahead, with a relative constant share each year. To the extent buildings constructed within this period are going to be demolished in the years to come, it would result in concrete comprising an increasing share of C&DW.

In order to estimate the potential for secondary supply of aggregates, the waste statistics from previous years will first be evaluated. As visualized in the result section, the amount of concrete waste generated in recent years in the Capital region adds up to around 360.000 tons/year. As stated, this number might be an underestimation as only a certain share of the actual amount generated are captured by the official waste statistics. Based on the fact that the average consumption of concrete per Dane adds up to 1,5 tons a year a simple calculation could be carried out by multiplying this amount with the number of people in the Capital region:

$$1.835.472\ inhabitants * 1{,}5\,\frac{tons}{inhabitant} = 2.753.208\ tons$$

Based on this simple calculation the demand of concrete in the Capital region would thus reach 2.753.208 tons and with an average density on concrete of 2,3 tons/m^3, this amount of concrete corresponds to a volume of:

$$\frac{2.753.208\ tons}{2{,}3\ tons/m^3} = 1.197.046\ m^3$$

Considering the fact that around 60 – 75 % of concrete are comprised by aggregates the amount required to meet this demand would thus amount to:

$$1.197.046\ m^3 * 0{,}7 = 837.932\ m^3$$

And converted into tons by the average density of aggregates:

$$837.932\ m^3 * 2{,}5 \frac{ton}{m^3} = 2.094.830\ tons$$

Finally, taking into account the claims applying to concrete only allowing a substitution of the gravel fraction by 30 %, the potential of secondary aggregate supply would end up at:

$$2.094.830\ tons * 30\ \% = 628.449\ tons$$

Considering this number being considerably higher than the parent generation of waste concrete, the whole amount could apparently be directed into the route of secondary aggregate supply. As the amount of waste concrete captured by waste statistic probably are underestimated the potential might even be higher in practice.

Interpreting the projections for raw material consumption in the Capital region and the region of Zealand unveils how the consumption are expected to increase until 2035/2040. The consumption supports not aggregates for concrete production solely but should also cover the demand for other construction works as filling for instance.

Based on the results from the dynamic building stock modelling the amount coming from the obsolete building stock would not suffice to cover the demand for new concrete. But as long as the restriction of maximum 30 % substitution by recycled aggregates in new concrete prevails the full potential of primary aggregate substitution could be satisfied, still leaving a certain amount available for other application. As the gap between supply and demand recycled concrete diminishes towards 2050, the surplus of recycled aggregates will increase even more, supporting the necessity of challenging existing constraints. In the case studies from Copenhagen, 100 % of the coarse fraction have been substituted by recycled aggregates without impairing its properties, so the upper limit might be raised in future paving the way for a larger share of the recycled concrete ending up in new concrete. Until 2050, the amount of concrete generated by the existing building stock becoming obsolete would not suffices to cover the total demand for new concrete, leaving a certain share to be covered by primary supply. Increasing the share of recycled aggregate in new concrete would however spare the consumption, postponing the date of running dry and buying some extra time for finding alternatives. On a longer term, where the building stock might become saturated and comprised by concrete to a larger extent the potential for recycling of concrete could evolve even more.

In the region of Zealand, the gap between demand for concrete and concrete from the existing building stock becoming obsolete is significantly more narrow compared to the Capital region. This might leave one with the impression that the potential for application of secondary aggregates in new concrete would be correspondingly higher. But other factors would have to be evaluated as well. As the main motivation for secondary aggregate supply from an environmental point of view, besides saving primary resource extraction, are limiting the transport distances related to supply of aggregates this aspect would be central to consider. In an area like the region of Zealand not densely populated and experiencing significant distances between individual buildings, favorable logistic conditions between demolition of one building and construction of another might be harder to achieve. To a certain extent this issue might be helped out by stock piling of crushed aggregates as a buffer between supply and demand and as available space are more abundant in this region compared to the capital, this might constitute be a minor issue. If the capital region would get more self-sufficient through secondary resource supply, this would also reduce the pressure on existing digging areas in the Region of Zealand, extending the supply horizon which are already longer compared to the Capital region.

As an important aspect, the composition of C&DW is highly relevant when trying to characterize this waste stream with the aim to improve its handling and promote substitution of primary resources. In the course of evaluating the different building structures a high diversity among the different materials was discovered also applying to the concrete fraction. Regarding this project, concrete of the following types was identified during the data collection:

- Concrete
- Concrete – screeds
- Concrete brick
- Fibercement
- Gas concrete/Yton/Aeratated
- Leca/lightweight concrete
- Mortar (limestone cement)

This array of different concrete fraction would be essential to consider when evaluating the potential for secondary aggregate supply as a substitute for primary supply of aggregates. All these different types of concrete would most likely display varying mechanical, physical and chemical characteristics during processing and later, upon application as new construction materials. This observation emphasizes the importance of efficient sorting on site in order to obtain clean fractions of homogenous materials displaying similar characteristics and determining their applicability for different purposes. At an earlier step in the process of demolition, a comprehensive identification of the materials contained in the building would help in this regard, visualizing the core concept of urban mining. As a pre-demolition audit, this mapping would assist in the planning of how to demolish different part of the building selectively and afterwards sorting the materials according specific types. In the end, this practice would hopefully result in more clean fractions of C&DW, making application as new construction materials more straight forward as the properties of the different fractions could be estimated. In an optimum manner this would also result in application of C&DW at higher levels of the waste hierarchy and if purchasers of the generated waste fraction are already identified before initiating demolition, utilization of the materials would be ensured preparing the way for a more circular build environment.

6.4 Reusing of bricks

As it is shown in **Figure 9** utilization of bricks as construction materials started earlier than concrete and until 1950, constituted the preferred construction material. This also appears from the results section were bricks account for a larger share of C&DW by 2020 compared to 2050 were concrete becomes more abundant. In the near future, demolition waste management might therefore concentrate on handling of the brick fraction and then turning more focus towards concrete waste later on.

Contradictory to concrete, bricks present more pronounced potentials in terms of reuse as whole bricks could be suitable to employ in new constructions. Alternatively, the brick waste will be crushed and employed as filling in a similar manner to concrete but if present in the mix together with concrete waste, it might contaminate this fraction and limit the possibilities for application. Further uncovering the potentials for reuse of bricks might thus comprise a desirable direction for further research.

The Danish environmental protection agency conducted an LCA on the reusing of bricks and employment within new building work on the precondition that a brick prepared for reuse, fully replace new bricks technically as well as functionally be it as a facing-brick or a brick in the backwall. The comparison is recycling of the brick-waste by crushing and reemployment as road aggregates or filling for other construction works. Results from the study might contribute the basis of a decision regarding requirements for treatment of brick waste. Processing of old bricks for reuse was modelled following the practice applied at the company “Old Bricks” in Svendborg. Brick waste originating from demolition works are received following mechanical and manual sorting, reprocessing a fraction of bricks ready for recycling in new construction works along a smaller fraction of residues in the form of mortar, sand, wood, cardboard and metals. The efficiency of the production amounts to approximately 65 % of the incoming brick waste. As an alternative, the brick waste is transported to a crushing mill crushing down the bricks preparing it for filling. The brick waste is received at the crushing mill sorting out minor fractions of metal, plastic and wood and by application as filling it replaces natural aggregates. The production of facing bricks and bricks in back walls are produced at different levels of energy-use which were considered in the substitution, however the claimed increased heat-insulating capacity of new brisk for use in backwalls were not taken into account. The reason for the higher energy level in the production of facing bricks result from harder burning leaving them more resistant towards rain and frost, not encountered by bricks in back walls.

Overall, it was concluded that processing of brick waste with the aim of reuse results in several environmental savings compared to recycling the brick waste by crushing and application as filling. The main cause for these environmental savings are due to the substitution of new bricks thereby avoiding environmental impacts related to production of new bricks including energy consumption and associated emissions. Considering the impact categories of greenhouse effects, acidification, photochemical ozone production and consumption of fossil fuels, reusing bricks thereby substituting new facing bricks was beneficial from an environmental point of view, compared to recycling (Environmental Protection agency 2013).

In the national resource plan the potential for reuse of old bricks are estimated based on data from BBR concerning the total building stock in Denmark and the information considers the age of the building, the area, number of floors and materials used in the outer wall. The rate of demolition was assumed to be the same regardless of age and type. The building expert in this project estimate few buildings to be demolished due to age, and the same demolition rate was therefore applied to all buildings based on the number of demolitions from Danish statistics. Solely bricks contained in buildings build before 1955 are suitable for reuse. In younger buildings, cement mortar would often have been applied making cleansing of the brick difficult as the concrete are stronger than the brick its selves, implying the brick to break during cleansing. Based on calculations from Danish Statistics combined with estimates regarding the height and thickness of walls, the amount of brick walls in buildings constructed before 1955 are balanced at 42,8 million tons. These might be suitable in terms of reusing bricks. The demolition rate in Denmark was estimated to 0,3 % for the years 2008 – 2012. If this demolition rate is applied to the stock build before 1955 it would amount to 146.700 tons of brick wall suitable for sorting and reusing of old bricks. Based on a reusing efficiency of 64,5 % and a single brick weighing 2 kg it would reach a reusing potential of 47,3 million bricks a year or 12 % of the total production of new bricks in Denmark saving 22.500 tons CO_2.

Lack in the sorting of bricks into clean fractions is a major barrier for reusing of bricks and the missing sorting might result in the mixing of facing bricks and bricks from backwalls. If bricks from back walls are applied as a facing brick a shorter lifetime might be assumed due to the lower quality of the brick.

Socioeconomic calculations unveil down crushing of waste bricks to be preferable from an economic point of view mainly due to the higher labor costs associated with reusing. In case of homogenous brick waste where all bricks are suitable as facing bricks, it might be more attractive to process the bricks for reuse compared to crushing them down for recovery, however. In addition, there might be a potential of replacing more exclusive types of bricks by reused brick leaving the practice more convenient in economic terms. A Danish standard brick would often be cheaper compared to a recycled brick due to the extra costs related to sorting and cleaning of useful bricks. The reduced costs experienced by demolition contractors by sorting bricks for reuse are often too small to outweigh the price payed to waste managers for handling the waste. The costs experienced by demolition contractors regarding disposal of waste depends on the price charged by waste disposal sites significantly higher in the Copenhagen area. In relation to large demolition projects within the capital region with high disposal cost and the receiving plant of “Old Bricks” in “Hedehusene” nearby, sorting out bricks for reuse might become economically attractive. The highest cost encountered when reusing bricks originate from the purifying process where all bricks are handled manually to sort, control and clean any remaining mortar. The amount of manpower required are thus almost proportional to the amount of bricks and as a result no significant economies of scale might be expected (Environmental protection agency 2016).

Recycling and reuse are not part of the existing statutory instrument regarding construction products and no harmonized standards applies to reused construction products making it challenging for companies to market their products. At the company “Old Bricks” a patented vibration technology prepares the ways for delivering recycled bricks at large scale for larger and smaller construction projects.

A CE-mark ensures manufacturers to declare the performance of building products regarding relevant characteristics of the products. According to EU regulation on construction products, they must be marked if they are comprised by a harmonized standardization, but this does not apply to reused bricks, however. CE-marking of construction products are primarily targeting trading and thereby becomes a competition parameter while consultants and conveyors should ensure that the construction products fits the application. This, as an already demanding technical task, becomes even more demanding in the case of reused and recycled materials. CE marking of reused bricks would thus accommodate the pull from the market and the certification and guarantee of the performance of the products would be assessed through a third party.

Tests applied to reused bricks have demonstrated good quality and strength properties of the reused bricks and unveiled their ability to “pass” existing tests applied to new bricks of today. A European Assessment Document (EAD) are on the same footing as the harmonized standard in legal terms and describes how the products must be tested in order to issuing the European Technical Assessment (ETA) forming the basis for a CE mark. As soon as the EAD are issued, it is valid throughout all countries of the European Union. An ETA has been issued by ETA Denmark and Old Bricks are thereby the first enterprise in Europe capable of CE marking reused construction products paving the way for transforming C&DW into actual construction materials transferable on market conditions. Recycling and reusing construction products are decisive if Denmark and EU are to create a circular economy exploiting the large market opportunities. Mapping of resources and preaudits are key aspects of the Circular Economy strategy of the European Union and the CE-marking of reused bricks further boosts the direction towards circular construction Environmental protection agency (2018d).

Reusing bricks imply and understanding of the collected system, comprising the end of life story of demolition and generation of C&DW and transformation into bricks and the life story of new construction projects. Preaudits include obtaining the drawings and specifications of the existing building as well as survey and measuring as required. In addition, a mapping of the resources in the building regarding the amounts of different material fractions should be conducted and an assessment of the potential for reuse and recycling should be handed out. An estimation of the possibilities for handling the waste should include an evaluation of the logistic, economic and environmental aspects. Regarding bricks, the estimation should distinguish facing bricks and bricks in back walls because facing bricks might be demanded solely. Also, the amount of bricks are important as large amounts of uniform bricks are easier to sell. The concrete demand for bricks in new construction project or reparation of existing masonries should be examined covering geographical and logistical preconditions for reusing bricks and including the distances to plants receiving old bricks for cleaning and temporary storage. As an important aspect, the cleanness of reused bricks should be proved and the trackability ensured throughout the whole process chain. As of today, demolition projects are normally handed out as selective demolition according to NMK 96 demanding the project to be carried out following the stages:

- Stripping of the object
- Demolishing the construction (roof construction and shell structure)
- Clearing of construction site

Before demolition the masonry, the building must be environmental rehabilitated and stripped of doors, windows, inventory, tiles, wallpaper and plaster etc. All inner and outer masonry walls should be completely stripped, ready for demolition without mixing with other materials of harmful substances. The costs associated with cleaning and prices of purified bricks are highly variable depending upon the quality of the material delivered again depending on the type of demolition performed. The rate charging models are also varying and depending on the purity of the waste fraction, the demolition contractor might either get paid for delivering the bricks, while payment could be charged in case of poor quality (Best practice bricks 2018).

It would thus be a balancing by the demolishing contractor if it is economically attractive to deliver the bricks for processing, opening possibilities for payment of single whole bricks but involving a more time-consuming process of demolition, however. In this regard, it might be more attractive to crushing down the brick waste at site or sending it for crushing elsewhere, selling the material as filling afterwards.

Logistic aspects are related to issues at the construction site and long transport distances during removal as well. If limited space prevails at the construction site, it might be easier to crush down the masonry applying it as a chair mat instead of storing out sorted bricks. The logistics issues related to transport concern the distance between the demolition site and the processer as well as the amount of bricks to be transported. With processing plants for old bricks in “Svendborg” on Funen and “Hedehusene” on Zealand, reusing bricks in other parts of the country might be inconvenient and small amounts of waste bricks, unable to fill up whole trucks further impair transport economics.

Time, as another important factor, relates to the compliment of deadlines for demolition projects and as demolition often must meet tight deadlines extra time as required by selective demolition could be unfeasible. Increased time consumption is also related to increased costs and the price received for reusable bricks might not outweigh the extra amount of time for demolition and transport. Development of mobile processing plants for bricks could possibly reduce these barriers but are mostly suited bricks to be reused at the same site.

The security of supply is mostly related to the construction process, but uncertainties about security of supply might affect the decision whether or not to apply reused bricks already in the design phase. The costs of construction works could increase significantly if construction materials are unable to meet the demand at the right place in the right time. This especially applies to larger construction works, demanding materials from several demolition sites. The opportunities for creating a linkage between demolition and construction projects might result in more efficient transport and logistics, however (Niras 2015).

6.4.1 Case study of reused bricks

In relation to the extension of "Katrinedals Skole i Vanløse" the municipality of Copenhagen decided to construct the buildings with facades using reused bricks arising from demolition projects at Bispebjerg Hospital. In between, the bricks were cleaned at the plant of Old Bricks in "Hedehusene". Due to the development in rational processes for cleaning of old bricks, the demand for reused bricks has increased significantly not only in relation to renovation and repair works but also for new construction on a larger scale. As the old bricks became available during the demolition work, they were loaded directly on trucks for transportation to Old Bricks thereby saving relocation of the material and temporary storage at the site, but resulting in no sorting of bricks on site, however. The demolition of 60 cm thick massive masonry wall leaved no possibilities for sorting of facing bricks and bricks from back walls. The experiences gained from this project clarified the importance of firm agreements between demolition contractors and receiving plants regarding prices and conditions associated with delivering and receiving of bricks for cleaning. Such agreements should build on detailed mapping of the amounts, quality and state of the bricks contained in the building before demolition. In conclusion, constructing facades using reused bricks turned out to be realistic in terms of economy, reduction of CO_2 emissions and technology but depends to a large extent upon the quality and share of whole bricks contained in the material handed over.

6.4.2 Potential of reusing bricks

As stated earlier, the potential for direct reuse of bricks might be more suitable compared to reuse of concrete. From an environmental point of view, LCA conducted on reuse of bricks demonstrated its merits, especially if substituting facing bricks. Under certain conditions reusing bricks could also be attractive from an economical point of view and the company "Old Bricks" in Svendborg managed to run a business, based on reusing bricks. The bricks are cleaned by a unique patented vibration technology and the company and are now able to CE-mark their recycled products. The application of bricks in construction works started earlier compared to concrete and the largest amount released by demolition would thus be expected to arrive in the near future. If this waste fraction is to be handled in optimum manner according to the waste hierarchy, waste management strategies should be geared to receiving brick waste applying it as new construction materials.

Visible from the results section the amount of bricks arising from demolition of the existing building stock exceeds the amount demanded by new construction work in the Region of Zealand as well as the Capital region. This especially applies to the Capital region in the near future, but the obsolete amount surpasses the demand until 2050 in both regions. Apparently, the total demand for new bricks, could thus possibly be covered by reused bricks, but reusing every brick coming from demolition might not be achievable. As an important limitation, masonry build after 1955 would typically contain cement mortar, making reusing of bricks unsuitable. As a starting point the potential for reusing bricks should this be restrained to the building stock raised before 1955, necessitating division of the building stock into time cohorts. Brick waste originating from masonry constructed after 1955 should thus follow an alternative route most probably the current practice of crushing down the brick waste for application as filling. In future construction works, alternative to cement mortar as a binding material might be strived for, in order to make reuse of bricks possible after end-of-life. Another constraint is related to logistic conditions. With the current location of Old Bricks near "Roskilde", most demolition sites in the Capital area would be within reasonable reach of their plant and the cleansed brick suitable for transport to new construction sites in the same area. Demolitions of large buildings, releasing sizeable amounts of homogenous brick waste ready for reuse remain more attractive. And as these types of buildings probably are more abundant in the Capital region this leave the potential for reusing of brick even wider within this area compared to the region of Zealand

At other places in Zealand the circumstances might be different, and long transport distances might become an impediment, but if mobile cleaning plants develops in future the situation might change, however. As a significant share of the brick waste arise in this area as well, this faction should not be neglected however, and stockpiling of bricks ready for reuse would also contribute to reduce the barrier of time delay between demand and supply. Compared to waste concrete, brick waste could probably travel longer distances, before becoming unattractive from economic and environmental point of views, especially applying to larger collections of homogenous bricks. Collection of bricks from diffuse smaller demolitions might thus be required to make this practice feasible in lesser densely populated areas. The mix of bricks from different sources could constitute a relevant barrier, but in some cases smaller batches of bricks might be inquired, for instance if targeted at renovation work.

6.5 Weakness of the model

Models would always be subjected to some uncertainty and that also holds true for the dynamic building stock model developed during this project. For this kind of model two major databases are required including the physical size of the built-environment components (m^2) and the material intensity coefficients (MIC) specific to each component (kg/m^2). In this case, data covering the physical size of the built environment have been derived from Danish Statistics, and this is regarded as a rather reliable source. From this source, the physical size of the build environment has thus been derived and aggregated into the different categories of residential and non-residential buildings respectively. The material intensities, used to estimate the amount of materials contained in the existing building stock, has been retrieved by evaluating architectural drawings beside the data directly apparent from the BBR database. In cases of limited information, the data collection was completed based on informed assumptions and by evaluating construction building codes typical of certain historical periods. This collection has been relatively comprehensive, probably well representing the building stock in Odense. For this project, the material intensities derived have been applied to the building stock of the Zealand region and the Capital region respectively and the assumption that the MI would represent the building stock of these areas as well, might be rather uncertain. Especially applying to the Capital Region, characterized by a more densely build environment with higher buildings compared to Odense. In addition, the material intensities developed for apartment buildings were applied to all non-residential buildings as well, including buildings for public, commercial and industrial purposes. This is also a rather rough assumption, as the different types of buildings serve widely different purposes and as a result might contain highly variable materials. As shown by (Ortlepp *et al.* 2016), non-residential buildings would typically contain more steel, for instance. These assumptions were made due to the limited amount of time and resources available for this project, but as a direction for further research this might be an area for further improvement.

Uncertainties are also related to the lifetime distributions applied to the building stock. The normal distribution was used in this project for simplicity but as discussed, this might not be the most suitable in terms of building stock development. Other distributions including Weibull and log normal might be more suited however, as they are able to capture the more intricate characteristics of the building stock development including an initial period without demolition, then a period with a peak in demolition activity followed by a long tail in the end. As another limitation of the model, the same lifetime distribution has been applied to the whole building stock irrespective of the different types. In reality, the lifetime of the buildings would probably vary considerably according the different use types. This was also the case experienced by Østergaard et al. They found considerably shorter lifetimes for institutional buildings (44) years, compared to residential buildings (67) and commercial buildings (72) years while agricultural buildings were found to last the longest (103 years). The model applied for this study would thus not capture this more diverse characteristics of the building stock development, predicting C&DW to arise in a more consistent manner. Developing the model by assigning individual lifetime distributions to different types of buildings would thus improve it significantly making predictions from the model more likely to reflect reality in terms of arising C&DW. In the end it would make the model more suitable as a tool to be used in the management of C&DW.

In general, dynamic building stock models might be better suited to represent long term development of building stocks based on historical evolution back in time and predicting the development well into the future. The shorter term developments might however be harder to interpret by the model as they would depend on an array of different factors difficult to integrate into the model. Dynamic building stock models like these might thus be better suited when trying to understand the overall trend of development in the built environment, while short terms fluctuations would have to be interpreted by means of other tools and methods.

Weakness of the model (normal distribution, MI from AB, Odense vs. Zealand/Copenhagen, same lifetime distribution to all buildings)

7. Conclusion

Evaluating the building stocks of the Capital region unveils how a significant share of the floor space are taken up by residential purposes, amounting to almost 70 % of the total building stock, the main type being apartment blocks. The nonresidential sector is characterized by buildings for trade and public administration as well as education and research. In the region of Zealand, the split between residential and non-residential buildings are more equal. The residential sector is occupied by detached houses to a large extent, whereas floor space for farm buildings and factories accounts for a significant share of floor space in the non-residential sector. The largest growth in floor space of the Capital region are expected to happen in the public building stock, but due to the large share comprised by detached houses and apartment blocks these buildings also responsible for a significant share of the material flows. In the region of Zealand, the growth is mainly driven by detached single-family houses and also by the public building stock, but to its relatively small size the material flows are small in absolute terms.

The amount of waste brick coming from the obsolete stock are gradually declining towards 2050, and this trend is more pronounced for the Capital region compared to the region of Zealand. The concrete waste on the other hand shows a slightly increasing trend and here the Zealand region applies for the most significant increase in relative terms. This probably reflects the historical development of construction, where bricks have been the main construction material applied until 1950 then gradually exchanged by concrete and metals since then. As a result, bricks would thus arrive earlier on in the waste stream compared to concrete and waste management strategies should presently prepare for this fraction then gradually turning more focus towards concrete. As an immediate impression, the obsolete brick fractions tend to be able to cover the total demand for new bricks in both regions, but this interpretation should be considered with a certain skepticism. As solely bricks contained in buildings constructed before employment of cement mortar would be suitable for reuse, the actual potential for would be reduced considerably. In order to calculate a reliable estimate of the potential for reuse of bricks, one would thus have to ascribe the waste flow of bricks to buildings constructed in certain cohorts. And in order to make reuse of bricks possible in future, alternatives to cement mortar as a binding agent of masonry works would have to be pursued.

Applying to concrete waste, reuse is not as likely compared to bricks, attracting the attention towards the next level of the waste hierarchy namely recycling. In this regard recycling of concrete and applying it as aggregates in new concrete would be preferable compared to the current practice of recovering waste concrete by filling. This would entail the concrete to be kept in a circular flow for longer time, substituting primary aggregate supply at the same time, compared to recovery as filling often comprising the last resort for the material. The demand for new concrete is larger than the amount coming from obsolete stocks, a picture that is more noticeable for the Capital region, but the gap diminishes by time for both regions, however. Until now, recycled are aggregates have not substituted primary aggregates in new concrete completely anyhow, still substantiating a demand for primary supply. As of today, the standards limit the substitution to 30 % for certain types of concrete and as long as this applies, the full potential could be achieved by waste concrete. This restriction has already been challenged by a couple of case studies however, applying concrete with 100 % recycled aggregates in the course fraction. If pre-demolition audits as prescribed by the European union are going to be common practice in future and more demolition come to be carried out selectively, larger fractions of homogenous concrete waste with measurable performance would probably be obtained. This would then prepare the way for substituting primary aggregates by secondary aggregates to a larger extent, making the built environment more circular. As the supply horizon for primary aggregate supply are limited to 13 years in the Capital region, new supply chains would have to be uncovered soon and in this regard crushing down concrete applying it as secondary aggregates might be an attractive way forward. The sustainability of this practice would have to be supported by LCAs considering the local aspects, by it would possibly release the pressure from existing gravel pits also in the region of Zealand currently exporting considerable amounts of aggregates to the capital region. At least it could buy some time, developing new supply chains of aggregates but on a longer term it might become the primary route for supply of aggregates to the Capital region in a sustainable manner.

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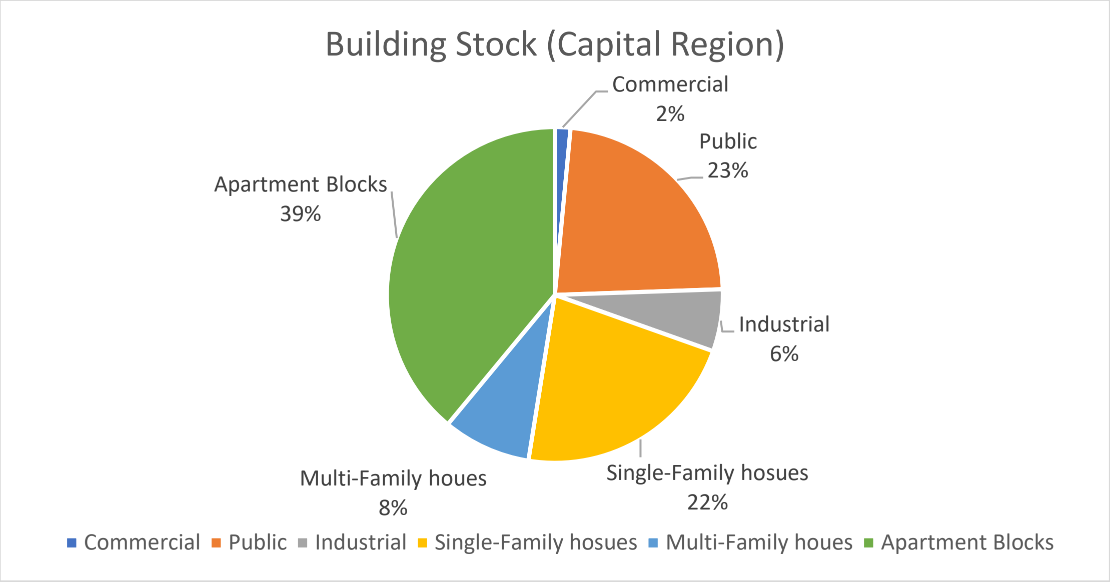
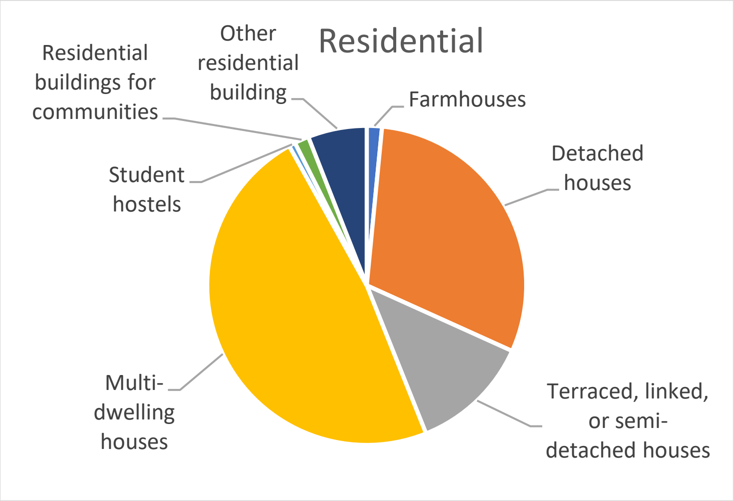
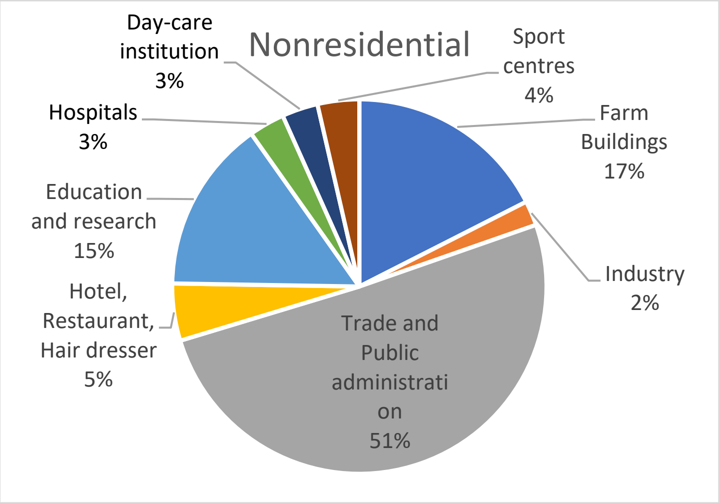
10. Appendix

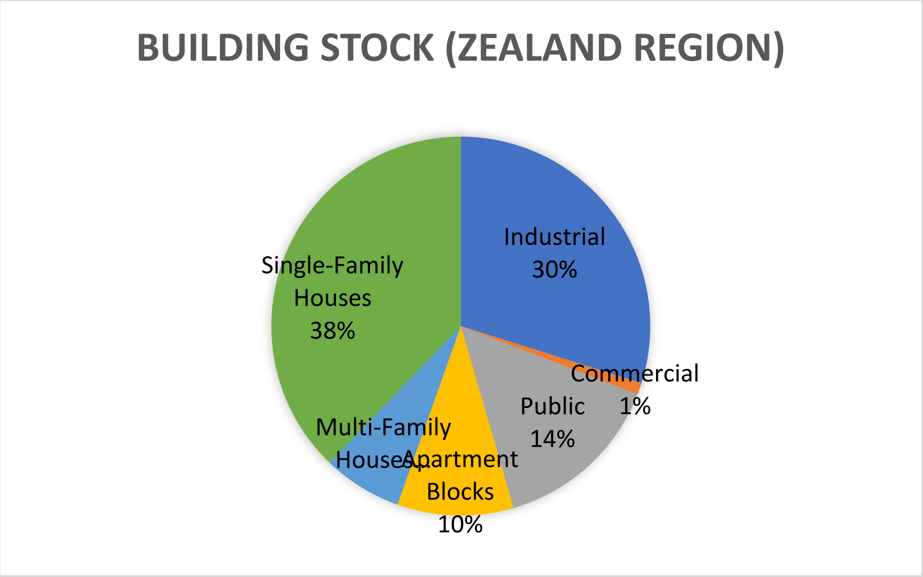
10.1 Building Stock Capital Region

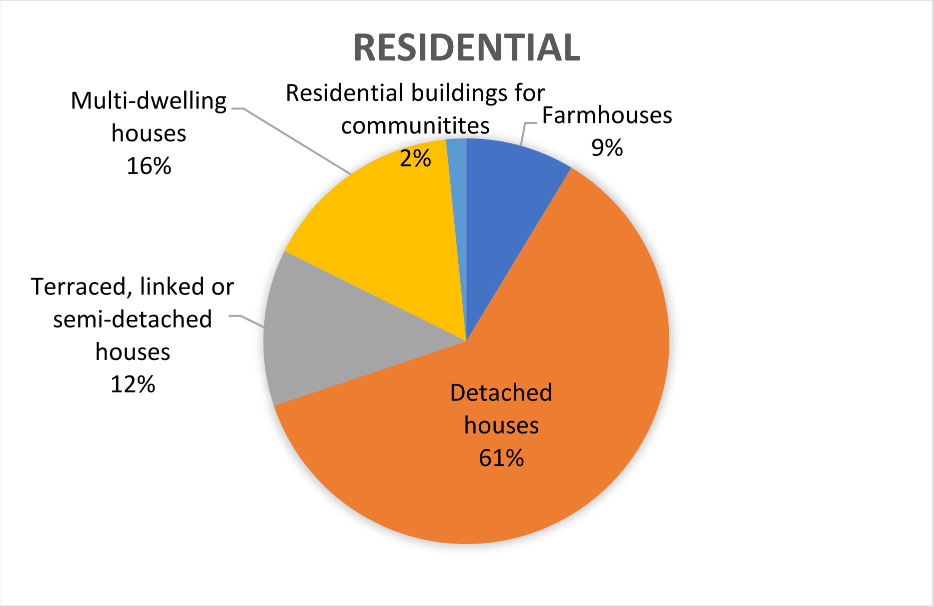


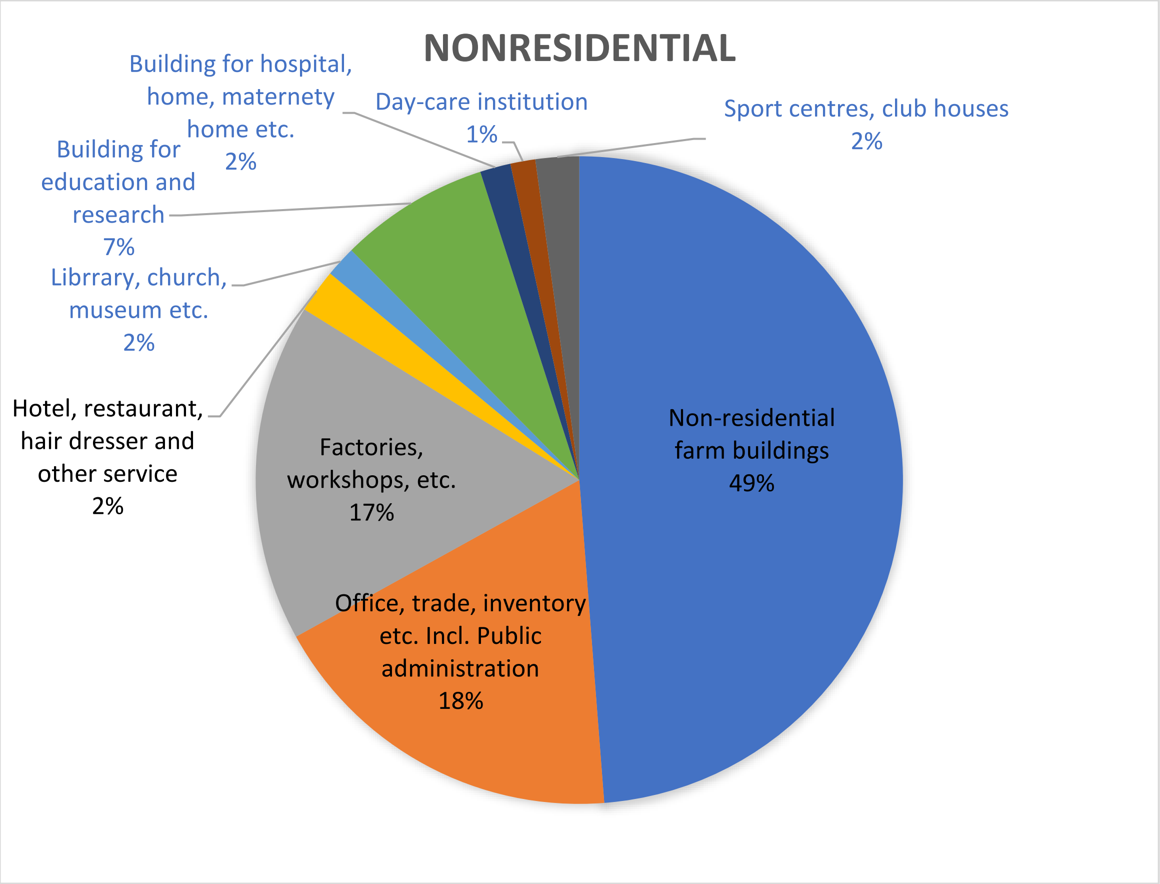




10.2 Building Stock Zealand Region






NONRESIDENTIAL
Building for hospital, home, maternety home etc. 2%
Day-care institution 1%
Sport centres, club houses 2%
Building for education and research 7%
Librrary, church, museum etc. 2%
Hotel, restaurant, hair dresser and other service 2%
Factories, workshops, etc. 17%
Non-residential farm buildings 49%
Office, trade, inventory etc. Incl. Public administration 18%

10.3 Turnover in the construction industry