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Circular bricks: Getting the circular construction industry to shore

A scenario analysis of building material streams through the Port of Oslo

Sirkulære byggeklosser: Hvordan få en sirkulær bygningssektor i havn?

En scenarioanalyse av byggevarestrømmer gjennom Oslo Havn

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Abstract

Every year, almost half of the world's extracted resources goes into constructing new buildings, tying up vast amounts of stone, minerals and metals for decades to come. The construction industry is responsible for more than one-third of global emissions. Meanwhile, the world's building stock is expected to more than double by 2050. Therefore, over the next decade, more attention must be given to cities' material intensity and their indirect emissions. This paper suggests using the Circular Economy as a paradigm for this transition and illustrates current policy dilemmas through the case of Oslo. The thesis investigates this transition in construction and identifies utilising material repurposing facilities linked to the seaborne trade-system to increase the circulation of Oslo's construction material flows. In a circularity scenario analysis for 2020-2030, where new regulations such as stricter recycling and waste disposal regulations are introduced, waste generation from the construction of new dwellings is found to almost halve, resulting in a radical shift in current waste streams outbound. Raw material demand from Oslo's construction sector is reduced by one-third, even as construction activity increases. Meanwhile, the proportion of construction-material residues available for reuse will remain stable as more materials are recovered. Therefore, the demand for waste treatment and re-distribution increases proportionally, requiring transport of materials at end-of-life. In a regionally integrated value cycle, port terminals can enable seamless transmission of materials across the chain, where materials are recovered and exchanged continuously, and facilitate for regenerative use of natural resources essential for building our future.

Key words: Circular economy, built environment, construction and demolition waste, material flow analysis, material footprint, scenario analysis

Sammendrag

Mer en halvparten av alle materialer vi utvinner årlig går til konstruksjon av nye bygg, som binder opp store mengder naturressurser som sand, mineraler og metaller i flere tiår. Bygningssektoren står for mer enn en-tredjedel av globale drivhusgassutslipp. Når den globale bygningsmassen forventes nært tre-dobles innen 2050, for å nå internasjonale klimamålsetninger så må en større oppmerksomhet rettes mot byers materialforbruk og indirekte utslipp. Denne studien peker på Sirkulærøkonomien som en mulig løsning på mellom-lang og lang sikt, hvor materialverdien bevares ved å sirkulere dem i lukkede kretser, og illustrerer nåværende dilemmaer for beslutningstakere en case studie av Oslo. Avhandlingen undersøker overgangen til en sirkulær økonomi i bygningsbransjen og identifiserer et potensiale for å øke sirkulasjonen av byggevarer gjennom å utnytte sjø-nære gjenvinningsterminaler En scenario analyse for 2020-2030 finner at, i et scenario der strenge krav til materialgjenvinning og forbud mot deponi innføres, vil avfall fra nybygg nært halveres, noe som kan føre til en drastisk endring av nåværende avfallsstrømmer gjennom byen. Etterspørsel etter råmaterialer fra bygningsbransjen reduseres likedan med tilnærmet en-tredjedel, selv hvis byggeaktiviteten forblir høy. Likevel forventes tilgangen til gjenbrukbare masser å holdes stabil, grunnet økt grad av gjenvinning. Dette medfører en økt etterspørsel av avfallshåndteringsløsninger som viderefører brukte materialer til neste ledd i materialkjeden. I en regionalt integrert verdikjede kan havneterminaler knytte bygningsmaterialer til skipstrafikkenen og sømløst fordele gjenbrukbare materialer på tvers av kjeden og føre til en større gjenbruk av våre essensielle naturressurser mens vi bygger ut fremtidens boligbehov.

Stikkord: Sirkulærøkonomi, bebygd areal, bygge- og rivningsavfall, materialstrømsanalyse, materiellfotavtrykk, scenarioanalyse

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Introduction

Cities in the 21st century need to enter a circular economy where materials are looped, and the built environment maintained without draining scarce natural resources. Cities are at the same time the largest consumers of raw materials and the greatest emitters of greenhouse gases and will need to engage in rapid decarbonisation in order to achieve the daunting task of mitigating climate change. If this is to be achieved in the rapidly growing and urbanizing regions of the world, affluent, well-resourced cities in the West needs to take a lead to prove that such a transition can happen at scale, within the very limited timeframe projected by international climate assessments. Among the greatest sources of emissions globally is the housing and construction sectors. This does at the same time represent a great potential for emissions reductions. To achieve decarbonisation of this sector however, the global value chains that comprise the industry today from the architectural design to production of building components, and the construction of buildings need to be considered systematically in order to assess leakages, wasteful practices and sources of emissions. Seaports are at the interface of these global value chains.

Yet material value chains are today largely linear, being extracted, assembled, used and then crushed for disposal at the end of the building lifecycle. All these material flows in turn, requires a sophisticated transport network, generating congestion and transport emissions. The large resource inflow depletes stocks and the massive waste outflows necessitate expensive treatment and management equipment. Sand and gravel are today increasingly scarce, while the production of new materials such as bricks and concrete generate large amounts of emissions. The solution proposed in this paper is a transition to a circular economy, based on the principles of regeneration and waste minimization. In construction, this means constructing qualitatively different buildings, designed for re-use and maintained for longer lifespans. It means looping the supply chain for construction materials and making waste re-enter the cycle. This is a logistical challenge requiring a plethora of actors to collaborate across disciplines, while resource flows are transmitted through logistical hubs. This paper point to the key role of international shipping networks and port systems for this new type of industrial symbiosis.

Problem statement

Buildings occupy around half of our annual material consumption, expanding the built environment by more than 230 billion square meters (Gross, 2019). Globally, construction work and building energy-demand generate more than one-third of annual emissions. Globally, the building stock will more than double by 2050, while 70% of new infrastructure will be built in urban centres and cities by 2030 (Circle Economy, 2019). In Europe, the total building stock of 95 billion tons is growing at 1% every year, adding more than 40 billion tons of materials just in 2015. (Circularity gap report, 2019). In Norway, Construction and Demolition Waste makes up around 25% of the total waste generation, resulting in 284 000 tons of non-polluted waste every year (SSB, 2016). Most of the materials are considered “clean” residues, mostly made up of concrete and bricks (40%), wood (14%) and asphalt (13%). These materials are largely lost after use, either disposed of in landfills or downcycled into crushed stone. Recovery and downcycling of these materials in Europe range from 98% in the Netherlands to just 5% in Finland (European Comission, 2011). Norway recovered and downcycled roughly 55% of the mineral waste from the construction sector for backfilling-purposes in 2014. More than 40% were disposed of (Grønn Byggallianse, 2017).

This loss of value is a significant cost to society and drives up demand for new virgin materials on top of that required for additional floor space capacity. As such, our expanding built environment is over-consuming ever more scarce natural resources. A greatly overlooked environmental issue is that the materials we use to construct our buildings are being “extracted faster than they can be replaced” (Bendixen, Best, Hackney, & Iversen, 2019). Sand and gravel, the most extracted groups of materials by far, are extracted from the lithosphere at such a rate that global demand might outstrip nature’s supply by mid-century (Bendixen et al., 2019). These materials make up the key ingredients of the most used material in the world, concrete. Every year, more than one cubic meter of this hardy building component is produced per person on Earth, each year (Watts, 2019). By some estimates, concrete today outweighs the combined mass of biological material on the planet (Gross, 2019).

While still a nascent field, the research on the circular economy in urban contexts has taken up over the last years (Ellen MacArthur Foundation and ARUP, 2019; Geisendorf & Pietrulla, 2017). Mostly, research on the built environment focuses on climate mitigation strategies, such as increasing energy efficiency in buildings and reducing emissions from the construction activities (Lamb, Creutzig, Callaghan, & Minx, 2019). Yet, consumption-based emissions or the emissions from material extraction and production are often neglected, as these industrial activities do not occur in the cities (Nersund Larsen, Brenna Raabe, Fuglseth, Borg, & Lia, 2018, p. 9). According to a report by the International Resource Panel, “cities can achieve some 30-55% reduction of GHG emissions… compared to baseline projections by leveraging connections and resource sharing across urban systems” (United Nations Environment

Assembly, UNEA, 2019, p. 19). The report concludes that, while significant effort is seen at the project level, these are not linked in a "broader policy and planning approach at the local and national levels" (UNEA, 2019). This represent a gross waste of vital resources and a missed opportunity to rapidly cut emissions from cities at a global scale.

Research objectives and scope of analysis

This study will seek to better understand the role of ports as enablers of the circular economy, through their role as gateways, transmitters and trade hubs for a significant proportion of material flows in use today. It will look at current policy objectives and governance mechanisms and identify new approaches. In this way, the paper will seek to answer the two correlated research questions:

1. how do construction material demand and waste flows change as the construction industry value chain becomes circular?
2. how can port cities adapt to facilitate a transition to a circular economy, where materials are looped and reused in a value cycle?

It will employ a theoretically framed circular economy concept to analyse scenarios for the building sector, material flows and port operations over the next decade within the context of the Municipality of Oslo. It will survey the activities in and associated with the Port of Oslo to identify leverage points for circular economy practices in the construction value chain. By tracing a narrow range of abiotic mineral material streams with potential for circulation in the geographically confines of Oslo, I will be able to generate a policy-relevant overview of the lifecycle and value chain of abiotic mineral construction materials. The end-goal is to assist the design of place-based interventions in the Municipality of Oslo. Providing a systems perspective of the situation and the way it is likely to evolve, will enable scaling project-based practices and highlight the possible negative side-effects of interventions. The objectives of the research presented here are to:

1. Define the role of the Port of Oslo as a hub for material streams in the building sector value chain.
2. Analyse the secondary material streams within the building sector in Oslo and map the value chain of activities in the building sector.
3. Identify potential for increased circularity within current building sector value chains in Oslo in a scenario analysis of the period 2019-2030.

4. Understand how a growing port city, such as Oslo, can adhere to circular economy principles within the building sector, through a systematic analysis of its localized and international supply chains

The scope of the analysis of the paper is limited to the setting of the case study, but lessons learned from this case study can be relevant to comparable urban contexts. In this paper's case study, the Port of Oslo is defined as the system nodal point where material flows gravitate. Only material streams limited to dry bulk shipments used in the construction activity within the municipal borders of Oslo are considered within the system boundaries. The system is thus limited geographically by the municipal boundaries of Oslo. Only upstream or downstream flows directly associated with operations of the Port of Oslo are included in the analysis in order to assess the environmental footprint associated with current construction and port operations. In this way, the system is inflow-driven, where flows are distinguished based on their mode of freight.

Thesis Overview

The system boundaries are first defined before the most relevant stakeholders in the building industry value chain are identified and placed within the system map. Then scenarios for future developments are assessed based on where the most relevant policy changes are likely to occur, presented in a funnel model. Then a material flow analysis of mineral dry bulk flows relevant for the building industry entering the Port of Oslo is illustrated through a freight example, to identify the greatest impacts in this system. A scenario analysis of this freight example will pinpoint some of the leverage points available to policy-makers moving forward before the final analytical task becomes to identify the policy leverage available to policymakers in Oslo and comparable cities. Some of the main barriers and solutions from interview subjects and international literature are discussed, as well as the implications for future research. The paper concludes with some recommendations to stakeholders and policy-makers.

Theoretical framework

In this section, the defining properties of the Circular Economy are presented, its key components are analysed and the practical implications for the study area discussed. Then, the ecological roots of the narrower concepts of Industrial Ecology and Industrial Symbiosis are introduced. Finally, an analytical framework for studying sustainability issues is introduced and tied to the broader tradition of systems thinking.

What is the circular economy?

Arguably, the principles underpinning a circular economy are not new to humankind. Natural cycles of nutrients, reutilising scarce resources and exploiting nature's regenerative abilities are as ancient as life on Earth. For centuries, survival depended on the cycle of solar power turning into plant-based energy, which was absorbed by the soil after its lifetime (Haberl, Fischer-Kowalski, Krausmann, Martinez-Alier, & Winiwarter, 2011; Geisendorf & Pietrulla, 2017). The circular economy is a more recent concept in political and economic disciplines, first popularized by the Ellen MacArthur Foundation in the early 2010s (Gallaud & Laperche, 2016). It was first termed in their seminal report "Towards the Circular Economy". While interpreted in almost as many ways as it has advocates, the original definition of Circular Economy introduced by the Ellen MacArthur Foundation (2015, p. 2) read: "*a circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles*."

The new economic paradigm of the circular economy is illustrated in the 'butterfly model' by the Ellen MacArthur Foundation (2015, p. 6, Figure 1). At its core, this model differentiates between the domains of the technical and the biological value-cycles. On the left side are the natural, biological flows of materials, renewable through their embeddedness in the regenerative biological cycles of ecosystems. Resources are extracted from renewable flows and residues are returned to the biosphere as nutrients. On the right side are the technical or human-made cycles, limited by industrial production capacities and resource stock availability (Ellen MacArthur Foundation, 2015, p. 7). Here, circularity entails prolonging the lifetime of the technical materials in a cascading loop.

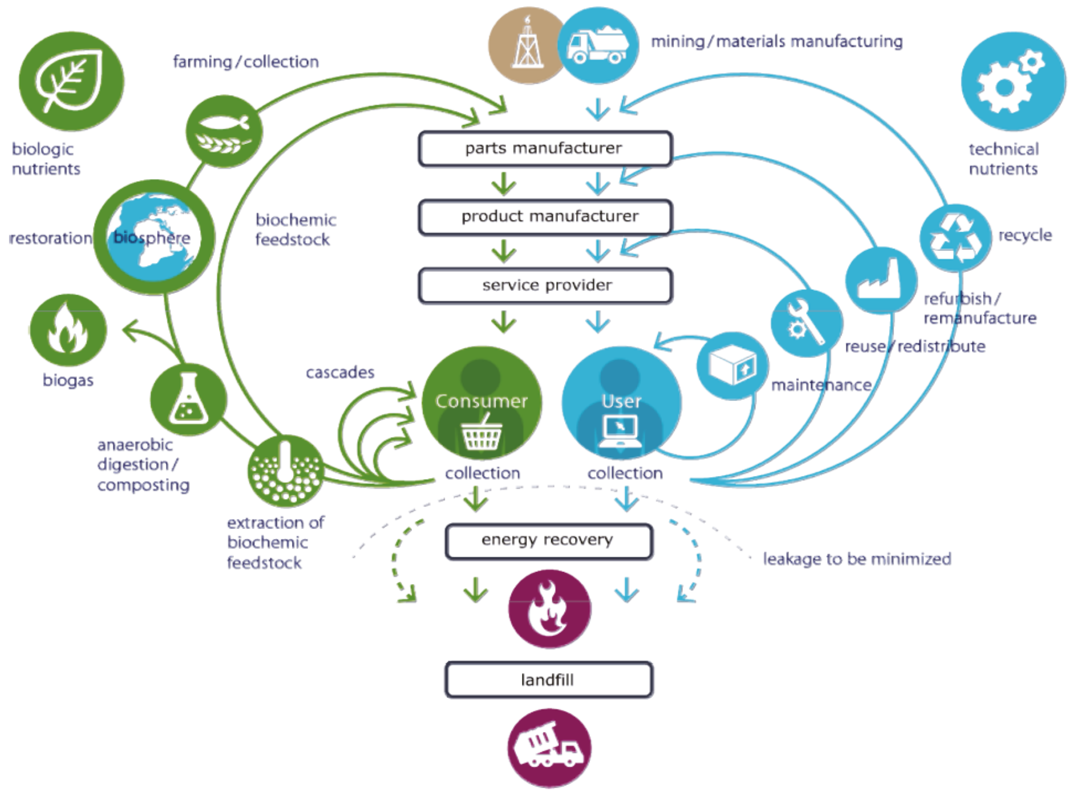

Figure 1. The Butterfly model for circular production and consumption, as proposed by the Ellen MacArthur Foundation (adapted from Gallaud & Laperche, 2016, p. 3)

An important principle of the circular economy is to maximise the life-span of all products, materials and components through increasing the number of cycles they go through (Ellen MacArthur Foundation, 2015). The first-order priority is to keep specialized products at the inner circle, maintaining its use-value. Recycling retains the technical nutrients, the bits and bolts, intact as lower-grade components, but reduces the use-value and requires the combination of other or virgin materials for its re-utilisation. The ultimate aim is to minimize the disposal of minerals and materials into the lithosphere and reducing the absolute demand for virgin resource extraction.

Many scholars and policy experts have studied the circular economy merely as a question of waste management optimization, defined by material and waste flows. The emphasis has been on reducing the lower levels of material treatment, such as energy recovery and landfilling. Many recent circular economy studies refer to the simplified 3R framework of "Reduce, Reuse and Recycle" (Geisendorf & Pietrulla, 2017, p. 5). The first R – reduce – deals with the resource intensity of production and aims at input factor reductions. The second R – reuse – aims to enable disassembly and repurposing of products and their business models. The third R –

recycle – refers to the recycling of raw materials and substances for reprocessing into new or re-purposed products and components (Geisendorf & Pietrulla, 2017, p. 6-8).

Regenerative by design: industrial ecology

This paper employs a more deep-rooted ontology of the circular economy. Here, besides creating systems for recycling materials, the circular economy represents a new paradigm of the economic system that is regenerative by design with the restorative use of resources at its core (Geisendorf & Pietrulla, 2017; Ellen MacArthur Foundation, 2015). The embeddedness of the circular economy within ecology requires a deeper understanding of the relations between the natural and human systems. This paradigm opposes the dominant linear paradigm, dominated by "single-use, programmed obsolescence, downcycling, legacy substances or loss of value" (Thelen et al., 2018, p. 6). The current economic modus operandi has evolved from its origins in the industrial revolution, based on a production line and vertically integrated value chains slowly evolving into global supply networks, traded across the world. In this model, natural resources are taken out of the lithosphere, to make products for single consumption, before being wasted at the end of use. This is what is referred to as the "take-make-waste"-economy (Ellen MacArthur Foundation, 2015).

According to its advocates, a circular economy will enhance nature's capacity to circulate nutrient flows within the system before returning them to the lithosphere and as input to the biosphere at large. Industrial ecology, biomimicry and industrial symbiosis are suggested as concepts to describe this process (Gallaud & Laperche, 2016). A circular industrial system imitates the natural environment where energy, water, waste and by-products are exchanged across the supply chain and constantly reutilised by others in a value cycle (Gallaud & Laperche, 2016, p. 22). The residues of production A serve as input for production B (Gallaud & Laperche, 2016). This builds on ideas of a self-organising Earth System where waste streams in one system become new energy and nutrients in another (Lenton & Latour, 2018, p. 1067). To avoid depleting our resource base, the challenge now is to design our economy based on these same principles, an economy regenerative by design. (Lenton & Latour, 2018).

Envisioning the circular: A funnel model

How can we achieve a strategic shift towards this design, based on circular economy principles, within our built environment? One can approach this from a broader perspective.

Fundamentally, the circular economy is about transitioning into a sustainable system, categorised by a low resource extraction to economic activity-ratio. This is essentially about reducing the material intensity or throughput and thereby the footprint on natural systems. Some scholars argue for adopting a systemic approach to moving towards sustainability. According to Broman and Robèrt (2013), we should shift our attention to general sustainability principles and establish universal and long-term visions of the circular economy.

The funnel-model (Figure 2) is proposed as a tool to this end. This allows the agent, industry or institution in question to visualise the route from the current, linear state towards a sustainable, circular state. The end-goal however, like most organisational visions, is not necessarily reachable. Rather it provides a compass to guide the choice of direction (Muñoz, Gladek, & Kennedy, 2016). The metaphor of a funnel is used by Broman and Robèrt (2017) to capture how the room for manoeuvre is funnelling into a narrower range, as planetary boundaries of the Earth System or its sub-systems are approached.

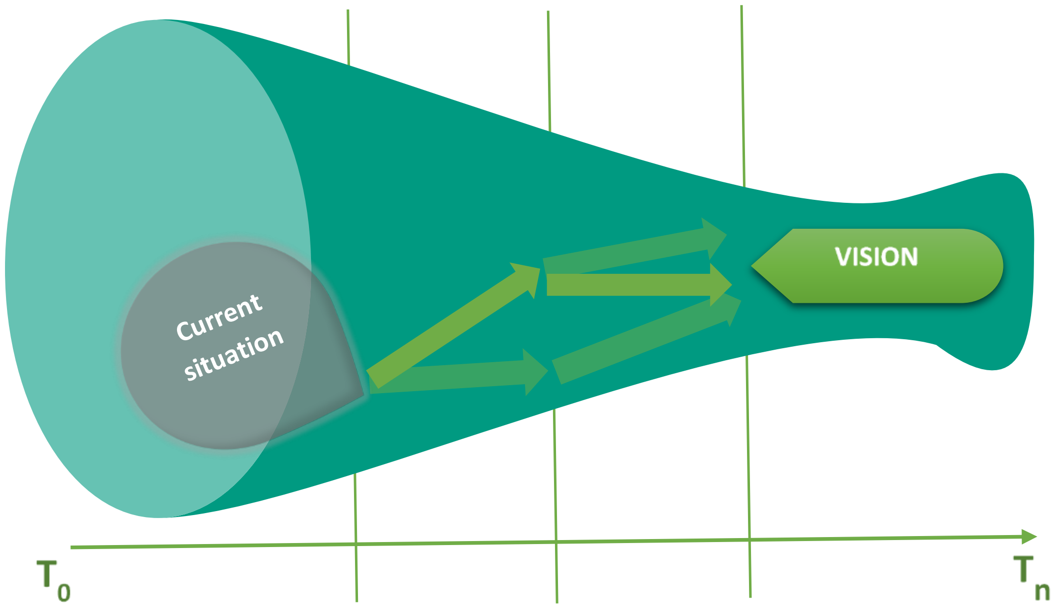

Figure 2. The funnel of future resource extraction industries (adapted from Broman & Robèrt, 2017).

At a micro level, hitting the funnel wall does not simply represent the collapse of an organisation's resource base. It also represents an increasingly tight business environment of legislation and regulation, as well as rising resource, insurance and credit costs and risks of lawsuits and fines. Fundamentally, the funnel allows a company to see where a sustainability-driven market is evolving. The individual entity or entire industry can conjure self-benefit by being an early-mover into new, green markets, besides reducing direct risks and costs (Broman and Robèrt, 2017).

The model has three analytical components. First, the steepness of the funnel walls illustrates the overall shape of the evolving market and legislative situation. Second, the time-dimension is given on the x-axis, which is made to represent a time-span of three policy periods. The time-horizon is set to 35 years, as this is the timespan for most climate and environmental goals today, starting from the empirically well-established situation in 2015. The third component is the web of arrows signifying alternative pathways for the organisation in question to approach the vision. The circle represents the "current situation" of operations, where the pointy end indicates the direction based on current trends. If an organisation is in a direction towards the funnel walls, it ought to shift course. There are, as with all future scenarios, multiple pathways that can lead to the vision, so the strategic dimension becomes to choose the most effective and feasible circular practices within the boundaries and context of the organisation.

Systems analysis

The transition from linear material streams to circular must be understood in its context of nested value streams and exchanges that make up the building industry. These streams can also be described as a social and economic system. This is commonplace in most contemporary organizational and business studies, as well as actor-network and stakeholder analyses. An epistemological systems-thinking is inherent to a range of social theories, from sociologist Niklas Luhmann's theory of autopoietic systems to Organisational Theory's isomorphism of organisational development and the resource dependency theory of Business Strategy. Over the last decades, systems analyses have been successfully applied by many managers, political leaders as well as academics (Kennedy, Gladek, & Roemers, 2018; Kubbinga et al., 2018; Meadows, 2008).

A system is a complex set of interrelations between its constituent elements. According to Systems Theory scholar Donella Meadows, all systems are comprised of elements, interconnections and purpose. In this definition, a system is an "interconnected set of elements that is coherently interconnected and organized in a way which produces a pattern of behaviours over time" (Meadows, 2001). Common to most academic studies is that they define the unit of analysis, such as an individual business, in relation to other elements and that the analysis centres on their interrelationships. Here, the individual business is the element, operating within a market environment, interacting with other elements in this system. By this definition, what then is not a system? Meadows (2008) argues that for example, when an organism dies, it loses its "system-ness" and becomes a conglomeration of individual parts "without any particular interconnections or function" (Meadows, 2008, p. 11). In this way, a building can be defined as a system, while a building window simply is glass, once disassembled from the building wall.

To Meadows (2008) systems thinking is the prescription to most of our societal ills, not least environmental degradation. "When the world is more messy, more crowded, more interconnected, more interdependent, and more rapidly changing than ever before we need to think in systems in order to grasp the causal mechanisms of the phenomena we are studying," Meadows (2008) maintain. Systems thinking prescribes holism as a tool for problem-solving, where the system is seen as more than the sum of its parts and interventions address the system as a whole (Kennedy et al., 2018). Fundamentally, this kind of systems perspective can ensure that we solve root causes rather than merely mitigating symptoms, such as reducing resource intensity, not just extracting more efficiently. It can stop us from shifting the problem to another part of the system, such as shifting the emissions from one part of the value chain to another. And finally, it can allow us to identify potential for synergies and collaboration across the system, triggering a domino effect for all actors to benefit from (Thorin, Blok, Voelkers, & Voss, 2017).

In this paper, the element, a port, is analysed as it exists in the interconnected web of material streams in an urban building industry context. Yet systems are often hard to describe analytically, as they transgress micro- and macro-levels of analysis and do not adhere to a single taxonomy of geographical or social categories. As such, the behaviour of these interconnected systems is very difficult to predict. In order to assess the capacity of change or the direction of a transition within a specified system, one needs to understand "what causes the system to function the way it does" (Kennedy et al., 2018). This leads us to the question of *how* the system functions.

As mentioned above, a system is defined by its elements, interconnections and functions. The elements are the most obvious pars of the system as they are often tangible and visible objects, such as the roots of a tree, or the subsidiary of a large company. Often elements interact with and affect each other. As such there are clear interconnections. These are sometimes visible through physical flows, such as flows of money or products between subsidiaries, but also appear as intangible flows, such as the exchange of nutrients or information and knowledge sharing. The functions of a system are often the most intangible and unintelligible aspect of a system. It is most easily accessible by observing the operations of the system (Meadows, 2008, pp. 12-17). Central to Meadows' (2008) theory of the system is that changes in the connections and functions of systems will have a great impact on the operations of the system as a whole. This implies for example that changing the direction and strength of material flows might impact a system more than changes in the composition of actors that operate them (Meadows, 2008).

Understanding the behaviour of a system is an exercise of tracing the stocks and flows that it generates, as well as understanding their feedback loops and delays. A stock is the accumulation of the system elements that have built up over time. Flows are the inflow and outflow of materials into the system stock. The size of the stocks changes with the strength of the flows into and out of the system (Meadows, 2008). Figure 3 shows a graphical illustration of a single stock and double-stock system. The "clouds" on both sides of the stock represent resource extraction and disposal. The arrows represent the size and direction of flows. This model shows how the direction and size of the flows impact the stock and how the composition of stocks affect the dynamics of the system.

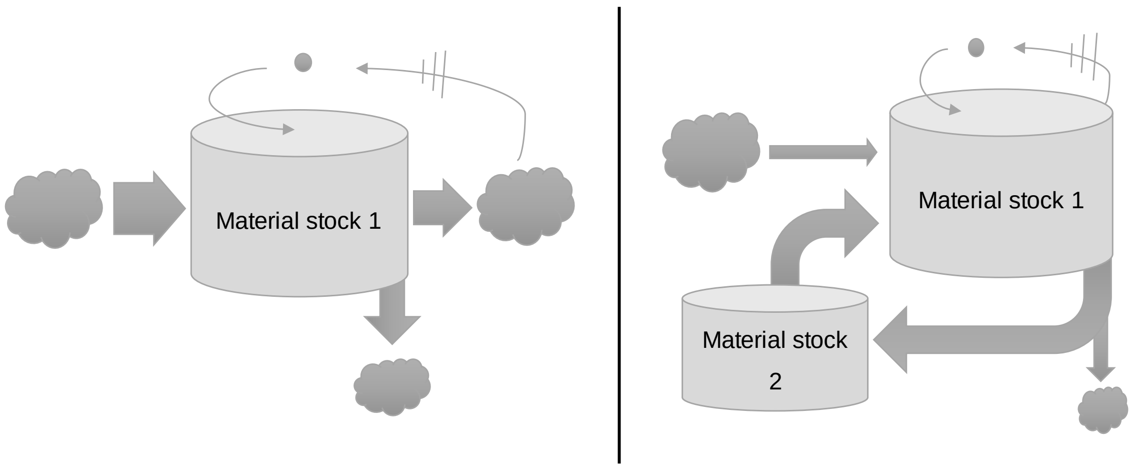

Figure 3. A simplified model of a single-stock (left) and two-stock (right) systems, illustrating stocks and flows in the built environment (adapted from Meadows, 2008).

One insight from Systems Theory, says Meadows (2008), is that if you see a persistent behaviour over time, there likely exists an underlying causal mechanism. Two of these mechanisms are what she labels "feedback loops" and "delays". Feedback loops can work to reinforce the strength of a flow, to stabilize and balance them or to drain the stock. As such, the stabilization of a stock within a given range or the growth and decline of stocks are driven by feedback loops internal to the system. However, these loops might in themselves be changed as a result of changes to the size of the stock itself (Meadows, 2008, p. 26). Stocks work as delays or buffers that can absorb sudden changes in the flows. As such the strength of inflows might temporarily be decoupled from the strength of the outflow. In the model, the small arrows illustrate feedback loops reinforcing flows from one stock to another, with a delay. As such, a theoretical proposition is that small changes in the driver, such as construction activity, might significantly impact the inflow of materials for construction, with a delay, without significantly altering the outflow of used materials. On the other hand, a change to the functions of the construction sector, such as to loop materials in cycles, might significantly alter both flows.

Summary of relevant theory

The circular economy is regenerative by design and loops material cycles so that waste outflows are minimized. Industrial Ecology seeks to solve this by taking nature's best recycling and looping strategies into industrial production systems. A system is more than just its constituent elements. Understanding the entire system, its inner dynamics, and its interactions with the surroundings are essential for effectively transitioning to a circular economy. Systems analysis and dynamic models are most useful to understand the present and future dynamics of a system. This analysis can help identify what parts of the system are not operating according to political objectives or sustainability principles. If so, the systems analysis will pinpoint a few places to intervene in the system where changes need to occur (Thorin et al., 2017). This Meadows (2008) refers to as leverage points: "Places within a value chain where a small intervention can produce big changes". These are characterised by having a key influence on the system, and if altered could create ramifications for the whole system. Finally, the funnel model can be used to visualize a step-wise approach towards a sustainability vision which seeks to shift system dynamics preventing negative outcomes, "which would perpetuate over time without systemic change" (Kennedy et al., 2018, p. 44).

Previous research

In order to study the material flows of the construction industry, one must at the same time understand the building, at the lower level of abstraction, and its larger built environment. The built environment is a broad concept and usually refers to all man-made structures in the cultural landscape, ranging from temporary structures for personal shelter to neighbourhood projects in sprawling cities and concrete-steel high-rise complexes. As such the circular economy needs to be defined in this rather unique context. The building industry is often identified as one of the least circular industries and disentangling the material knots of the building industry is impossible without first understanding its integrated supply and value chains. In this review of recent related literature, the paper's core analytical concepts such as 'urban metabolism, 'circular buildings' and 'circular value cycles' are explained and some of the most recent research on circular construction is presented.

Research on the urban metabolism of built environments

Urban metabolism refers to "the balanced flows of energy and materials between the human and natural subsystems of the material realm" (Hu, 2010). In any metabolic cycle inflows of raw materials are consumed by system-processes, in turn generating outflows of waste residues. The concept borrows from the 1815 application of the metabolism to refer to the nutritional process within the human body (Hu, 2010). In an urban system characterized by a high metabolic profile, it is important to consider where materials come from, how they are transported and what their destination is. Establishing a city's metabolic profile can aid in understanding ecological footprints, the resilience of resource flows and to see changes over time. Scholarly attention to this kind of urban ecosystem is relatively new and a standardised methodological approach is yet to emerge (Hu, 2010; Sartori, Bergsdal, Muller, & Brattebø, 2008). Here, pioneering work on mapping material flows in the construction sector and identifying circularity potential in cities are presented.

Studying the effects of European recovery targets on Construction and Demolition Waste (CDW) management, Arm and colleagues (2017) investigate the recovery rate for concrete, bricks, tiles and mortar waste in the Nordic countries. Between 2011 and 2013, Arm and colleagues (2017) estimate that a total of 710 000 - 840 000 tons waste was generated from all construction activity, where roughly 664 000 – 747 000 tons were from building activity alone. In this timespan, the recovery rate from building activities was 79 – 84 %, however backfilling was the clearly most prevalent, making up around 89 % of the total. They find that the most dominant construction waste management strategy is downcycling, where concrete and other mineral materials are homogenised, crushed and subsequently used as aggregates in unbound layers in roads, in new concrete production, as drainage layers at landfills or as backfilling of construction sites (Arm et al., 2017, p. 1495). Recovering tiles, bricks and ceramics occurs, although at a very low rate, and also these materials are mainly downcycled for backfilling.

In a circular economy report on the Dutch city of Rotterdam, Gladek and colleagues (2018) perform a material flow analysis of the construction sector. They find nearly 386 000 tons of materials enter the industry as building material inputs annually (Gladek, Roemers, de Winter, & Dufourmont, 2018, p. 14). As a general rule they see demolition following the trajectory of new construction floor area: Where roughly 247 300 m^2 new buildings were erected, 238 300 m^2 were demolished (Gladek et al., 2018). Construction of housing and commercial buildings demanded around 225 000 tons of concrete. Demolition of buildings produced 386 500 tons of waste, where almost 87 % were downcycled into lower value materials, landfilled or incinerated. Only some 19 700 tons (around 5 %) were fully recovered. In conclusion, they maintain that more materials must be designed for longer lifespans, high-quality reuse and resold at secondary material markets. They stress that renovation must be prioritized over demolition, issuing fewer demolition permits (Gladek et al., 2018). They point to the role of a central construction hub where materials can be temporarily stored, accessed by new developers and re-used in new construction.

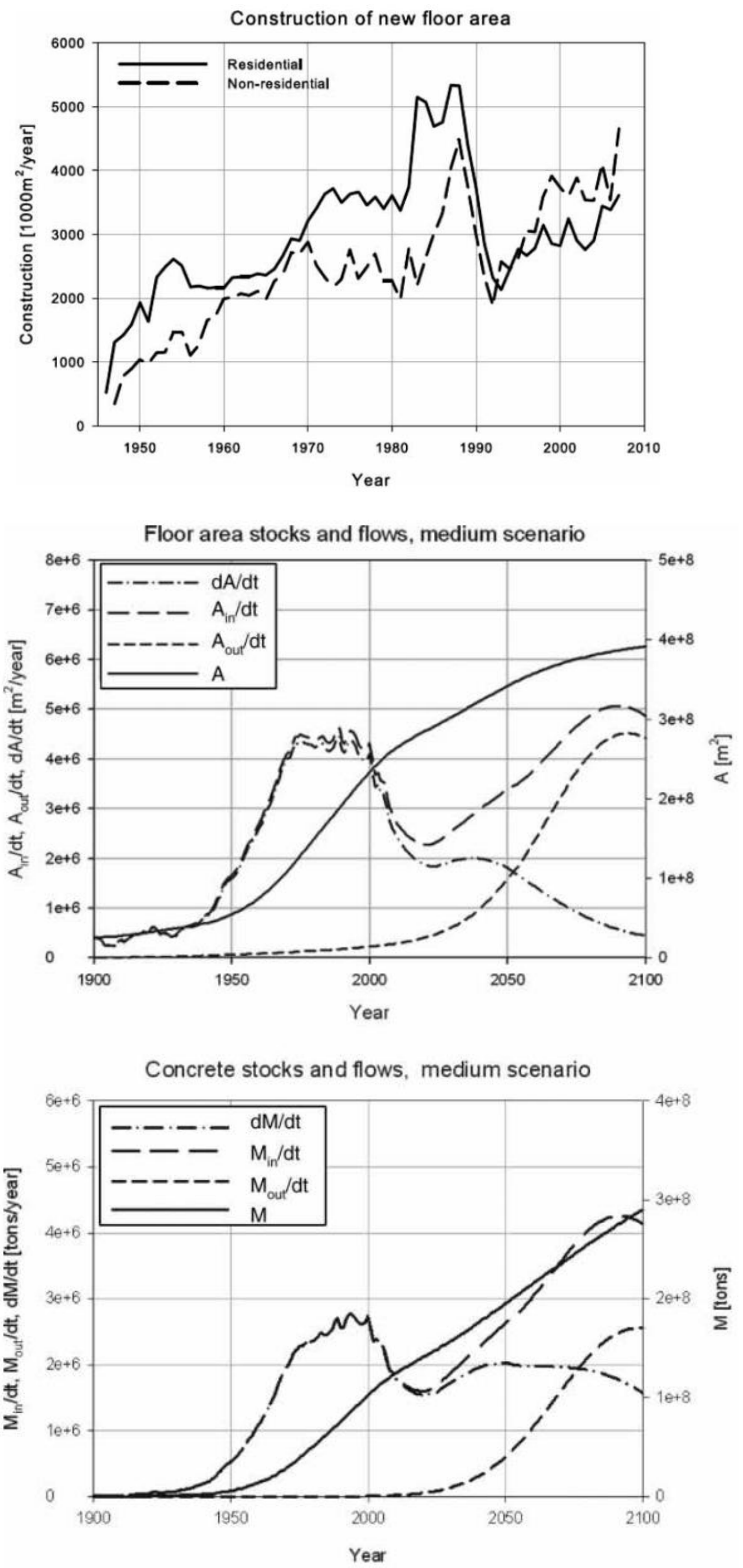

Figure 4. Historical construction activity by type. The correlation between construction activity and material flows (adapted from Brattebø et al., 2009, p. 575)

Brattebø, Bergsdal, Sandberg, Hammervold & Müller (2009) propose a framework for exploring the built environment metabolism and material flows. They divide the built environment into three subsystems: 1) residential buildings, 2) non-residential buildings and 3) infrastructure, and define them as interchangeable stocks (Brattebø, Bergsdal, Sandberg, Hammervold, & Müller, 2009, p. 573). The upper panel of Figure 4 shows that historically, the construction of residential buildings and non-residential buildings are highly correlated. Furthermore, growth in floor area appears to be a driver of material demand. In the middle and lower panel, historical data for floor area and inflows of concrete are compared and forecasted, based on a middle scenario for construction over the next century. The model suggests that concrete stocks will continue to increase over the century, while the input-output ratio reduces slightly as more concrete exits the system. Concrete inflow is modelled to hit a floor around 2025 before increased construction causes flows to increase again. The model assumes in parameters such as building lifetimes and the material density of buildings will follow trajectories of current trends into the future (Brattebø et al., 2009, p. 575).

Studying the built environment of dwellings in Norway, Sartori and colleagues (2008) develop a dynamic stock model to estimate both retrospective construction stocks since 1900, and prospective flows, modelling future construction, renovation and demolition activities up to the next century. The model estimates future activity based on a low, medium and high scenario for input parameters such as population growth, persons per dwelling and average dwelling size. In general, their modelling finds that the total Norwegian building stock is expected to increase by one-third of its current size within the next century (Sartori et al., 2008). The predicted development in construction, renovation and demolition activities in a low and high building lifetime scenario. In a low lifetime scenario, new construction activity increases significantly after 2015, with an associated increase in demolition activity. In the high lifetime scenario, renovation quickly overtakes new construction as the dominant activity and peaks around 2030. Demolition activity is significantly reduced but increases into the 22nd century. They conclude that on a country-basis "construction activity is expected to slow down in the coming decades" (Sartori et al., 2008, p. 424). They expect that a new construction boom will occur around mid-century unless current dwelling lifetimes are extended significantly through renovation.

In a comparative study on dwelling construction in Beijing, the Netherlands and Norway, similar conclusions are reached. Comparing the historical stock-flow dynamics it was found the per capita floor area is the key driver for the material inflows (Hu, van der Voet, & Huppes, 2010). Modelling material demand into the future, they predict that the average concrete intensity (the tonnes per square meter floor area [t/m^2]) for dwellings in Norway would remain relatively stable at 0.7 t/m^2, significantly lower than in most countries (Hu et al., 2010). Analysing three different scenarios for Beijing's construction activity, they show that volumes of concrete CDW are closely correlated with inflow volumes, with a delay equal to the lifetime of dwellings. Given this insight, they generalize the claim that prolonging the dwelling stocks lifetime through renovation activity can postpone CDW flow peaks in a growing city (Hu et al., 2010, p. 440). Even with a 168% increase of total floor space area in Beijing, concrete inflow only increases 25 % and outflow with an 82%, in a long life-scenario for concrete compared to 83% and 474% respectively, in the reference scenario (Hu et al., 2010, p. 451).

Studying future waste-streams from the construction and demolition-sector in Norway, Bergsdal, Bohne & Brattebø (2007) make "projections on flows of waste materials leaving the stocks in use and moving into the waste management system" provided waste generation factor for each type of construction material, based on the kind of construction work. (Bergsdal, Bohne & Brattebø, 2007, p. 28). They conclude that waste flows are to increase up to 2020 on a country-basis, but that new construction on a national basis is in decline. Yet, the most waste intensive construction work, demolition, grows throughout the century as more buildings approach end-of-life. They also conclude that all types of construction work on average are at a higher level in the biggest counties in Norway. They also identify that the main contributor to CDW is and will continue to be the concrete and bricks fraction, which was expected to increase fourfold over the period 2010-2020 (Bergsdal et al., 2007).

Envisioning the circular building

A circular built environment is often defined in opposition to the current linear model. Central to this transition is the challenge imposed by the traditional practice (Thelen et al., 2018). In a take-make-dispose building value chain, finite, non-renewable raw materials are extracted, manufactured into composite building components and assembled permanently in building complexes for its life duration (Thelen et al., 2018; Zuidema, 2017). Large volumes of raw materials become permanently entangled into the frame of the building, where new elements are steeped on top of it. In this linear model, material downcycling is predominant. Approaching end-of-life, the building is demolished, rubble and shattered materials collected and either sent for disposal or used in low-value applications such as backfilling. This is regarded as the lowest-value strategy in the circular economy materials management, as materials are permanently lost for future use (Thelen et al., 2018, p. 6).

A circular building, on the other hand, is defined as: “A building that is developed, used and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation. Technical elements are demountable and reusable, and biological elements can also be brought back into the biological cycle.” (Kubbinga et al., 2018, p. 11). According to the Norwegian sustainable building consortium Future Built a circular building “allows for resource utilization at the highest possible levels and consist of at least 50% re-used and reusable materials and components” (Future Built, 2019, p. 3). Here, ‘reduction’ is defined as “planning buildings so that you reduce resource consumption and waste generation” and reuse means “to retain or refurbish a building over demolishing it, or to re-utilize used building components” (Future Built, 2019, p. 4). According to one of the authors, the key is to “design for things that can be taken apart and avoid composite solutions… it’s a process of awareness-raising [about reusability]” (Informant 1, in conversation on 08.03.2019).

In the future, all buildings are circular by design and materials are made for re-use. A circular building consists of minimum 20% re-used materials and is designed for disassembly at the end-of-life. According to the 2050 predictions by the national environmental fund ENOVA, refurbishment and renovation activity have increased substantially by 2050 (ENOVA, 2015, p. 86). In the real estate sector’s own roadmap to 2050, they develop a scenario-based ideal vision for the sector labelled Vision 2050 (Grønn Byggallianse & Norsk Eiendom, 2016). According to them, all buildings will be climate and environmentally neutral, causing no more harm than it produces benefits. All floor spaces will be utilized effectively and for multiple purposes. Buildings are demountable, and materials are reused. Virgin materials are seldom used, and material upcycling is the norm. It also stresses that “all technology [in buildings] must go along with the circular economy,” signifying that no “smart connectivity” ought to hinder disassembly (Grønn Byggallianse & Norsk Eiendom, 2016, p. 28). Taken together, the principles of a circular building can be summarised in terms of five “visions” (Fischer, 2019):

1. Resource extraction from the lithosphere is minimised
2. All buildings have flexible use and are reusable
3. Buildings are designed for longevity and durability
4. The disassembly and reuse of materials and components is facilitated
5. Regenerative utilization of space, energy and materials

Form linear to circular value chains in the building industry

Fully comprehending how the building industry works, and more importantly, how it can be shifted towards more circular and sustainable practices requires viewing it as a coherent system. One needs to have an industry-perspective, identify constitutive business-entities making up the industry and understand the system dynamics within the industrial network. Only through such a systemic approach, can you achieve circulating the materials produced and consumed by the industry. According to circular building consultant Remko Zuidema (2017), a key barrier to more circular building practices lies in the fragmented nature of the building value chain. Each actor has its own stake in a building, and most have incongruent interests to the others. Zuidema (2017) holds that we are currently operating in a highly linear value chain, where each actor operates in isolation within its part of the chain or layer of the building. The best way to illustrate that the construction industry value chain ought to be viewed in terms of a system, not seeing industry actors as isolated entities, is to trace the flows of natural resources flowing throughout the industry.

In Figure 6, this complex actor-network is depicted as they operate within the construction value chain. It characterises the actors and illustrates their involvement with each other. The white arrows represent flows of residual materials from previous activity in the value chain. It clearly illustrates how secondary material flows would supersede conventional industry division of labour and how the value chain would have to interact to achieve circular practices. In the cycle of a single material category, actors would engage with each other throughout the value chain, operate across disciplines and follow the building process through its stages. Doing this enables what Zuidema (2017) considers new forms of partnerships and contracts between building actors.

Raw mineral extractors engage in the global market for natural resources, such as stone, gravel and sand. Crude materials are then transported from mines and sold to manufacturers of building products and components, who through a supplier network, sell refined products to construction contractors (Zuidema, 2017, p. 16). Contractors and developers then assemble the components "according to the demands of real estate investors and housing corporations, on the advice of architects and consultants" (Zuidema, 2017).

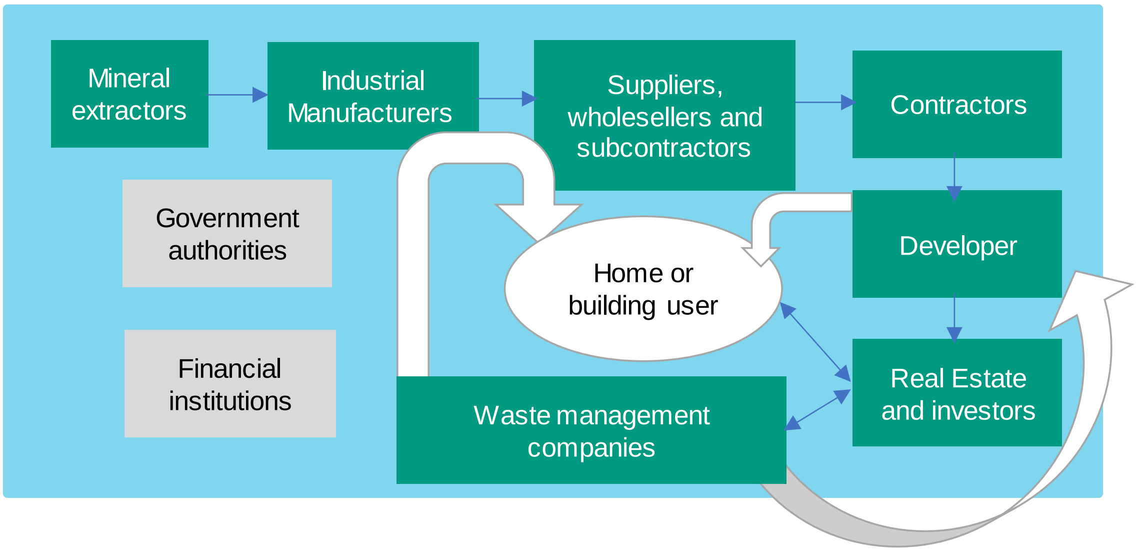

Figure 6. Generic stakeholder map in the construction value chain

A few intermediary and administrative actors are highlighted by industry experts as key gatekeepers in enabling the circular building industry (Thelen et al., 2018, p. 22). There are the specialized suppliers and vendors, who sell (and sometimes re-sell) building components, products and materials to the contractors and building companies. There are also wholesalers who indirectly enter the building market, buying "large quantities of goods from various producers or vendors and resell these to traders and end clients" (Thelen et al., 2018, p. 22). They also buy and sell larger prefabricated building structures, often outside of the standardised construction market. Finally, administrators, government bodies and financial institutions intervene throughout the building process for different purposes. These have vital functions in regulating the construction, building and housing markets, through various incentives, financial or oversight-functions (Thelen et al., 2018).

Ports as circularity hubs in international supply chains

A natural next step is to consider the geographical scale of construction industry value chains and transport logistics. No other process has been more profound to the current composition of value chains, than economic globalization. The globalization of industries, production and material streams have meant that most industrial value chains today are global in scope. But all goods on the international market needs to be transported, and the easiest means of doing this over long distances is by sea. The globalization of construction materials production over the last decades have meant that ports attain an increasingly important role in their supply chain. While building projects and construction works are highly localized, the materials that go into them are entwined in increasingly global value chains. Ports are key nodes in the logistic systems of global supply chains and are today natural gateways for many building-related materials (Hatteland, 2010, p. 47). By one estimation, major world ports now handle more than 15 billion tons of goods each year (United Nations Committee on Trade and Development, UNCTAD, 2018, p. 65). On the other hand, the structure of supply chains has also shifted, impacting port operations. A shift to more circular supply chains may represent a significant change to flows of goods to ports.

de Langen & Sornn-Friese (2019) investigate how the ongoing circularity transition will impact port operations, and how some ports are already adapting to the new situation. They identify two key processes in the transition to a circular economy expected to impact trade flows at ports: 1) the move to a more territorialized renewable energy system, and 2) more localized, circular supply chains. The first effect reduces the relative share and absolute volumes of fossil fuels entering ports as liquid bulk, but also certain dry bulks, such as coal, the demand for which is expected to decrease rapidly. The second effect is to shift the international trade patterns. The goal of most circularity interventions is to move from linear, largely global value chains, to regionally closed-loop material cycles. de Langen and Sornn-Friese (2019) employ a typology of supply chains based on the geographical scale of material streams. Historically, most consumer good supply chains have moved from local community production and consumption to highly interconnected, global value chains (the thick arrow in the figure). Figure 7 illustrates two alternative future scenarios as product value chains become more circular.

As an example, one can consider the global trade in dry bulk, such as sand, rubble and metals. Dry bulk shipments have long been the backbone of most port operations. These material streams are however changing already as more and more materials are sent for recycling and remanufacturing, either locally or in regional waste management networks. As an example, glass and stone rubble are usually part of local and, if collected and sorted, largely circular value chains, representing the bottom-right corner of Figure 7. Certain types of plastics, metals in steel and cement are entering the top-right corner, produced in one country, utilized in a second and remanufactured or reutilized as input to new materials in a third country (de Langen & Sornn-Friese, 2019).

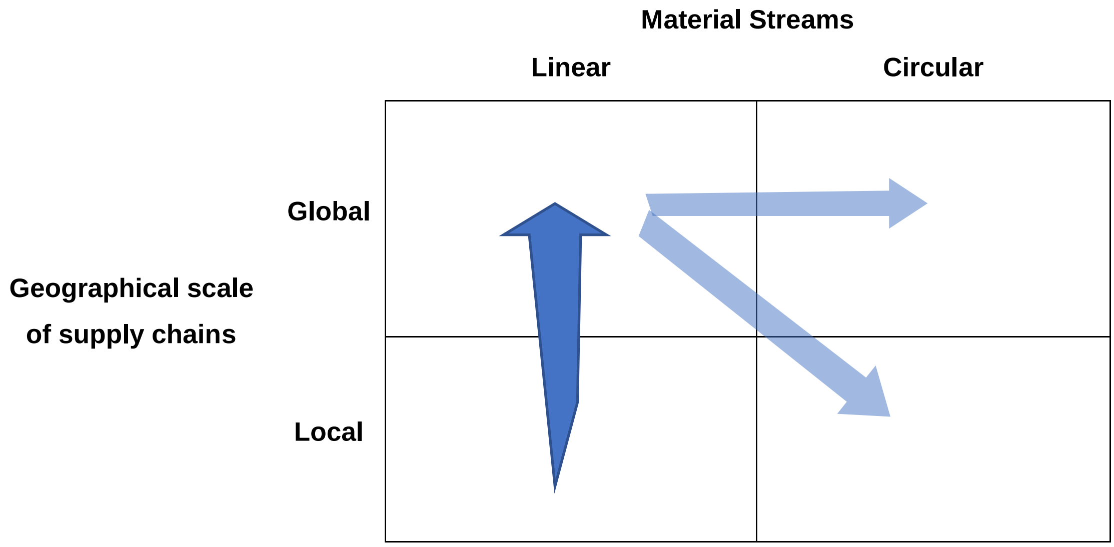

Figure 7. Four scale quadrants for supply chain categories (adapted from de Langen and Sornn-Friese, 2019, p. 6)

Summary of the literature

The built environment today is characterised by a large 'metabolic profile', meaning that there are large inflows and outflows of materials, that often end up as downcycled ground-filling or disposed of at landfills. Sartori et al. (2008) predicted construction and demolition waste to increase rapidly over the coming period, as the large new building stock constructed during the 1970s and '80s is demolished at end-of-life. The rate of activity in renovation and demolition is to increase rapidly over the next two decades depending on building lifetimes and renovation cycles. Bergsdal et al. (2007) predicted that concrete and brick waste would be the most significant fraction with a fourfold increase in waste generation over the previous period from 2010 to 2020 and continue to increase as the dwelling stock grows. Hu et al. (2010) and Sartori et al. (2008) concluded that extending dwelling lifetimes is a key lever to reducing material throughput and waste. Urban areas, from Oslo to Beijing, needs more attention to the way buildings are designed, used and treated at end-of-life and a greater understanding of how to re-utilize building layers will be key to this.

de Langen and Sornn-Friese (2019) have argued that ports can indeed be central to the transition to circular material streams and value cycles. Ports have three beneficial attributes: As logistical nodes for large volumes of materials, as gateway hubs for regional distribution and, potentially, as centres for industrial activity (Mangan et al, 2008 in Hatteland, 2010). Ports are at the centre of many global value chains, opening the potential for synergies between many industrial actors. By attracting circular economy activities and becoming material transmission and redistribution hubs, this vital transportation infrastructure can facilitate industries to operate in symbiosis. This will be especially key to the construction industry as it transitions from a linear value chain, with regional as well as international supply chains managing vast flows of materials, from distant mines via product manufacturers to suppliers and developers before they enter the final building.

Overview of empirical work

This part will describe the choice of the case for the case study. It will then present the case systematically based on analytical frameworks developed by previous literature. Here, the point is to identify the key actors involved and to discuss some of the mechanisms within the construction sector of Oslo, such as current material flows. The central goal will be to describe the context of the case to such a detail as to be able to apply all case-relevant variables to the analysis. Then a material flow and scenario analysis will be performed, based on official statistics and empirical data from reliable secondary sources, such as the Norwegian Burau of Statistics, Oslo Municipality and academic researchers.

Case selection

This paper utilizes a heuristic case study to illustrate the potential implications of adopting a circular construction city through port management. A heuristic case study is said to be hypothesis-generating to the degree it exploits the "author's familiarity with a given case to help generate new hypotheses or theories, which can subsequently be tested with a more rigorous design" (Moses & Knutsen, 2012, p. 140). The complexity of an open system such as the building industry it requires attention to both the company and industry level and demands interdisciplinary work "across economic, environmental, behavioural, societal, technological and governmental dimensions" (Stephan & Athanassiadis, 2018, p. 260). This can best be done in the smaller scale a specific case, where the author has a greater overview of the study context.

In this paper, the choice of case is based on two separate criteria. The first relates to the authors existing familiarity with the case context, namely the municipality of Oslo's climate and environment policy. The city of Oslo is chosen in part to convenience and in part to its interest as a global laboratory for climate action. Technically any port city in the developed world could have been chosen, but the availability of data and informants due to the proximity of the author played a central role. Secondly, Oslo is said to be a unique case internationally, while at one hand being conceived as a climate leader (Mills, 2016) and the other being a city facing significant city development and materials management challenges (Nersund Larsen et al., 2018; Informant 2 in conversation 22. March 2019). The case topic of the circular economy within the building sector related to flows of building materials is chosen in part due to its relevance in the current policy debate, and party because of its persistent listing as a priority sector for the interviewed stakeholders.

The Port of Oslo as an actor and materials hub

The Port of Oslo is a central actor in the material streams of Greater Oslo. It is the largest public goods and passenger port in Norway and defined as a back-bone port in the National Transportation Plan of the Department of Transport (Oslo Kommune, 2018a). It is described as the gateway and hub for freight to the entire Oslo-region, servicing more than one-quarter of the Norwegian population (Oslo Havn, 2013). It consists of two port areas: the city port (Byhavna) and the South Port (Sydhavna). Most of the flow of goods occurs in the southern port terminals, from Kongshavn to Nedre Bekkelaget (Oslo Havn, 2013, p. 5). The port and municipal boundaries are shown on the left side of Figure 8. The port will go through a significant transition over the next 10 years, embracing a modernisation and expansion of capacities at the port premises. Substantial areas of the current port operational zones (in yellow) will be transformed for urban development purposes (dark blue), while freight operations will be centralised around Sydhavna (Oslo Havn, 2013). The planned development is illustrated in red on the right-side illustration.

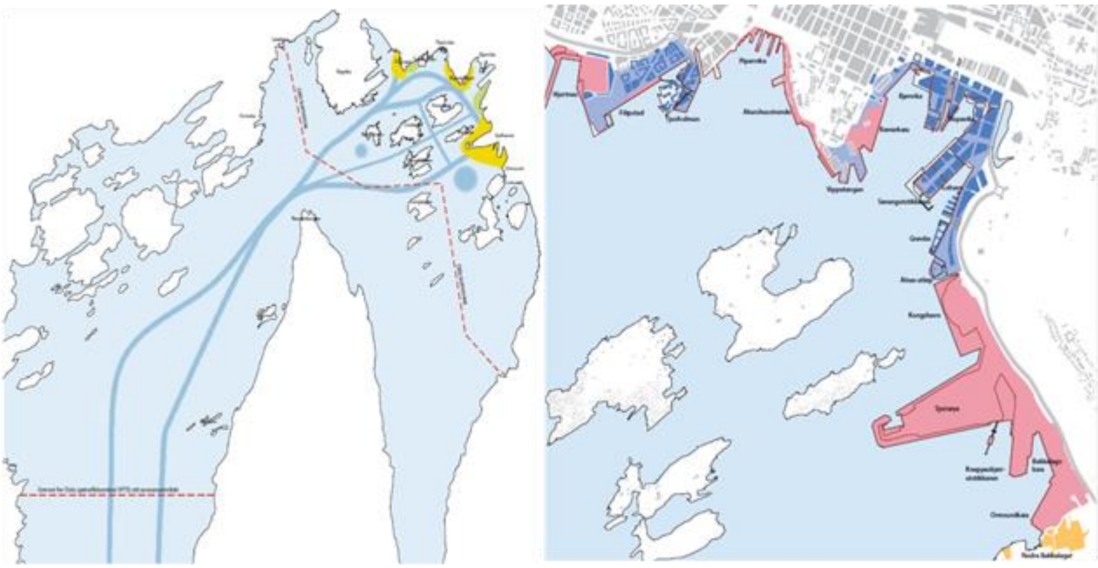

Figure 8. Left, port inner and outer boundaries (dotted red line) and main fairways (blue). Right, the port property development plan for 2000-2030. The red lines illustrate the current shape of the port area and the pink area illustrates the planned future port area in 2030 (adapted from Oslo Havn, 2013, p. 15-17)

Together with the municipality strategy for a zero-emissions port (Nullutslippshavnen), the “Port plan 2013-2030” provides six overall goals for the development of the port operations by 2030. The two main pillars of the plan are 1) to encourage a 50% growth in goods and 40% growth in passengers by 2030 as to “accommodate the population growth in the region” and 2) to transfer more cargo freight from road to sea (Oslo Havn, 2018). The ability to transport more cargo is stressed in the port’s letter of award, where around 5 million NOK will be allocated to this end over the years 2020-2022 (Oslo Kommune, 2019). In the period since 2013, the dry bulk segment has increased by 18%, mainly driven by urban development in the Oslo region (Oslo Havn, 2018). The dry bulk segment alone is predicted to grow by 31% by 2030, or an annualized 1.82 %, to more than 1 700 000 tons (Oslo Havn, 2013). This growth is predicted due to a large number of planned construction projects, while conditions for road transport are worsening.

The port authority is currently working with actors to increase the total capacity in Sydhavna. One such project is Skanska Industrial Solutions’ proposal for a new bulk- and recovery-terminal for residual building and infrastructure bulk at the Grønlia terminal (Oslo Havn, 2018). The aim is to “modernise and streamline dry-bulk management for adding capacity to these streams of goods” (Oslo Havn, 2018). Skanska Industrial Solutions sees this as a business opportunity, providing a competitive edge (Informant 4 in conversation XX. April

2019). Recycling is a core business in their portfolio already and they have significant experience in this field from development projects at Fornebu. They now see a significantly increased demand and interest in this kind of operations, especially with a new legislative agenda from the municipal and national authorities (Byggeindustrien, 2019; Brekkhus, 2018). The rationale for a new terminal at Grønlia would be the reception and management of locally generated mineral bulk, before treating it for re-use, ideally within the municipality. Unusable or residue materials are shipped out through the fjord. Skanska estimates a capacity to handle around 300 000 to 400 000 tons of bulk goods in the terminal per year (Informant 4 in conversation 3. April 2019).

Port dry bulk operations

Dry bulk freight is one of the largest segments of traded goods globally (UNCTAD, 2018). These are large quantities of non-liquid and unpackaged commodities transported in bulk. Dry bulk freight was the single largest fraction, accounting for almost half of world seaborne trade flows. Loads were estimated to 5.1 billion tons in 2017, which was an increase of 4% since 2016 and more than 38 % since 2000 (UNCTAD, 2018, p. 11). At the Port of Oslo, this segment represented over 30% of total freight in 2017 and is expected to grow 31% by 2030 (Port of Oslo, 2018). The Port of Oslo estimates that the total dry bulk segment amounted to 1.8 million tons in 2017, up 1.3% from 2016. The total inbound dry bulk material unloaded at the port was 1.6 million tons in 2017, constituting 88% of total loads (Oslo Havn, 2018). It is estimated that up to 70% of the total volumes are bound for Oslo’s construction industry (Oslo Kommune, 2018a, p. 37).

Dale, Stokke, Ljungberg, and Laugen (2018) find, in accordance with the illustration above, that road transport dominates this segment for short hauls. However, on distances longer than 18 km/ton, shipping constitutes around 53% of the total freight. The total seaborne imports of building-related materials to Oslo between 2010 and 2018 are illustrated in Figure 9. In a dry bulk freight case, it was estimated that the two main cement distributors, Norcem and Cemex, combined receive around 600 000 tons of cement at their Oslo Port terminals each year, making up around 60% of the regional market (Dale et al., 2018). As can be seen from the illustration of shipping routes in Figure 10, a large fraction of shipments originates in Europe (40%). Most shipments are from Brevik, Norway, followed by Rostock in eastern Germany.

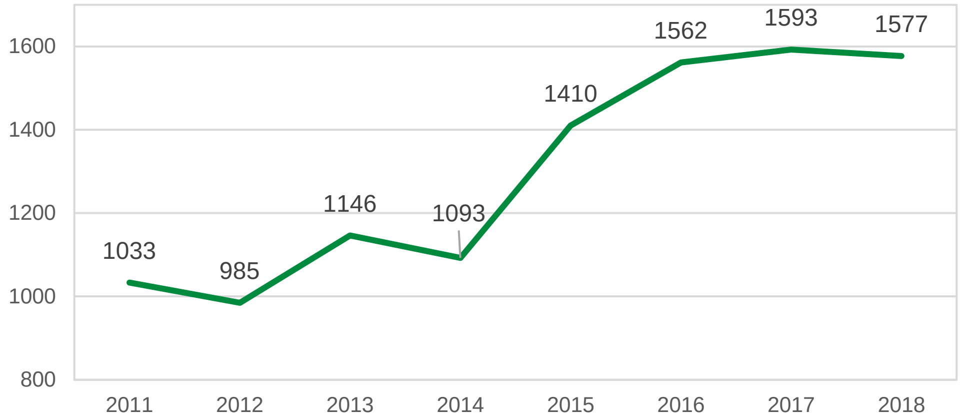

Figure 9. Total dry bulk cargo at the Port of Oslo, building-related materials (in 1000 tons, includes ores, stone, sand, gravel, clay, salt, cement, lime, fertiliser and manufactures; SSB, 2018)

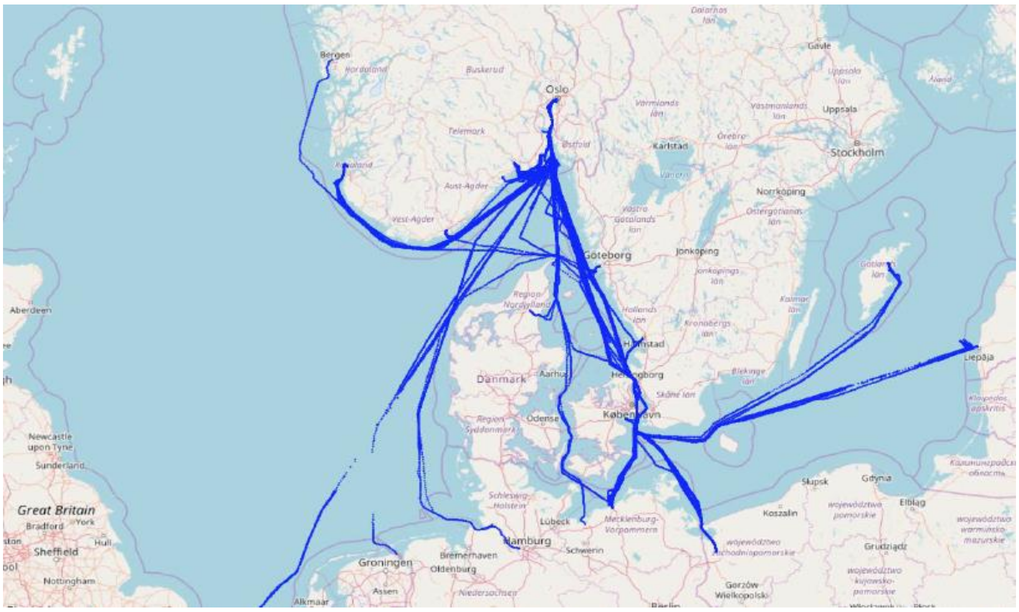

Figure 10. Overview of dry bulk shipments to and from the Port of Oslo in 2017 (adapted from Oslo Kommune, 2018a, p. 3)

Building material flows in Oslo

This brings us to the relevant case industry, namely the building industry in Oslo. This industry is simultaneously the greatest driver of dry bulk material demand and waste generation. The case study of Grønlia recovery terminal is relevant exactly because the logistics of this flow is a big challenge at present, with a high environmental footprint. Before, moving on to the analysis of system inflows and outflows, a closer look at the background for this persistent challenge is necessitated.

Current and future building activity in Oslo

Oslo's construction industry is relatively large in a national perspective and is expected to grow. Figure 11 below describes the growth in new dwelling floor space by type of dwelling since 2010. The figure shows that around 70% constitute large residential dwellings with more than five stories. The development for small dwellings is largely flat over the same period. According to the 2018 market report from construction consortium Entreprenørforeningen Bygg og Anlegg Oslo, Østfold & Akershus (EBA O, Ø & A, 2018) construction of new public and private offices has been at record levels, peaking at around 800 000 square meters new floor area in 2017, but is now expected to decline (EBA O, Ø & A, 2018).

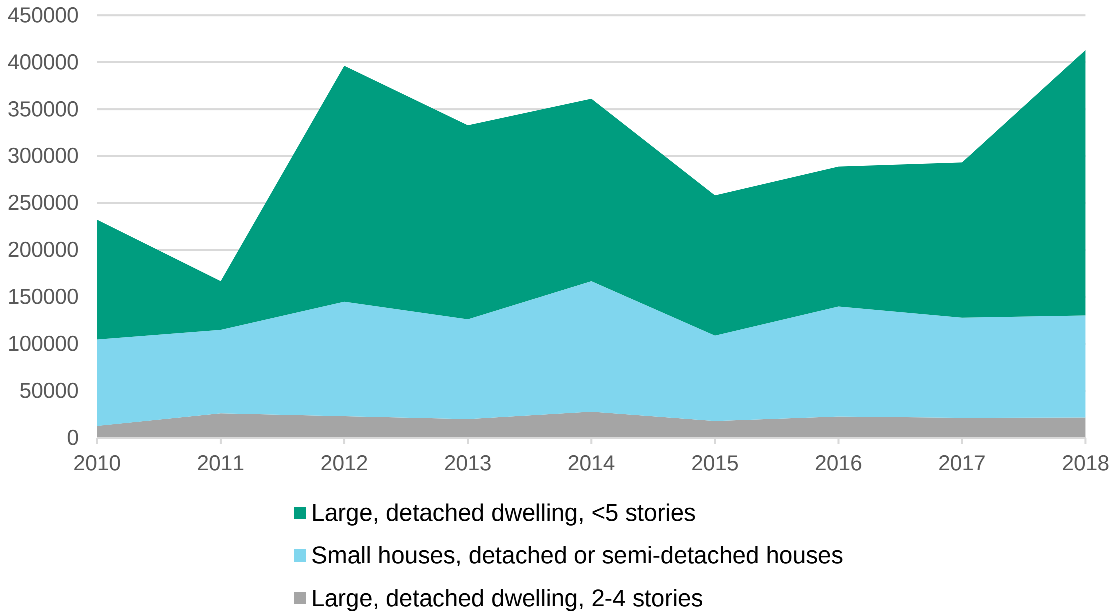

Figure 11. New floor space commissioned in that year in Oslo for large, semi-large and detached residential buildings in square meters (SSB, 2018)

Infrastructure projects are expected to increase its share over the next years, with several large public projects getting underway in the region but are currently minuscule. Construction material demand is expected to grow rapidly over the coming years. The Municipality of Oslo estimates that the construction sector will demand 12 million tons of new construction materials over the next 15 years (Skanska, 2018). Just between 2023 and 2030, increased construction activity will require over 1.6 million tons of concrete. Luleå University of Technology analysed the total bulk demand and supply from Oslo's dwelling sector from 2015 to 2030. They estimate that more than 2 million m^3 of construction materials flowed through Oslo in 2015 (Lundberg, Johansson, & Magnusson, 2016). They also conclude that at this point the total outflow outnumbered the inflow. Construction, renovation and demolition activity will generate between 4 and 5 million m^3 residue construction bulk by 2030, of which large residential buildings will be the largest source. They estimate that the total demand for primary gravel and concrete in 2015 was 255 000 m^3 (Lundberg et al., 2016). Assuming a population growth of 19.4 % as a middle scenario, they estimate that increased dwelling construction will require an additional 145 000 m^3 of gravel and concrete by 2030 (Lundberg et al., 2016).

The main driver of demand for construction material is the housing market. What matters here is the total amount of new floor space that is constructed to make dwellings. Dwellings today make out around 60 % of the total building mass in Oslo. Of this, large residential housing covers 75% of the total dwelling floor space and small detached houses 15% (Sandberg et al, 2018, p. 13). The Municipality of Oslo (2018b) estimate, based on official projections for population growth, that there will be a total of 52 050 new dwellings constructed up to 2029. A large part of this construction will occur in the early part of that period, with more than 8852 new dwellings commissioned to start construction in 2018. Further out in the period, activity is expected to flatten out to an average 3 300 dwellings constructed per year (Oslo Kommune, 2018b). Sandberg et al. (2018) predict the total dwelling floor space to increase by 35 % over the next 20 years. Their models show that the weight of the population living in large residential buildings compared to small houses is expected to increase, but marginally. By 2040, just half of the current building stock will still be in use, 25% of the current stock will be renovated and 25% will be new buildings (Sandberg et al, 2018, p. 14).

Regional construction bulk management

The Municipality of Oslo produces almost none of the material it consumes for construction activity within its own borders. Historically two quarries within Oslo have produced around one-quarter of the constructed-related materials consumed internally (Wolden, 2014). In 2019 only the Bånkall quarry is still in operation. Reduced production internally will increase the import of materials from the neighbouring regions from 75% to 80-90% (Akershus fylkeskommune, 2016, p. 15). This also means that a large quantity of construction materials come in from neighbouring areas through roads. Estimations by Norsk Geologisk Undersøkelse (NGU) for gravel, sand and stone material streams transported by road in 2011 illustrate the volumes of flows we are talking about. Figure 12 shows that Oslo in 2011 imported 849 000 tons of sand and gravel and 1.55 million tons of bulk stone materials respectively from neighbouring counties, flowing in through the regional road system (Wolden, 2014). Furthermore, between 2014-2040 Akershus and Oslo would need to exchange an additional 256 million tons of construction materials to maintain the current bulk balance (Wolden, 2014).

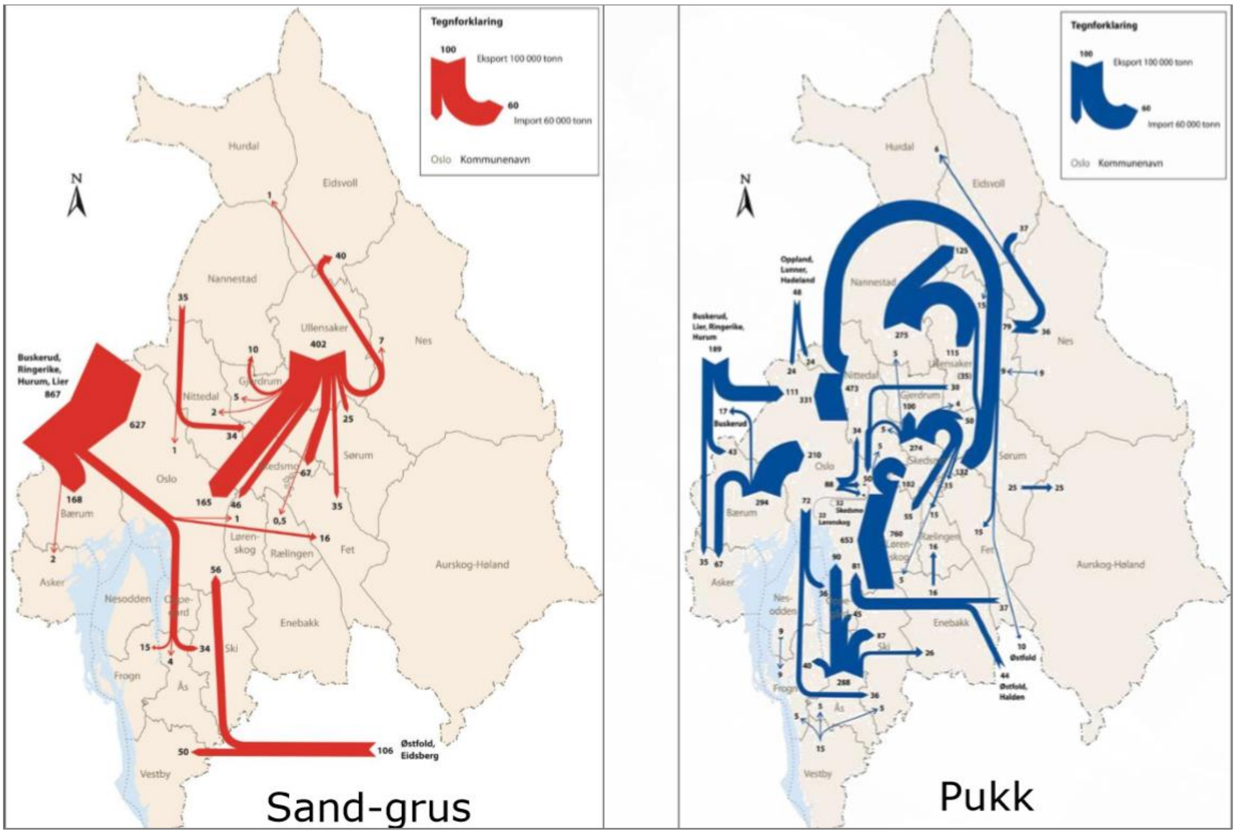

Figure 12. Material flow analysis of sand and gravel (red) and bulk stone (blue) in Oslo and Akershus counties, illustrating absolute volumes, their origin and destination in the year 2011 (all numbers in 1000 tons; adapted from Wolden, 2014)

Case study approach

This paper utilizes a heuristic case study methodology with scenario analysis of future possible outcomes in the case of Oslo. The purpose is to study how material and waste flows operate under different system models and to understand how to get circular economy policy leverage in this space. The principal objective is to map and describe the dominant flows within the system. This is done through a simple top-down flow-driven material flow analysis (MFA). The aim is to describe the "as-is" situation as a basis for future scenarios, indicating possible interventions. This is done through four sub-studies, where study 1 will map the system and set empirically determined system boundaries, study 2 will pinpoint the greatest environmental impacts within the system, study 3 identifies possible future outcomes through a scenario analysis, and study 4 discuss how policymakers can gain leverage on dry bulk inflows and outflows was collected from a range of sources, such as industry reports, national statistical databases and model calculations. The scenario analysis uses empirical data on both virgin and secondary resource-flows, and use specified input parameters to model future developments.

It is acknowledged that the explanatory power of a single-case study and scenario analysis is limited to indicate possible tendencies of input variables that can be expanded upon in a more generalisable model. A range of single cases can potentially be assembled, much like building components "into a stronger theoretical edifice" (Moses & Knutsen, 2012, p. 140). Such efforts have already been undertaken successfully in the context of urban sustainability, with Lamb, Creutzig, Callaghan, & Minx (2019) as a notable example. Here the emphasis is however on explaining a single outcome, where the narrow scope allows better analysis of "causal processes as they actually existed in the Real World, untainted by control techniques" (Moses & Knutsen, 2012, p. 135). The emphasis is not on general variables, but rather on specific contingencies that may or may not lead to a certain outcome.

Method

In this section, I utilise the theoretical concepts developed in the previous section to develop an analytical framework for the subsequent case study. First, I synthesize the gust of Systems Theory and the Framework for Strategic Sustainable Development (FSSD) to a step-by-step guide for the analysis. I do this in the order suggested by the FSSD, building on the work of Thorin, Blok, Voelkers and Voss (2017). Secondly, I explain the basic elements of the statistical method of scenario analysis, using a dynamic material flow model. Then I detail the purpose of, and the reasoning behind the use of case study methodology for this paper, before explaining the sources of the data and the data-collection process. Finally, I discuss the limitations of the methods and delimitations of the paper.

System analyses of circularity interventions

A system is more than just its elements. Understanding the entire system, its inner dynamics, and its interactions with the surroundings are essential for effectively transitioning to a circular economy. However, in order to systematically analyse the case study, the systems analysis is broken down into smaller functional units. Here, I will operationalise the system analysis and develop a dynamic systems model for understanding current and future flows of building materials associated with the building sector in Oslo.

The first step is to define the system by analysing the constituent elements, interconnections and functions of the system. Then I identify the drivers of the flows of the system and discuss relevant feedback loops and possible delays. Finally, I impose a quite narrow system boundary and flow definition, mainly determined by the scope of the analysis. The circular economy vision for a zero-waste construction sector is visualised in a funnel model. The principal objective becomes to map and describe the dominant flows within the system. This is done through a simple top-down flows-oriented material flow analysis (MFA). The aim is to describe the “as-is” situation as a basis for future scenarios, setting input parameters according to alternative policy trajectories. To develop sound scenarios, the paper first investigates in what ways the driving factors are likely to unfold. Then, if they did unfold in such a way, how would the system as-a-whole react in a loop of feedback mechanisms? (Meadows, 2008, p. 45). If a scenario with no or poor interventions turns out not to be in line with policy objectives, evaluating policy leverage becomes fairly straight forward highlighting the main barriers and to target negatively driving factors directly.

The goal of this analysis and the case study is to identify potential leverage points, where small changes to the system might lead to disproportionately large changes in the environmental impact. Inspired by a methodology introduced by Thorin et al. (2017) for system analyses of circular value chains, the task of identifying effective leverage can be divided into four interconnected steps (see examples of this methodology in Kennedy, Gladek, & Roemers, 2018; Muñoz, Gladek, & Kennedy, 2016). The first step is to map the system in order to understand its basic dynamics and functioning with attention to the environmental impacts and set empirically determined system boundaries. In the second step, the greatest environmental impacts within the system are visualised through a material flow analysis. In the third step, a scenario analysis will identify possible future outcomes. The final step concerns the discussion of leverage itself, where one seeks to stake out whether and where policy has leverage over the system dynamics described in scenarios In the following, I will elaborate the methods for performing each of these steps in turn, in the order of the analysis in the case study.

System boundaries

Rephrasing the original definition of a system as a set of elements that are interconnected in a coherent and organised way to produce certain outcomes, the objective of a systems analysis becomes to map out the different elements of the system and trace their relationships. This is done through a stakeholder and value chain analysis. However, in order to functionally delimit the number of actors relevant to the study, some clear system boundaries must be set. Where to draw these system boundaries is a fairly ontological question. What is exogenous and what is endogenous to the system. In reality, as most systems are overlapping and open to outside influence, all system boundaries are somewhat artificial and set *a priori* (Muñoz et al., 2016). 'Natural' system boundaries are often rather blurred and shifty. The point is to narrow the scope of analysis and provide enough context to the system elements studied. One way to set these boundaries is to look for the direct links to a nodal point, indicating that actors and material streams are relevant for the system.

A value chain is defined as "the serial connection of all the people and organizations involved in producing a certain valuable and commercialized product or service." (Thorin et al., 2017, p. 18). The objective of a value chain analysis is to visualise the material flow through its operators. Thorin et al (2017) propose a five-step procedure for this step. First, one should describe the links in the chain between the primary stakeholder, i.e. those directly involved in the production of goods, services and materials management in the value chain. Secondly, one identifies the main companies involved and define whether they fall within the defined system boundary. Then one map the inner layer of the value chain relevant to the system. The fourth step is to pinpoint the suppliers of the final goods supplied in the market and what happens to goods after they have been consumed. The final step is to generate a value chain map, where clear links between all the blocks of the chain and the direction of flows (Thorin et al., 2017).

Defining system impacts

Once the direct links and flows within the value chain have been understood, one must gain an overview of the magnitude of impacts within the system. An impact can be defined broadly as any detrimental effect to an actor involved, either environmental, social, economic or legal (Muñoz et al., 2016). The emphasis here lies on the direct environmental impacts caused by the operations of the building industry. There are several methodologies available to assess environmental impacts, such as their release of greenhouse gas emissions, hazardous chemicals, or levels of deforestation. Here, the goal is to understand the impact of material flows within the construction value chain. A detailed description of the exact impact is out of scope and while occurring outside the system boundaries. It is nevertheless important to discuss how impacts in terms of actual lifecycle footprint can be quantified.

Many products do indeed include labels such as “recycled” and “sustainably sourced”, yet the actual performance indicators vary (Gladek, Kokkos, Fraser, & Gladek, 2015). For instance, one can measure the total mass and respective share of abiotic and biotic materials present in the final product (E Gladek et al., 2015, p. 16). One can also distinguish between the fraction of the total mass that is either theoretically recyclable or strictly focus on the fraction that can realistically be disintegrated, sorted and recycled. One can also measure the total weight of virgin materials avoided by using a new composition of products, or through a product’s extended life (Dodd, Mauro, Marzia, & Donatello, 2017). For this analysis, the most relevant exercise will be to assign values for the weight of materials used by floor area of the building and to differentiate based on end-of-life use. This is illustrated in the table below, as suggested by the EU sustainable building initiative LEVEL(S). In this analysis, there will only be two relevant categories: Waste disposed of, and reusable material. This final category could be further divided into the purpose for which it is re-used, but this is beyond this analysis.

Table 1: Performance assessment matrix, example values for a construction project. Source: Dodd, Mauro, Marzia, & Donatello (2017, p. 96)

Concrete waste streams	kg/m2	% of total mass flow
Waste disposed of:		
Hazardous, sorted	100	5%
Non-hazardous, mixed	200	10%
Pure materials, reuse and recycling	700	30%

Material flow analysis

Generally, this kind of hotspot analysis focuses on the highest volumes with the greatest amount of ecological impact, both upstream in terms of materials extracted, and downstream in terms of how much and what kind of wastes are generated**.** In the context of building materials, a general causal relationship between the amount of raw materials extracted in volume and environmental harm is assumed. These volumes are categorised as material footprints, the total amount of raw materials extracted from the lithosphere. A Material Flow Analysis (MFA) can thus work as a proxy for the total material footprint of an economic sector.

A material flow analysis is defined as "an analytical method to quantitative and qualitative assess energy, material flows, and stocks" (Thorin et al., 2017). According to Rasch (2018), such an analysis can be used to "determine flows prior to construction" and as such "support optimized utilization of construction aggregates". To her, an MFA can be used to provide a framework for creating an overview of material stocks and flows, give a better understanding of current material management issues and highlights potential for improvement, and "predict material flows based on current stocks and planned stock development to support coordination across the industry" (Rasch, 2018, p. 8). Such an analysis can also give insight into recycling potentials and future secondary resource availability (Müller, Hilty, Widmer, Schluep, & Faulstich, 2014). According to Hu (2010, p. 10), a material flow analysis should provide information on current flows of materials, the size of stocks and the origin and destination of the materials prior to and after use. Stephan and Athanassiadis (2018) claim it allows scholars to identify "major flows of materials, anticipate time periods of intense material replacements or flows and better understand where these flows take place" (Stephan & Athanassiadis, 2018).

One can distinguish between static and dynamic analyses. Static MFAs describe a "snapshot" of the system at one moment in time (Müller et al., 2014). A dynamic MFA traces the behaviour of that system over time. In this paper, a dynamic MFA is applied. A dynamic model can either be retrospective "analysing past stocks and flows based on historical data, or prospective, looking into the future using data extrapolation," or both (Müller et al., 2014). Secondly, the literature distinguishes between what is called flow dynamics models or top-down approaches, and stock dynamics models or bottom-up approaches (Hu, 2010; Müller et al., 2014) The top-down approach "derives the stock from the net flow: the difference between inflows (consumption) and outflows (discard)." A bottom-up approach "directly estimates the stock by summing up the material in question present within the system boundary at a certain time" (Müller et al., 2014, p. 2103). Here, a top-down approach is chosen due to the limited availability of data, and the fact that this analysis concerns the inflows of variables through imports to the Port of Oslo.

Further in studies of the circular economy, one distinguishes between MFAs based on the type of circularity intervention one models. Aguilar-Hernandez, Sigüenza-Sanchez, Donati, Rodrigues, & Tukker, (2018) review different circularity analyses, based on the type of circular economy strategy applied to the system in question. The two most relevant for this analysis are called 'Closing supply chains' and 'Product lifetime extension'. They are closely connected and investigates strategies for "re-integration of materials at different levels of the supply chain after being used, via for instance product reuse" as well as the extension of lifetimes through recovery and repair activities (Aguilar-Hernandez et al., 2018, p. 3). This can be modelled by "changing input and output coefficients to closed-loop activities, such as reuse and recycling sectors" (Aguilar-Hernandez et al., 2018, p. 16). Here the assumption is that closing these loops, in effect reducing the input and output factors of the system, would "drive the reduction in extracting virgin materials as a consequence of their replacement with secondary circular flows" (Aguilar-Hernandez et al., 2018). This would result in a proportional replacement of virgin resource A with secondary resource B (Aguilar-Hernandez et al., 2018).

Scenario analysis

The goal of the analysis to this point has been to describe the system, understand flow dynamics and understand current trends so to develop sharp scenarios for the future. The scenarios will be utilized to describe alternative future developments. Importantly, scenarios are not tools for precise prediction of the future, but rather enables a better understanding of future dynamics. The purpose of a scenario analysis is rather to stake out the options available for policy planners to design strategic interventions to the system. A key feature of well formulated scenarios is that it can challenge established perceptions of the future and contribute to making informed decisions and planning processes (Skancke et al., 2018).

The scenario methodology is inspired by a study by Bergsdal, Bohne and Brattebø (2007) which is divided into three steps: a) Construction activity is estimated as square meters of new floor area built out per year, b) the waste generation factors in kilograms per square meter is determined for each type of activity, and c) the projection for the total tons of waste generation is calculated based on predicted developments of input variables. The three development scenarios are determined with inspiration from Hu, van der Voet & Huppes (2010, p. 450), where the first assumes current trends to continue (Reference, REF.), the second a high growth in per capita floor area (Maximum, MAX.), and a third where the raw material intensity of dwellings are reduced, throughout circularity practices and lifetime extensions (Circularity, CIRC.). Only the origin, process and destination of the flows are considered and the size of each category of waste flows are determined by current and predicted ratios. As such, the only relevant factors in the outflow are a binary between materials for 'repurposing' and 'disposal'.

Three scenarios are investigated over two time periods. In general, each scenario asks the what-if question: how will construction material dry bulk imports to the Port of Oslo look in year t, if the key driver changes. In all scenarios, it is assumed that building material structures and mode of material transport remain constant at current ratios. Today, more than half of all 18 kilometres are seaborne (Mortensen et al., 2018). Also, over 60% of the concrete used for construction in Oslo is produced at the port, signifying that more than half of the material enter port operations (Mortensen et al., p. 35). In the high and reference scenario, the building characteristics averages are also kept constant in terms of material density and materials composition. This is in line with findings of Hu, van der Voet & Huppes (2010) and Stephan & Athanassiadis (2018) that conclude that construction practices change very little in the medium-term.

Using updated data on material flows through the Port of Oslo from reports and databases, I have generated a scenario model based on a data spreadsheet. The material flow analysis of port inflow was performed through collecting empirical data from the Port of Oslo's own reporting and case estimations by Dale, Stokke, Ljungberg, & Laugen (2018) using national statistics. The data on outflows was collected from databanks by SSB, calculations from Lundberg, Johansson, & Magnusson (2016) and Mortensen, Davidsson, & Lie (2018). This data was triangulated through other available sources, national statistics and model-generated estimations based on Bergsdal and colleagues (2017). The scenario analysis to predict probable flows of building materials uses empirical data on both virgin and secondary resource-flows, and use specified input parameters to model future developments. The different scenario policy paths described above define three clear directions for the key input parameters. The software graphical tools of Word, Excel and e!Sankey has then been used to visualise the results in graphs and flow-charts.

Three main input variables are considered in the scenario analysis. The first is the trend in building-related material imports to the Port of Oslo. Historical data for 2010-2017 are extrapolated into the future to create a trend-baseline scenario for the following 10 years. The construction activity in Oslo is defined as the key driver of the system. Historical trend data was collected for 2013-2018 and extrapolated to give an indication of the medium-term trend development. There exists only scarce data on absolute construction activity at the local level, and estimations deviate greatly, so a proxy variable is used. By using SSB's population growth forecast for Oslo up to 2030, combined with dwelling stock model parameters identified by Bergsdal and colleagues (2007), a trend for total housing construction based on increased demand can be modelled. Only data on large residential buildings and small detached houses could be extrapolated with confidence. The third variable, waste generation, combines a statistical calculation of construction waste, based generic waste generation factors, and projections of future floor area additions to estimate future waste volumes. Waste volumes were separated into the two categories defined by Dodd et al. (2017): reusable and disposed.

Additional interview data

Qualitative methods have been performed in terms of interviews with a selected few stakeholders as a means of triangulating the desk research and quantitative data. This has been performed as a supplementary method to "view problem statements from another viewpoint (Johannessen, Kristoffersen, & Tufte, 2011). Early interviews formed a foundational structure for the applied methodology and the chosen problem statement. Interviews with central stakeholders are also recommended in much of the literature (Kennedy et al., 2018; Thorin et al., 2017).

Four stakeholder interviews were carried out in individual semi-structured interviews. The interview subjects were considered key informants within the system, with each organisation occupying separate parts of the construction value chain. Two of the actors, the Port of Oslo and Oslo Municipality, are administrative stakeholders engaged in the value chain from a top-down position. One is an economic actor, Skanska Industrial Solutions AS, directly involved in the value chain. The last, Future Built, is a consultancy and consortium of building, municipal and architectural actors involved indirectly throughout several stages of the value chain. All interview subjects were given a choice to remain anonymous, and whether their organisations could be mentioned explicitly.

The interviews were semi-structured based on a broad interview guide relating to general themes within the study topic. All actors were asked to provide their own assessments of the current situation as well as their predictions for the short-term future. The interviews were recorded and transcribed as general notes. Important information was transcribed directly in full. A standardised interview guide is provided in Appendix 3. Key to interview analysis was to translate interview answers into their relevant context and understand what information was provided as subjective assessments, and what is factual organisational positions. This was done by juxtaposing the interviews with official documents and organisation websites.

Table 2. Overview of interviewed stakeholders

Actor	Role in the value chain	Knowledge gap filled
Port of Oslo	Dry bulk transmission terminal and port area manager	Supply chain management, dry bulk loads, Grønlia terminal, ports as actors, green port operations
Municipality of Oslo	Local administrator, bureaucracy and legislator	Port activities, zero-emissions strategy, building sector development, building standards, city development plans
SKANSKA Industrial Solutions AS	Case terminal operator, key stakeholder across the value chain	Building and construction market, Grønlia terminal operations, bulk management, national policy development
Future Built	Knowledge-sharing and standards issuer	Circular building definition, regional building sector, international best-case examples

Results

The following analysis traces flows and stocks directly associated with the port operations at the Port of Oslo. Based on the analysis of the secondary data presented in the previous part, the paper now turns to presenting results from this analysis combined with model projections. The system boundaries are first defined before the most relevant stakeholders in the building industry value chain are identified and placed within the system map. Then future scenarios are developed based on how the most relevant policy areas are likely to evolve, presented in funnel model. Then a material flow analysis of abiotic, mineral construction materials entering the Port of Oslo is illustrated through a freight example, to identify the greatest impacts in this system. A scenario analysis for the development in the construction of large and small dwellings will highlight some of the future impacts while pointing to a few leverage points for how to alleviate them through circular economy policies.

System and value chain analysis

The system is strictly delimited to the case material flow of mineral dry bulk materials bound for the building industry in Oslo. There has been scarce research yet at this level of resolution and most official statistics are collected for the national level (Dale et al., 2018). Therefore, a more specific freight-case is chosen, where a clear network of actors can be drawn up, providing an overview of their relationships, relative and absolute flows of goods, as well as their purpose as materials. The goal here is to be able to give a quite detailed overview of the flows, flow-links and their direction.

In the model in Figure 13 the value chain of Oslo's construction sector is illustrated. Each blue box represents a category of actors and the orange arrows represent virgin flows between the actors. The light blue rectangle represents the system boundaries. At the centre are the current building stock within the Oslo municipality borders (grey cylinder). This defines the total amount of materials in-use that at some point will either exit the system as CDW bulk or potentially be processed for re-use by the original or new developers. The white arrows represent all used materials flowing through the system. These flows are central to the circularity analysis later in the paper. The model describes the key value chain actors involved in these flows. Secondary materials will collect the used materials and re-manufacture them for re-purposing in new projects before they are re-distributed to the relevant construction sites by contractors, where real estate developers assemble the material to the final good – a residential building. The treatment of the materials is not part of the analysis of this paper, so these actors are not inside the system boundaries.

Actors considered as key stakeholders either defined by their influence on the system or their impact by changes to it are considered the key elements of the system. The model below presents a sample of the key actors organised according to their key operations and position within the chain, in the categories identified in the Literature Review. The arrows illustrate the direction of sales and interaction between actors. It is important to stress that for most stages of the value chain there are several smaller actors engaged, but these are examples of the most significant stakeholders in terms of impact and influence within the value chain. In the current economic situation of globalized and vertically integrated supply chains, no actor operates in isolation, either geographically or as a market. Actors obviously interact and operate much more across chains than in this simplified model. The following analysis will reveal that certain actor networks may be deemed more central to the circular economy, with special emphasis on the top right corner boxes, as well as the centre bottom box, consisting of companies specializing in end-of-life materials management at different scales.

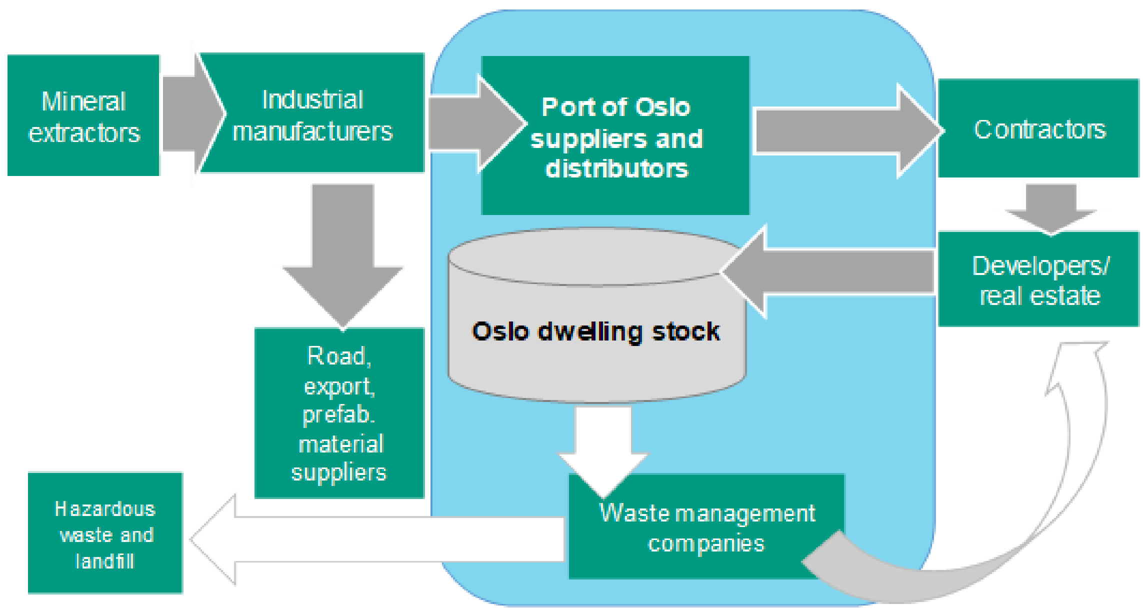

Figure 13. Map of the actor-network and value chain of the building industry in Oslo, from the perspective of the Port of Oslo (the blue background box represents the system boundaries)

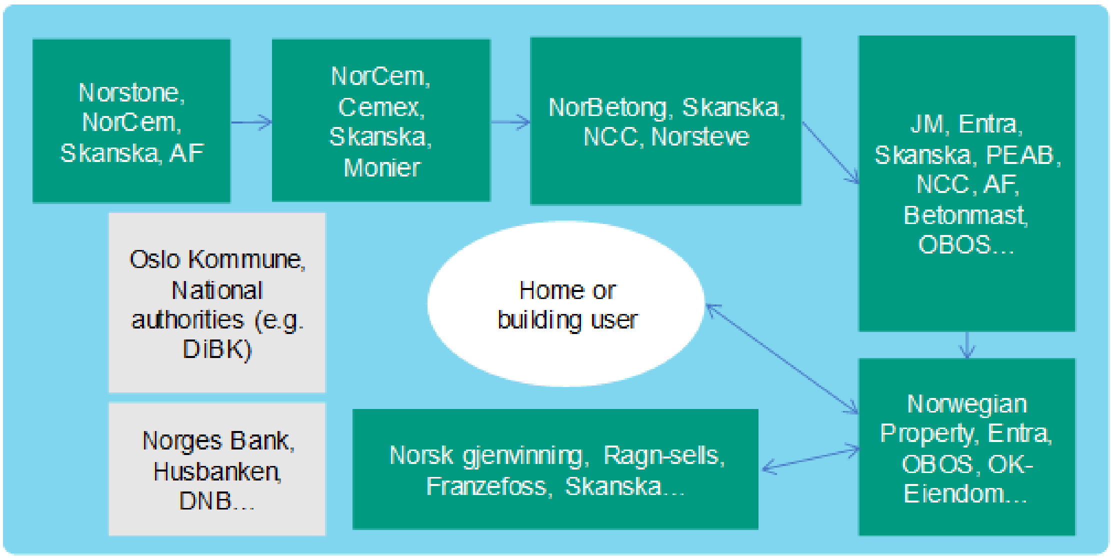

Figure 14. Stakeholder map illustrating the links within the value chain relevant for the defined system (most chain links have several additional actors, and those included are only meant as indicative examples; OK-Eiendom: Oslo Kommune Eiendoms- og byfornyelsesetaten; DiBK: Direktoratet for byggekvalitet)

Material flow analysis: mapping current impacts

To assess the future state of environmental resources, it is important to first understand the impacts of the current system. In the subsequent analysis, the present-day situation, well empirically documented up to at least the year 2015, will be used as a basis for the business-as-usual reference scenario. Assuming no further interventions, the baseline scenario will estimate trend-trajectories evolving from the 2015 situation. Figure 15 portrays this baseline. The most relevant variables, namely inflow of raw building materials and waste outflows from the current system are analysed.

Table 3 present construction and demolition waste estimations by Lundberg, Johansson and Magnusson (2016) based on a methodology developed by (Bergsdal, Brattebø, Bohne, & Müller, 2007). These values are considered to be absolute and include waste from residential and non-residential buildings, both private and public. It shows that waste streams varied greatly between the two years. Therefore a weighted average is used for the baseline concrete waste generation. The flows of concrete out from the building stock in Oslo are visualised in a material flow chart below. In Figure 16, the material inflow to the construction sector is presented in a freight case for concrete going into the Port of Oslo, but also a few material streams transported to Oslo otherwise. It starkly illustrates the total resource extraction to satisfy the Oslo construction industry material demand. It also shows that the port handles a large fraction of total inflows, annually supplying the local market with more than 600 000 tons of cement. A large fraction of this cement is transformed at the port area providing an annual flow of 1,4 million tons of concrete, distributed throughout the wider Oslo region.

Table 3. Construction waste in Oslo 2014 and 2015 (adapted from Oslo Kommune, 2016, in Lundberg, Johansson, & Magnusson, 2016)

Year	*Concrete, pure (t)*	*Concrete, polluted (t)*	*Hazardous waste (t)*
2015	43 464	76 583	19 891
2014	81 255	38 791	4 276
Average	62 360	57 687	12 084

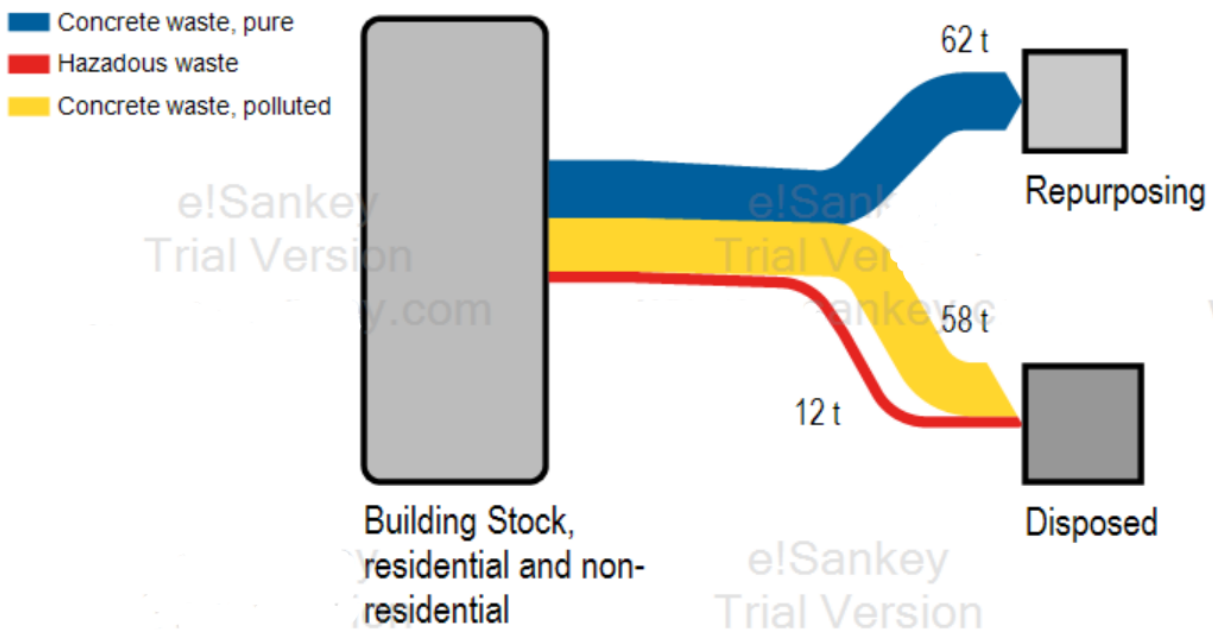

Figure 15. Illustration of concrete waste outflows from the system (in 1000 t; based on Lundberg, Johansson, & Magnusson, 2016)

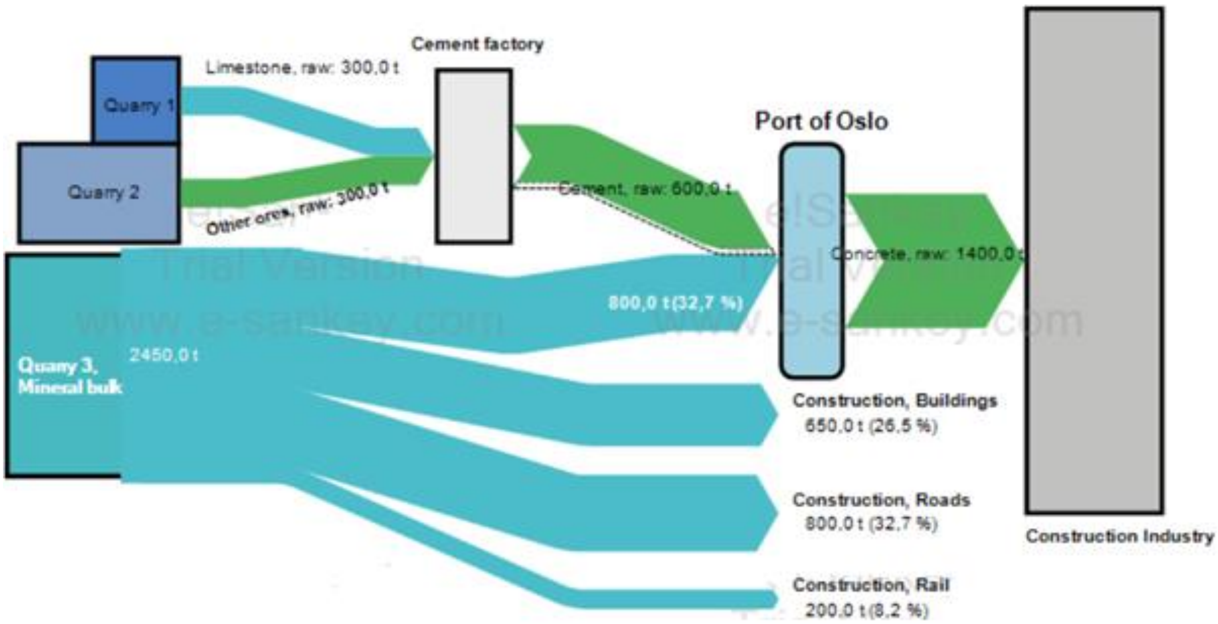

Figure 16. Illustration of raw material inflows to the Oslo region construction industry (in 1 000 tons; numbers and proportions are indicative of a standard year as reported by the Port of Oslo; based on Mortensen, Davidsson & Lie, 2018)

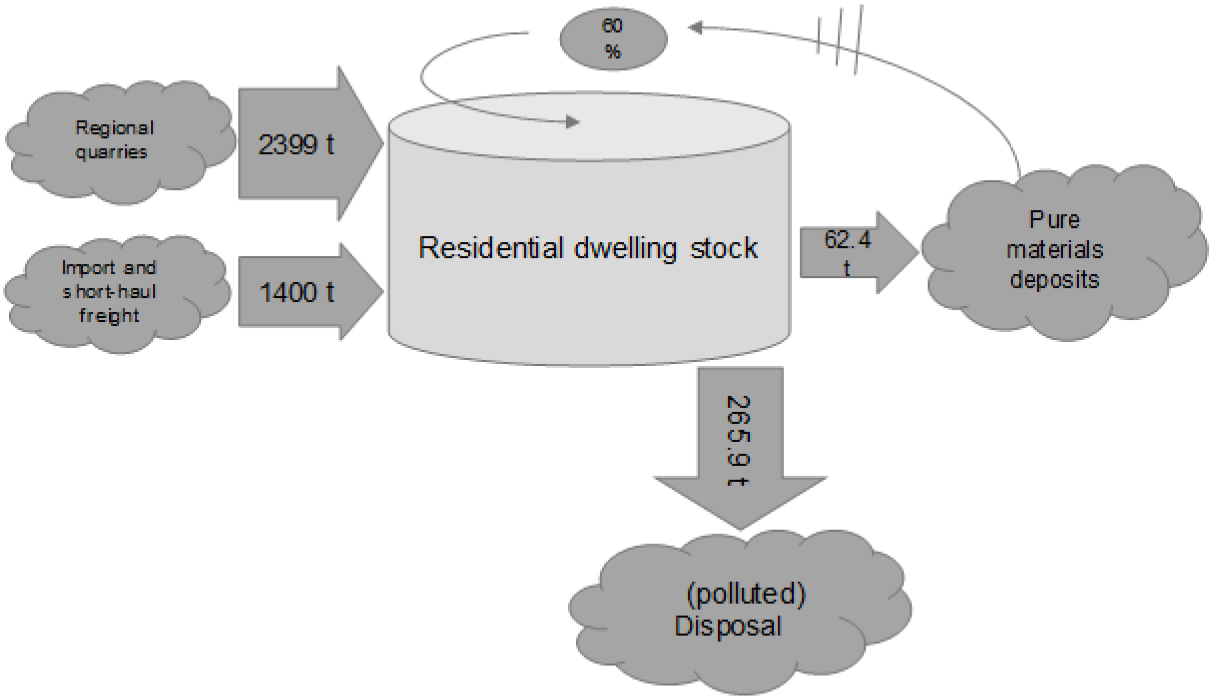

Figure 17: Total stocks and flows 2013-2018: simplified model of material flows and the residential dwelling stock of Oslo as an average between 2013-2018 (in 1 000 tons; numbers based on latest available data and calculations)

Scenario analysis

Future policy pathways

In Figure 18 the assumed policy development in an ambitious circularity scenario is described in the funnel model earlier described. Each box describes new policy interventions in the system in a relevant policy period, based on a document analysis. These are the assessments made by stakeholders themselves, in municipal strategy documents industry roadmap. The timeline illustrates the relevant project time-horizon, where T0 signifies the as-is situation and T35 represents the situation in the ideal vision.

Defining realistic scenarios for the analysis is a task of assessing possible future developments within the relevant system variables. In this analysis, the key driver of the system is the building industry activity, using new dwelling construction as a proxy for the total level of activity. The most relevant scenarios here then deal with the market conditions for building construction and the materials trade.

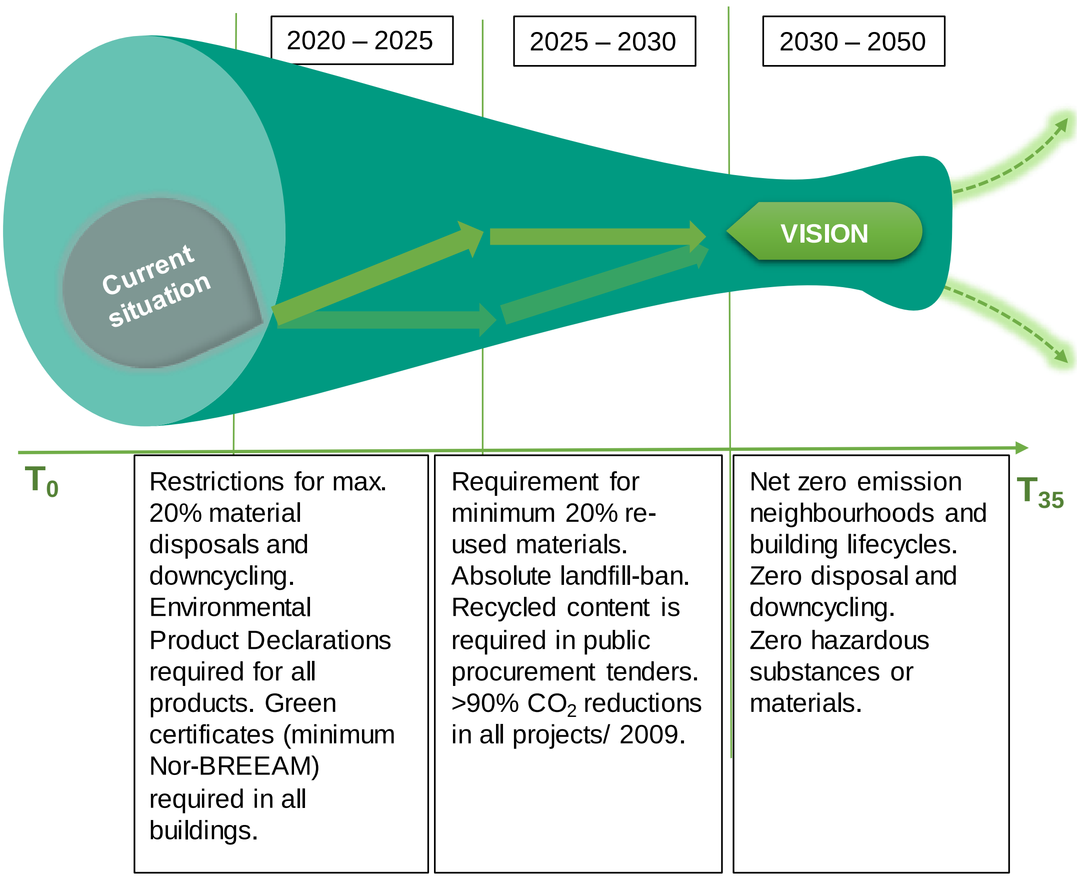

Figure 18: Circularity policy development towards the sustainability vision

It is assumed that the most impactful developments will come from policy changes at the municipal level. In Figure 18, climate and circularity policies developments are divided into three different policy periods. The relevant time-horizon for this paper's analysis spans 2015 to 2030, with 2050 defining the long-term vision. The first policy period starts in 2020, assumed to be the first year where policies have effect, going to 2025 as this is a benchmark for several policies. 2030 is defined as a policy target year in several policy domains, such as Oslo's climate targets and port strategy. The period 2030-2050 is included to illustrate the long-term direction of policy.

Scenario definition

Table 4 defines the three scenarios identified. The key driver in all three scenarios is changes to the amount and composition of building activity in Oslo.

Table 4: Scenarios

Scenario/ Period	Current trend scenario (REF)	High growth scenario (MAX)	High-circularity scenario (CIRC)
2020-2025	Construction activity is consistent with current growth trends (average 4000 new dwellings p/y). Abiotic mineral material input factor and concrete density are constant. Waste generation reduced by 20%. Raw material/ secondary material ratio = base year, 2015	Construction activity growth increase from current levels, based on high-growth scenarios for the exogenous drivers, e.g. population. Waste generation reduced by 20%. Abiotic material is the main input factor. Raw material/ secondary material ratio = 2015	Construction Waste Factor reduced by 20%, 20% landfilled. Raw abiotic material input factor reduced. Concrete density reduced by 2%. Other raw abiotic inputs are reduced by 20%. Raw material/ secondary material ratio = 80/20. Renovation dominates.
2025-2030	Construction activity is consistent with current growth trends (average 3300 new dwellings p/y). Abiotic mineral material input factor and concrete density are constant. Raw material/ secondary material ratio = 2015	Construction activity continues growth from previous levels, with high population growth. Waste generation factor constant. Raw material/ secondary material ratio = 2015	CWF reduced 30%, no landfilling. Raw abiotic material input factor reduced. Concrete density reduced by 15%. Other raw abiotic inputs are reduced by 40%. Raw material/ secondary material ratio = 70/30. Renovation dominates.

Model input parameters

Population growth. In Figure 19, the development of the population of Oslo is given for 2013 to 2018 based on statistics by the Norwegian Bureau of Statistics (SSB). Three scenarios for the development up to 2030 is given, based on four main variables: birth rate of the current population, amount of Norwegians moving into Oslo, number of current residents moving out and immigration to Norway from abroad (Oslo Kommune, 2018b). The projected growth, especially in the later years of the period has been reduced in the last few years. The population of Oslo in 2040 was expected to reach 890 000 when projected in 2016. This number was reduced to 833 000 in the latest projection of 2018 (Oslo Kommune, 2018b). Of the 673 469 people living in Oslo in 2018, 32% lived in smaller houses, such as detached and semi-detached dwellings (Sandberg et al., 2018). The proportion of the population living in large and small dwellings is projected to remain relatively stable.

Person per dwelling. The average amount of people living in each individual dwelling is calculated by SSB based on national census information. This number is somewhat lower for dwellings in Oslo than the national average (Sandberg et al., 2018). However, on a ubiquitous trend has been a sharp decline in the average number from above five persons per dwelling in the early 1800s to around 1,98 today.

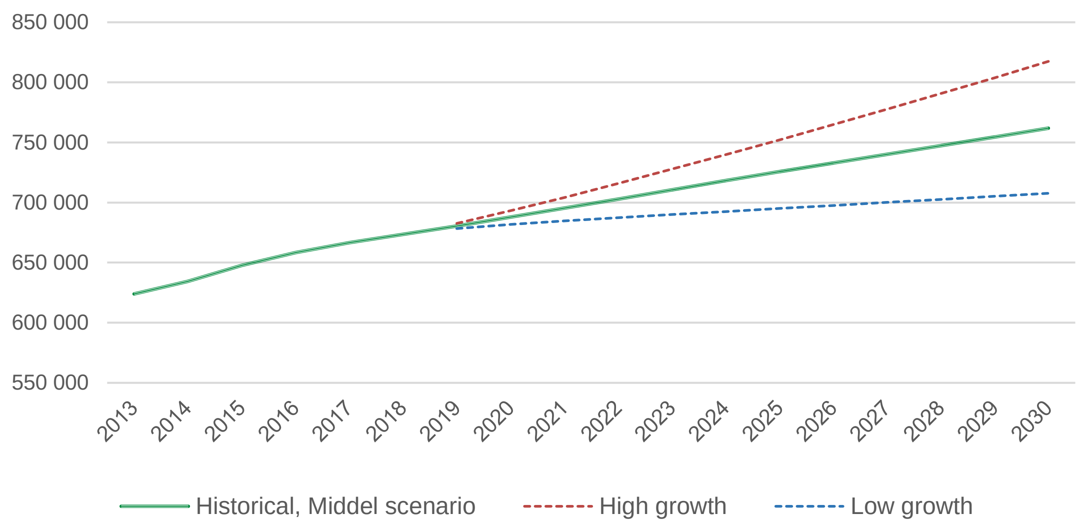

Figure 19. Population development for the city of Oslo: historical to 2018 and middle, high and low scenarios for the period 2019-2030 (based on SSB, 2019)

In Oslo, with a large and diverse stock of dwellings, the number varies greatly depending on the type of building, from 1.74 persons per apartment in a large residential building to 2.62 in detached small houses (Sandberg et al., 2018). In the scenario analysis, as only large residential buildings are considered, the 1,74 value will be used.

Average floor area per building. The average floor area per building is important to assess the total amount of building mass that will be constructed, as the material demand and waste generation are given per square meter of new dwellings. The area per dwelling varies greatly between large residential buildings and detached houses. The statistics department of the Municipality of Oslo estimates an average floor space per dwelling of 112.8 m^2 over the last five years (Oslo Kommune, 2018b). Sandberg et al. (2018) however, calculates that the average floor space for detached houses are 127 m^2 constituting 15% of the total building mass, while large residential constitute 76 % and have an average floor space of 67 m^2. Apartments are on average 4% smaller in Oslo than in the rest of the country. These numbers will be utilized in scenario models.

Abiotic construction material input factors. The parameter used for determining how much materials are needed for constructing a unit of dwelling is based on international standard levels. These statistics might vary depending on the context and building practices but are considered largely universal for the construction type (Sartori et al., 2008). Based on estimations by Bergsdal et al. (2007) there is on average 0.7 tons of concrete per square meter floor area in Norway, significantly lower than in other countries where the concrete intensity is larger. This is predicted to remain relatively stable over the next 50 years (Hu et al., 2010). In the circularity scenario, the average concrete intensity of residential buildings is assumed to decrease by 2% from 2020 and 15% from 2025 as new materials are introduced. The material composition of a standard unit of a concrete-brick structure residential building is estimated based on the type of material and given in the table below. The amount of raw materials is assumed to reduce in the circularity scenario by 20% from 2020 and 30% from 2025, respectively as used material is introduced.

Table 5: Abiotic material intensity

	Concrete	Cement	Sand	Gravel	Brick
Reference and high growth scenarios	0.700 t/m^2	0.148 t/m^2	0.574 t/m^2	0.658 t/m^2	0.364 t/m^2
CIRC scenario, 2025	0.686 t/m^2	0.118 t/m^2	0.459 t/m^2	0.526 t/m^2	0.291 t/m^2
CIRC scenario, 2030	0.595 t/m^2	0.104 t/m^2	0.401 t/m^2	0.460 t/m^2	0.255 t/m^2

Table 6: Waste generation factors

Reference and high growth scenario			Circularity scenario		
Large residential buildings					
2000-2020	19.1	kg/m^2	2000-2020	19.1	kg/m^2
2020-2025	15.3	kg/m^2	2020-2025	13.4	kg/m^2
2025-2030	15.3	kg/m^2	2025-2030	9.6	kg/m^2
Small residential buildings					
2000-2020	6.5	kg/m^2	2000-2020	6.5	kg/m^2
2020-2025	5.2	kg/m^2	2020-2025	4.6	kg/m^2
2025-2030	5.2	kg/m^2	2025-2030	3.3	kg/m^2

Waste generation factors. Bergsdal et al. (2007) have proposed a methodology for determining the flows of waste coming from the construction of new large residential buildings. The main parameter here is based on their analysis of construction waste for all of Norway in the period 1998 to 2005. It varies greatly for construction, renovation and demolition activities due to the different quantities of pure materials handled (Bergsdal et al., 2007). In this analysis, only new construction of large and small dwellings are considered. First, they estimate that brick and concrete constitute around 45.8% of the total waste from construction activity nationally. They calculate a factor for the generation of concrete and brick waste of 19.11 kilograms per square meters for large residential buildings, and 6,5 kilograms per square meters for small building structures. In line with current waste reduction targets, waste generation is expected to decrease by 20% from 2020 onwards for all scenarios. In the circularity scenario, waste generation is assumed to reduce significantly over the coming periods as more stringent policies and practices are implemented. This is set to 70% reduction from 2020 and a 50% reduction from 2025.

Input parameters uncertainty. The modelled results are not better than the quality of the input data. Uncertainties in the underlying dwelling construction model could significantly impact the ultimate scenarios for future flows. In this paper, the best available data and model assumptions, used and tested by authoritative national and international studies have been applied (further developed by Sartori, Sandberg & Bergsdal, 2016). Yet, it must be stressed that these input parameters are only estimated aggregate values that are sensitive to incremental variation in other dependent variables. A sensitivity analysis on the Norwegian stock model performed by Sandberg et al. (2016) showed that the model is responsive to parameter changes and that conclusions regarding key model outputs are largely robust (Sartori, Sandberg & Bergsdal, 2016).

Reference scenario

Figure 20 portrays the changes in the demand for new dwelling floor area per year from 2018 to 2030 for the middle scenario of population development. The numbers are computed based on the methodology developed by Sandberg et al. (2018) to calculate demand for new floor space. This includes the population projections by the Municipality of Oslo and historical levels for person per dwelling and average floor space area for Oslo described above. Historical data for 2018 is included based on early estimations by SSB to show how construction activity starts from an unusually high level. It is then projected to reduce to more traditional levels, based on a metric of population growth and the demand for new dwelling space. This also reflects analysis by the EBA O, Ø & A (2018) that predicts activity to reduce due to recent reductions in housing prices. It is then predicted to rise to keep up with rapid population growth from 2020 to 2023, mainly occurring in the inner city. The reason for the fall from 2024 is due to a relative reduction in the growth of the population. It will be seen that this trajectory differs substantially from the high growth scenario, explaining most of the variation in outflow variables.

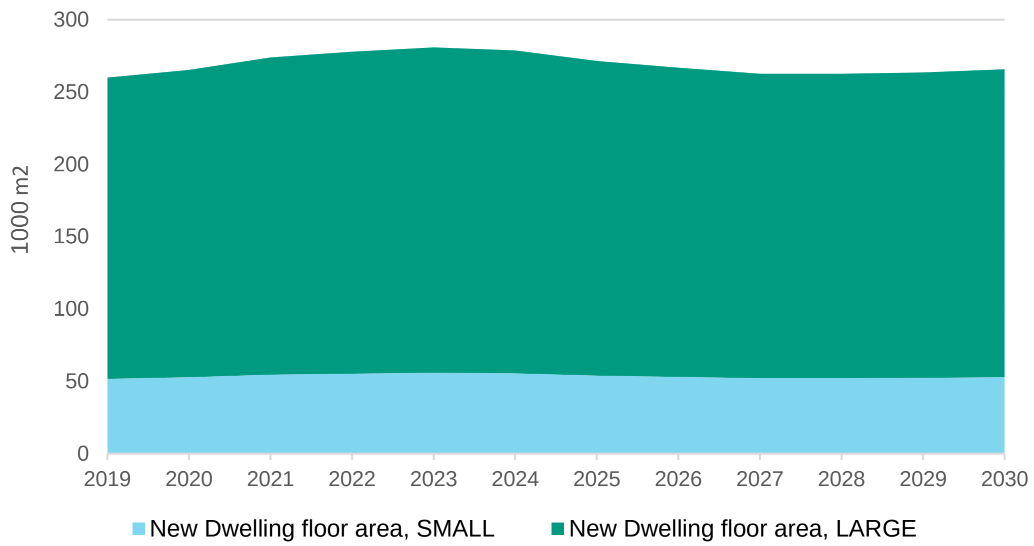

Figure 20: Additional residential floor space area, based on trend population growth and fixed input parameters (in square meters; SSB, 2018)

Here the results of the analysis of total material demands for the abiotic construction materials concrete, cement, sand, gravel and brick respectively can be seen. The total abiotic materials demand shows a substantial increase in the projected demand for construction material in line with predictions. The historical period from 2013-2017 was chosen as a reference based on sound statistics. The year 2018 was excluded from the analysis due to the uncertainty of total construction activity in that year. It is worth noting that demand peaks in the middle period of 2019-2024. This corresponds to the development in new dwelling floor space described above and resonates with analysis made by the Municipality of Oslo (2018) and Sandberg et al. (2018). Concrete demand is given by the total demand for new floor area times the constant parameter, concrete density, which is assumed to remain the same throughout the period in the reference scenario. The other variables are calculated based on the material compositions for large residential buildings described above.

As can be seen from Figure 22, in the reference scenario, construction waste from meeting the demand for new large and small dwellings in Oslo will remain relatively stable over the next decade. It is largely in line with the historical values for construction waste during the years 2013-2017, slightly less than 10 000 tons. The waste streams have the greatest increase in the period 2019-2024 as the population is expected to grow the most. As can be seen, the clear greatest fraction of construction waste will come from the construction of new large residential buildings.

Table 7: Total raw abiotic material demand from new construction

Input Parameters	2013-2017	2019-2024	2025-2030
Population growth (persons)	42 793	44 808	43 604
New floor area growth (m^2)	1 407 560	1 991 467	1 937 956
Materials			
Concrete (t)	985 292	1 394 027	1 356 569
Cement (t)	208 460	294 936	287 011
Sand (t)	807 236	1 142 106	1 111 418
Gravel (t)	925 893	1 309 987	1 274 787
Brick (t)	512 774	725 491	705 997
Total abiotic materials demand (t)	3 439 654	4 866 547	4 735 782

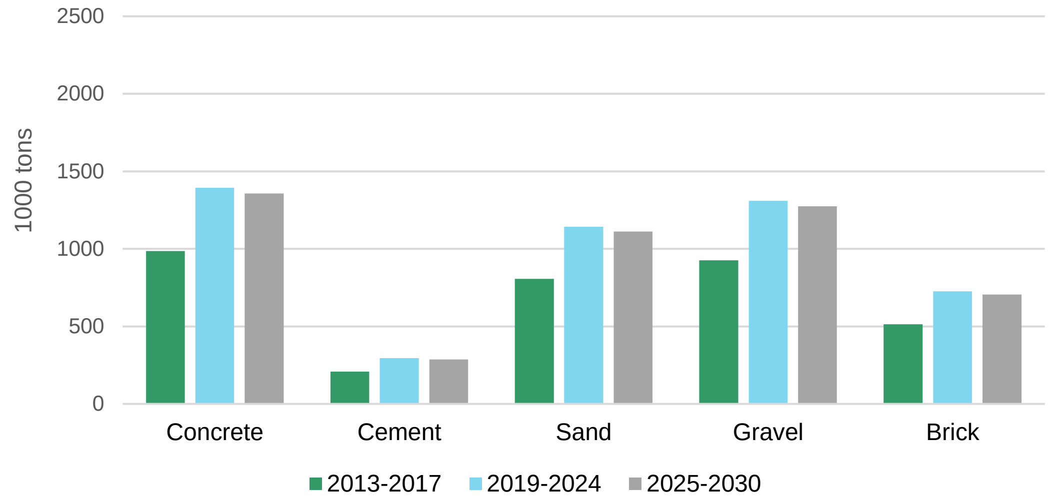

Figure 21: Total raw material demand from the construction of residential buildings for the periods, 2013-2018, 2020-2025 and 2025-2030

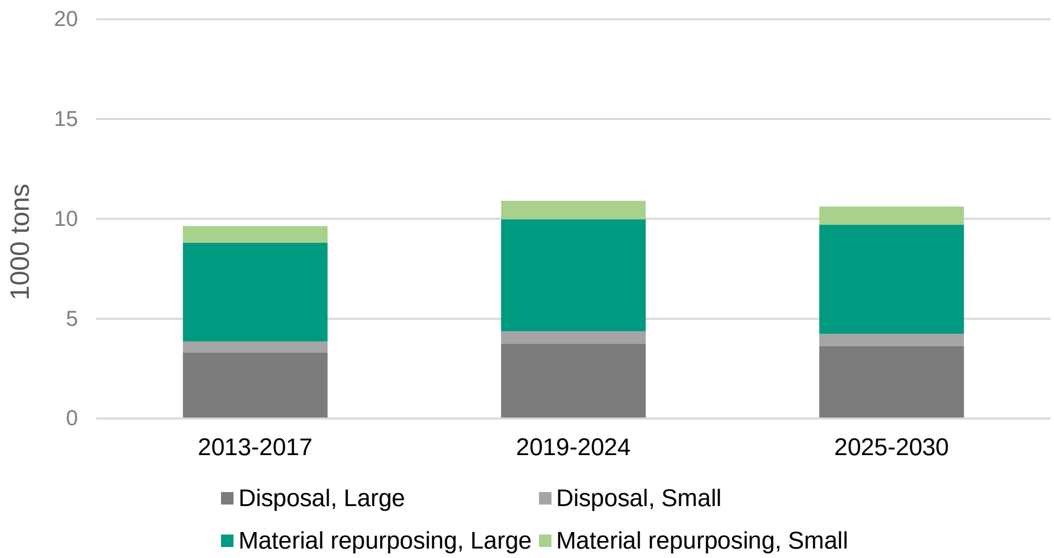

Figure 22: Waste diversion from the construction of large residential buildings and small houses for the three periods, by waste management strategy

Yet, it is important to note that waste from other types of buildings are not included in this analysis, nor are the waste streams from renovation or demolition activities – activities that generate a considerably larger share of the total waste streams (Bergsdal et al. 2007).

High growth and circularity scenario analysis

Here, two alternative scenarios for dwelling construction, material demand and construction waste are juxtaposed to analyse the implications of the different policy pathways. This allows for comparison and to directly see the difference in the variables resulting from incremental changes to a few key input parameters. In the graph below the trajectory development in the dwelling sector is illustrated in the form of demand for new floor space area per year.

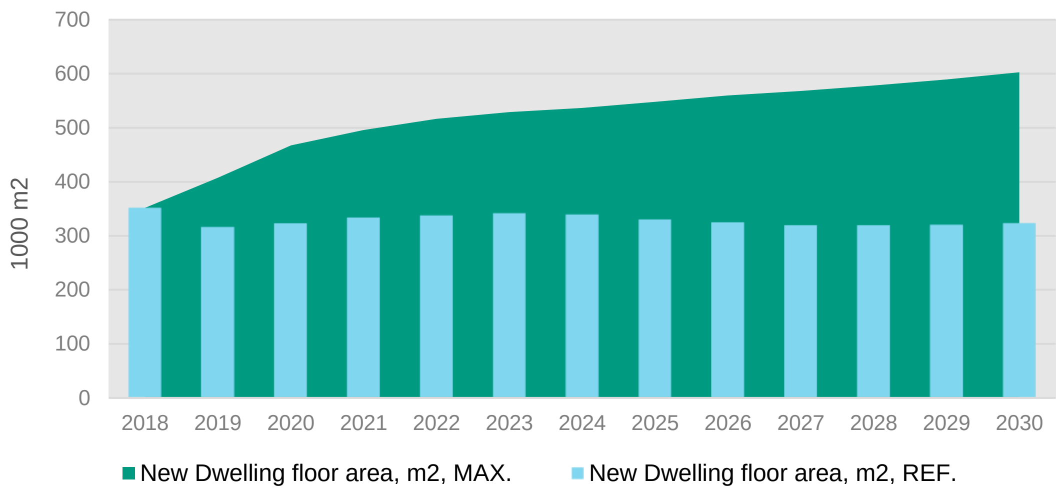

Figure 23: Additional residential floor space area in high (green) and middle (blue) population growth alternative

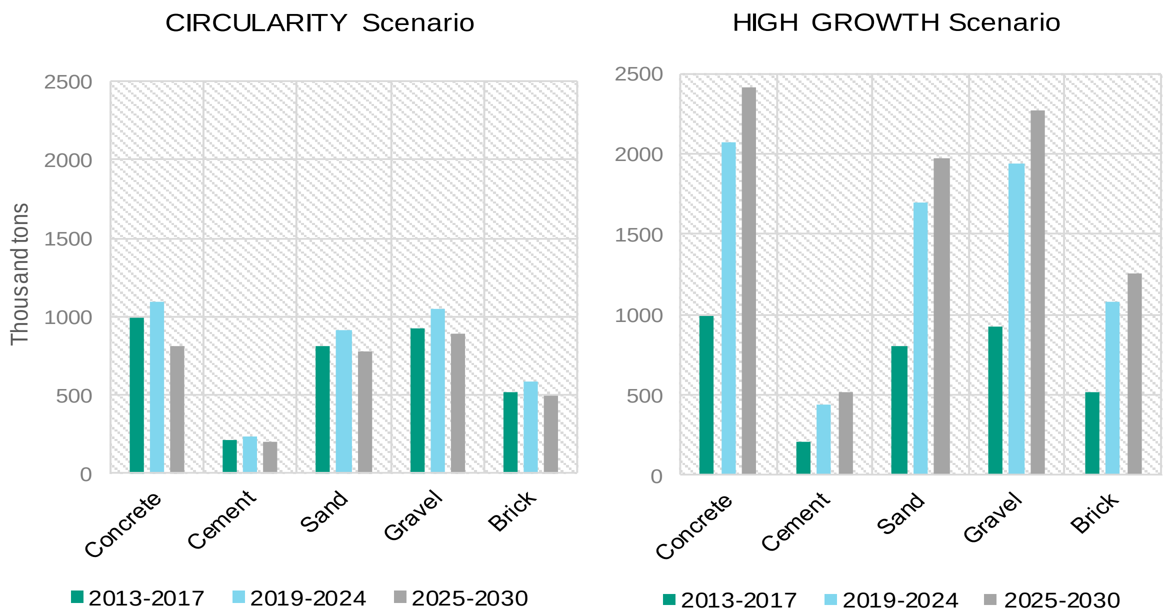

Figure 24: Total raw material demand in the high growth and high circularity scenario for the construction activities in the three periods.

The entire difference is explained by the population growth projections described earlier, wherein the high growth scenario, the maximum population growth is assumed and used as a proxy for a higher-than-normal activity in the dwelling construction sector. In the circularity scenario, this level is identical to the reference scenario, as a shift to circularity is not assumed to affect these parameters to any significant degree. Here however, weighted averages for persons per dwelling and floor space area in the Oslo dwelling sector are used. Nearly all the differences in the material demand and waste fractions between the reference and high growth scenarios are described by this variable. The difference in waste streams is explained by changes to the waste generation factors and material intensity in the two alternative policy pathways.

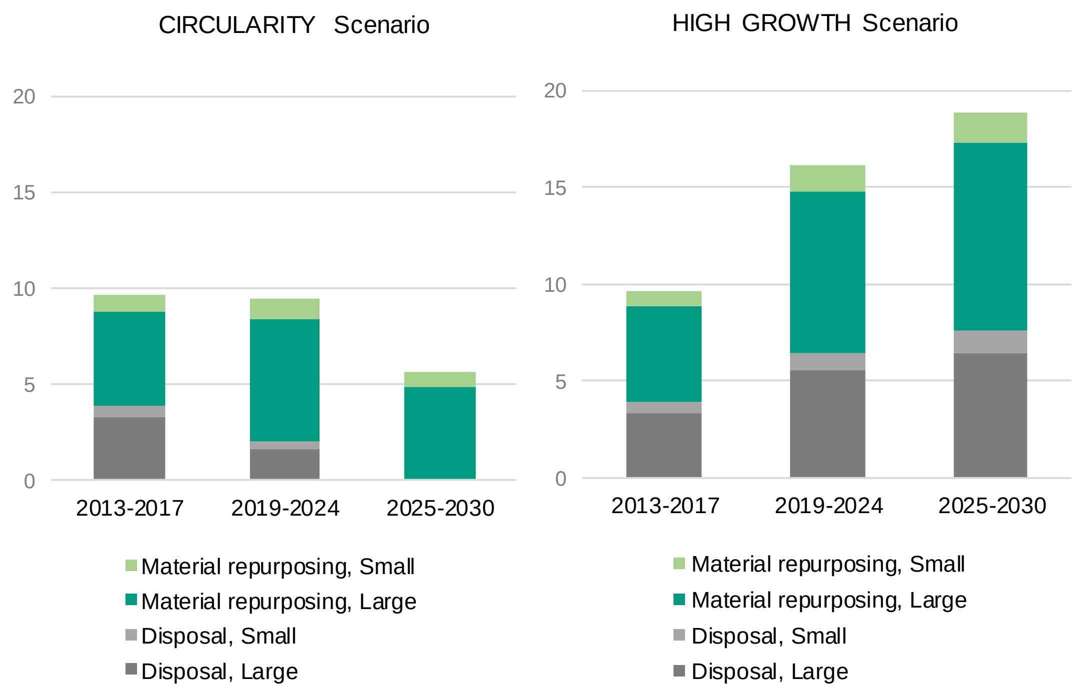

Figure 25: Concrete and bricks waste generation from the construction of new dwellings for the periods, in high growth and circularity scenario (1000 tons)

Discussion

Future material flows and footprint

The analysis paints a clear picture of the material streams from construction activity in the city of Oslo. There are currently significant flows of raw abiotic construction material into and out of the city. Volumes are predicted to increase significantly if input parameters develop with current trends. The reference scenario predicts that the volumes imported to the city will multiply in each period from 2019-2030, compared to the base-period 2013-2018. In a high growth scenario, volumes will more than triple. In the reference scenario, total waste flows from new construction will only increase marginally. However, this is assuming a general reduction of the waste factor by 20% in the current period and tells nothing about developments in demolition and renovation waste flows. In the high growth scenario, this amount almost doubles by 2030, generating more than 7 500 tons of unusable concrete and brick residues. On the other hand, more than 10 000 tons of materials will be available for repurposing, provided that there is capacity within the system to transported and re-processes these materials.

This is in line with the trends identified in the academic and policy literature. As already stated, the Municipality expects that construction activity in Oslo will demand more than 12 million tons of materials by 2030. At the same time, they predict that around 50% of old materials will have to be treated before re-use. Modelling of the Norwegian dwelling stock by Sartori et al. (2008) and waste streams by Bergsdal et al. (2007) predicted that system outflows would increase rapidly in the current and coming period as there is a stock replacement nationally. In Figure 26, the values for inflows and outflows over the period 2020 to 2030 in the reference scenario are given. This represents the predicted impact of the current system over the next ten years.

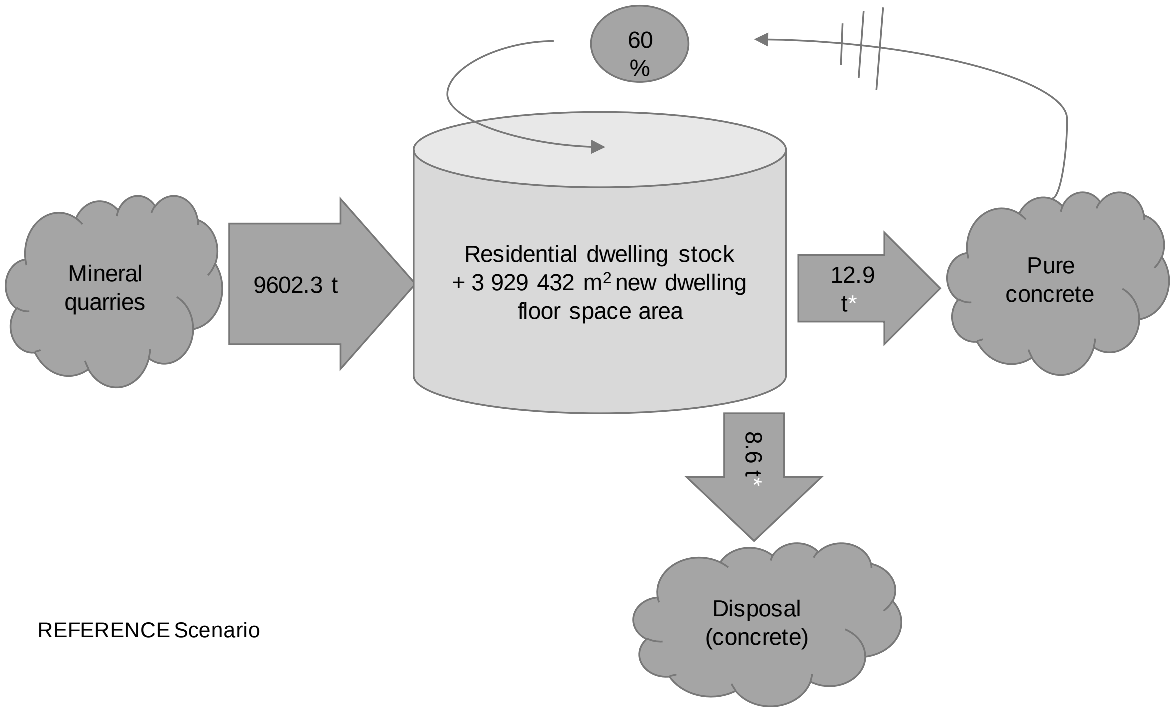

Figure 26: Stocks and flows 2020-2030: Medium scenario prediction for future material flows in the built environment of Oslo in the period 2020-2030, with no policy interventions (all numbers in 1000 tons, based on the latest available data; *model predictions of concrete and brick waste from the construction of small and large dwellings)

The increased flows also represent a construction bulk transportation demand, potentially increasing the freight volumes of freight operators such as the Port of Oslo. A recent regulation prohibiting the direct disposal of unpolluted abiotic materials could further strengthen the demand for quick dissemination of quality residues (Byggeindustrien, 2019). There are however fears that, contrary to national goals of shifting more cargo over to sea and rail, these operators are indeed losing market shares (Informant 4 in conversation 3. April 2019; Port of Oslo, 2013). Furthermore, materials are extracted further and further away from urban areas, where construction activity is most intense, resulting in ever-longer transportation distances (Informant 4 in conversation 3. April 2019). Both the Port of Oslo and Oslo Municipality express that they have little policy leverage in this area, as these conditions are largely driven by national and international drivers. The municipality is now investigating how to better manage flows of construction bulk through the city (Informant 3 in conversation 27. March 2019). According to Skanska, having reuse and recycling-terminals close to the city will be key to a sustainable urban development.

Indeed, Akershus county reached the same conclusion in its bulk management plan (Akershus fylkeskommune, 2016). Surveying the availability of raw and secondary construction materials the county summarised key reasons why re-use of bulk materials is currently under-utilized. First, they conclude that the quality of bulk that can be reused is not satisfactory, mainly due to poor sorting and storage at present. Many materials that are reusable are therefore wasted. Secondly, there are too few approved storage sites for longer-term storing of bulk materials. Thirdly, those storage sites that do exists are too small and far apart, making it costly for operators to manage these streams. Their key recommendation is to increase the reuse of residue bulk material through “ensuring areas for intermediary storage and treatment of residue masses,” in a regional perspective (Akershus fykelskommune, 2016, p. 26). Skanska seems to agree: “The circular economy and recovery solutions will play an important role in ensuring that national goals for emissions reductions are reached” (Informant 4 in conversation 3. April 2019).

Could, as these two stakeholders argue, circular economy practices and the facilitation of material re-purposing be a solution to the increasing challenges faced in the city of Oslo? Is the establishment of a recovery terminal in the port a real policy lever to alter the way the current system operates? One of the key objectives of this paper is to analyse the potential of the port as a materials hub, transmitter and location for circular economy activities**.** In the circularity scenario for dwelling construction in Oslo, this was one of many uncertainties to be tested. Based on insights from the circular economy literature and Donella Meadow’s systems theory, possible lessons will now be discussed.

Figure 27 presents the findings for the circularity scenario in the period from 2019-2030. The model illustrates a two-stock system, compared to the one-stock system in the reference scenario. The new second stock represents the Grønlia terminal (or other potential future waste management facilities) adding to the system a temporary, medium-term bulk material storage and treatment site, providing a secondary supply-stock for new construction in the city. In the circularity scenario, the system generates 18 700 tons of unpolluted concrete and brick residues prepared for recovery and 12 500 tons polluted materials for disposal. It is assumed up to 80% of the unpolluted materials can be redistributed at the local market. The remaining 20% is transported out of the system for landfilling. Up to 30% of residues from renovation and demolition activity in the main dwelling stock are directly reusable at site upholding stricter material re-use regulations and applying the latest industry sustainability standards, such as the Future Built circular building code.

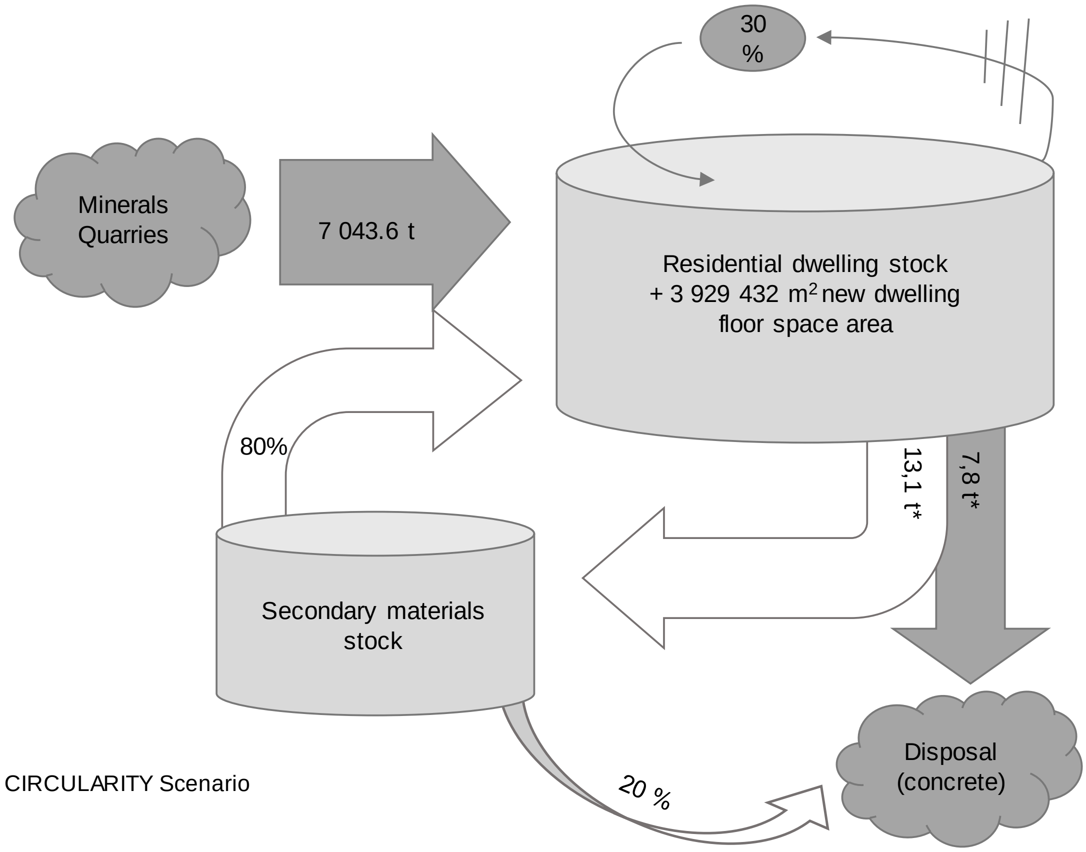

Figure 27: Stocks and flows 2020-2030: Circularity scenario prediction for future material flows in the built environment of Oslo in the period 2020-2030, with a significant shift to stringent circular economy policies (all numbers in 1000 tons, based on the latest available data; *model predictions of concrete and brick waste from the construction of small and large dwellings)

The benefits of a two-stock building materials system

In the scenario analysis, two of the scenarios assumed no changes to the structure of the system with stock and flow-dynamics being fixed. In the circularity scenario, the stock-dynamics were modelled to function as a two-stock system as new waste management facilities enable used, secondary materials to stay inside the system as a second supply-stock for the construction industry in the region. We recall from Meadows (2008) that non-renewable resources are stock-limited, meaning that the size of flows of for instance abiotic construction materials depend on readily available abiotic mineral stocks. Also, changing the structure of the system from a single-stock to a two-stock system alters its feedback mechanisms as well. For instance, when the dwelling stock grows, a reinforcing loop will make the secondary material stock grow as well as renovation or demolition activity picks up. Yet, this does not substantially alter the size of inflows or outflows, as import flows of virgin materials are substituted with re-distributed secondary material that is designed to last. Looping existing materials in this way, significantly reduce the extraction of new natural resources, thus stabilizing environmental footprints.

Implications of circular buildings on material streams

The construction system is characterised by the inflow of new building materials extracted from the lithosphere, flowing into the residential building stock, while outflows of residue and demolition materials are generated from new construction, renovation and demolition activity. Polluted or hazardous waste is permanently landfilled, while most pure waste streams are downcycled and used for backfilling. In the single stock system, the backfilled materials may re-enter the stock after a longer delay, but only as a lower grade product, e.g. rubble. The outflow of demolished materials does not respond to changes in the demand for materials in new construction, there will still be surplus, virgin materials entering the system. This is due to the growth in the total stock size, as well as the delay of outflows, given the long lifespan of most building materials. Similarly, there will always be spillages involved in recycling and recovery activities, generating new waste outflows. However, as circular buildings become the norm, materials will stay in the system much longer, as renovation extends their lifetime and materials from construction and demolition activity loop back into productive use. The changes to transportation needs depend on whether re-use takes place directly at site or at a used-materials treatment facility.

Port operations as a leverage point

The last lesson that will be discussed is the role that a port could play in the material management of a city. With the significant urban metabolism of Oslo’s built environment and the very limited internal production of building materials, large amounts of material input and waste output flows to and from the city every day. These materials must be transported over ever-greater distances and if materials are to be re-introduced into the value cycle, needs to be transmitted to treatment and repurposing facilities.

To mitigate this challenge, policymakers hold at least two levers for facilitating circular supply chains; 1) use ports as material hubs for the dissemination of used, pure materials or 2) place repurposing activities in the port itself for immediate reintegration of the materials. There are two reasons why port operations are policy leverage here. As ports already are at "the interface between different modes of transport," they can effectively link materials between consumers and producers willing to re-manufacture goods, even at great distances from each other (Hatteland, 2010, p. 43). de Langen & Sornn-Friese (2019) argue that ports are ideal clusters for enabling synergies between industries, as well as being well-positioned for circular economy activities. More than most other industrial sites, ports have high-quality connectivity to distant countries by sea as well as to their urban hinterlands, providing "access to circular feedstock as well as markets" (de Langen & Sornn-Friese, 2019, p. 17).

Evaluating leverage

The paper has here presented some of the benefits of adding a secondary materials treatment and storage facility in relation to the expansion of Oslo port operations. The absence of a centrally located materials hub has presented itself as a key obstacle to transitioning to a circular construction sector. Not only does such an intervention address secondary materials availability, but also provides a viable business model for the repurposing of materials. It could also prove to be a solution to traffic congestion and transportation emissions. There is however a range of other potential obstacles to the transition to a circular economy in the construction sector. Here I discuss some of the barriers and possible solutions to achieving circular construction that was identified in conversations with informants and from reviewing the literature.

Competing national policy objectives and outdated regulatory frameworks

At the same time, there are a whole range of related, potentially competing objectives that can counter a direction towards the policy objective of achieving circularity in the building sector. For instance, the Norwegian parliament has ratified a target for a ten terawatt-hours energy-use reduction in existing buildings by 2030, compared to current levels. Similarly, the main pillar in the governments housing market policy is to: "facilitate conditions for faster, easier and cheaper dwelling-construction" (Regjeringen, 2018). It might very well be that these targets pull in opposite directions with regards to material consumption and waste generation. Existing building codes and regulation on materials and waste management must also be adapted to a circular economy.

Attention to non-structural materials

In the 6S-framework, the base structure is but one of six layers producing building material waste. Indeed, there are also significant flows of shorter-lifetime, non-structural materials from the outer layers of the buildings, with glass from windows, timber from walls, and plasterboards and carpets from floors making up the largest waste fractions. Stephan & Athanassiadis (2018) survey the replacement flows of non-structural building materials within the city of Melbourne, Australia. Using scenario analysis about the building stock development, they map where secondary resources are available to substitute virgin material use and reduce waste generation. They conclude that there is untapped potential for restoring and reusing materials in the current building stock. In the city of Melbourne, these materials alone annually produce more than 750 tons of construction waste per square kilometre (Stephan & Athanassiadis, 2018). Yet, recovering non-structural materials is often very different from treating large quantity, abiotic bulk materials. Separate attention to non-structural materials is therefore needed, mapping outer layers of the built environment.

Sustainable renovation activity and demolition minimization

Sandberg et al., (2016) conclude that in order to achieve current European energy efficiency targets renovation cycles must be significantly shortened, allowing for substantial energy upgrade instalments. While this may provide benefits in a climate perspective, this amount of renovation activity might in itself generate substantial new flows of waste, putting a strain on mineral resources and disposal management systems. The recent trend towards demolishing rather than renovating existing buildings, such as public schools, is another issue in Oslo. The construction consortium EBA expects renovation activity in Oslo to slow down over the next years, from its average growth rate of 3 % to <1,5 % a year, due to “older private buildings increasingly being demolished as an alternative to renovation” (EBA O, Ø & A, 2018, p. 5).

Environmental product declarations must be integrated into the design phase

Demolition and renovation of the existing building stock generate large waste streams far into the future. As we expand on this stock, we need to design buildings for low environmental footprints as well as circularity. One informant claimed that attention to the process of approving and accrediting buildings early on was key in this regard (Informant 4 in conversation, 3. April, 2019). Architects and engineering consultants are often some of the first actors to engage with the building, at the design phase. If EPDs are not considered at an early stage and implemented into plans and architectural designs, most likely will they not feature at the time of construction either. Buildings must be constructed as designed, and thus all materials must be assessed and approved for environmental and safety standards prior to the implementation of construction plans.

A professional market for secondary materials

All interview informants mention the lack of a professional marketplace for secondary materials. This must be a professional marketplace where materials are bought, stored and re-sold by certified vendors. As mentioned, this task could be taken on by existing industry actors where especially sub-contractors and waste management companies already have relevant experience, or by new entrants. This marketplace needs to be physical but could have synergies with digital platforms for information dissemination. A digital tool for the local industry could foster greater interaction, enabling placing orders in advance and planning exchanges of materials

Industry partnerships and coordination at projects in close proximity

Another point that featured in interviews was the importance of industry coordination and partnerships. The informant from Skanska consider the industry actors to operate within silos, leading to traditional material choices and procurement (Informant 4 in conversation XX. April 2019). This was also stressed in the literature, underlining that synergies exist from one part of the value chain to another exchanging expertise for different stages of the material processing (Fischer, 2019; Zuidema, 2017). There are also positive examples from urban area developments at Fornebu, Lilleaker, Hovinbyen, where materials have featured in closed loops (Informant 3 in conversation XX. April 2019).

Method, model assumptions and limitations

This paper has tried to model the effects of circularity policies on final demand for raw abiotic construction materials and the generation of waste in three future scenarios. It has used scenario analysis to describe three different scenarios of the future development for the specified material streams. How the paper's scenario analysis can be used is suggested in the conclusion, yet it is important to acknowledge that all predictive models are uncertain and become ever more so further into the future. Overall, the paper holds the critical realist perspective that it is unrealistic to expect to be able to model and predict how complex, open social systems will look in the future (Sayer, 1992). Rather, scenarios are supposed to stake out future uncertainties and lay out possible outcomes for the future based on a sound, empirical description of the present and trends from the past. These scenarios can illustrate possible uncertainties and the greatest potential for change (Skancke et al., 2018).

The paper's circularity analysis methodology is referred to as a 'product lifetime extension' model. Unlike most applications of this model based on macroeconomic, demand-driven systems (see Aguilar-Hernandez et al., 2018), the model here has been applied to a local case, where part of the analysis involved other circularity strategies than lifetime extensions, such as closing supply chain loops. As such, the model tried to implement several change variables in one circularity scenario. This significantly increased the number of dependent variables and a need for high data resolution, complicating quantitative analysis. The model could also be accused of being overly reductionistic, where qualitatively interdependent social phenomena are separated into quantifiable variables. This increases the complexity of the model and the number of unknown factors and ignores interconnections increasing the likelihood of missing key causal mechanisms (Sayer, 1992). Here I discuss some of the most important shortcomings of the analysis.

The first regards the reliability of the model's input data. Uncertainty within the data and disagreement on these between sources on population projections (SSB, 2018 and Oslo Kommune, 2018), on commissioned floor space and housing construction (SSB, 2018 and EBA O, Ø & A, 2018) and on general input parameters (Sandberg et al., 2018, Sartori et al., 2008, Mortensen et al., 2018 and Hu et al., 2010) provided difficulties. As an example, SSB data is of high-quality assurance and the greatest frequency but does imply uncertainties at a micro-level such as on Oslo's construction activity as they measure activity based on where contractors are registered, not necessarily where the activity takes place (Mortensen et al., 2018). Further, the data suffers somewhat from being old, and perhaps outdated. The oldest values used for input parameters stem from 2001, 2007, 2009 due to a lack of access to updated sources on this. The variation of building types (and thus their embodied floor space) in a city like Oslo provides for further uncertainty within the data. The law of large numbers does somehow correct for this, however there was a trade-off between high resolution at the micro level and a dwelling sector as-a-whole perspective, for instance.

The analysis considers only considers a fraction of the building and material stock of Oslo and does not include categories such as infrastructure or office buildings. This can be expanded upon in future studies, however as infrastructure projects make up a small share of total construction and office construction market has much the same drivers, the case study findings still have analytical value. Further, the analysis does not consider building activity in the surrounding counties that make up the greater regional market and flows through the Port of Oslo to a certain extent. Another simplification of the model that limits the analysis of material demand is that all buildings were considered to embody the same concrete density-ratio. The calculation of material demand for other abiotic materials, such as cement, sand and bricks, assumed that all buildings are categorised by a concrete-brick combination structure that requires substantial abiotic materials. This category was however chosen for simplicity and as it is on the middle range for the material intensity of large buildings, and so is balanced by the prospect of there being constructed even larger heavy materials intense buildings (e.g. the new government offices planned in Oslo).

The model also fails to capture future renovation and demolition activity to assess material outflows relevant for recovery. According to model predictions by Sartori et al. (2008) renovation waste-streams will increase substantially over the coming decades and could greatly increase outflows. However, these flows are even more uncertain in the future, depending on renovation intervals, building lifetimes and material quality. Also, the dwelling models predict an increasing amount of construction activity in the coming period with a growing demand for housing, while renovation activity increase first after a longer time period. As such, this activity will fall outside of the period considered in this analysis. It was thus chosen to exclude this variable from the analysis. Still, as the model considers only absolute demand for housing floor space some of this naturally includes some renovation activity, where remodelling or rehabilitation of existing buildings is an alternative expansion strategy. It is worth noting that direct reuse of old materials might be significantly more feasible in rehabilitation and area development projects where secondary materials are significantly more accessible.

Further, for the dwelling construction scenarios described to be realized it is a necessary condition that markets are efficient and competitive. In an efficient market, contractors respond immediately and proportionally to increasing demand for dwellings and housing prices are given by supply and demand-functions. It also assumes that regulations are enforced by authorities and that as demand for recycling activities increase, the supply by industry actors increase proportionally. Some have argued that the market for housing is marked by imperfect information and competition, for instance due to large barriers to entry of new actors (Winther, 2019). Yet, these market mechanisms are very hard to predict in a scenario model. A final relevant point on market supply mechanisms regards capacity and production constraints. For instance, the circularity scenario assumes a direct substitution of raw abiotic materials to secondary materials and to alternative building structure materials, such as glued laminated timber. This substitution is contingent on the supply of these materials by the market.

Implications for future research

The limited analysis allowed for in this paper could by no means cover all areas of interest for the assessment of environmental footprints or circularity interventions in the construction industry. Here I discuss some of the relevant topics for future research.

Alternative assessments for material recovery

Currently, most assessments of the amount of recovered material in a construction unit, for instance a concrete-frame wall, is based on the total share of secondary material in the final product, in tons. With concrete, one of the most used and heaviest inputs is water. When we measure this share solely in terms of the total weight of materials in a building the heaviest materials such as concrete and steel tend to be emphasised. Rather than simply measuring the heaviest materials, more attention should be given to the environmental footprint or embodied carbon emissions of the relevant material categories, even if they are light-weight.

Distinguish between upcycling and downcycling

Another point is the increasingly important task to distinguish the types of repurposing strategies in recycling statistics. As waste management strategies become more sophisticated and more secondary materials can be utilized in new buildings, it is vital that material quality is maintained at the highest possible level. The repurposing of concrete and bricks can have mainly two strategies: Downcycling or upcycling. Downcycling crushes down the product to a lower grade material, such as rubble and machine sand. However, most of these materials are more valuable if they are reused at the same product category or higher. This must be reflected in statistics on recyclable material contents. It could also be relevant to investigate possible synergies between different material recovery systems, that today are highly saturated based on material type, with little attention to the final use-stage.

Carbon-intensive materials

It is also essential to map flows and stocks of other, more carbon-intensive materials, such as plastic and metals. This analysis only covered abiotic mineral construction materials, as these are currently the most common building materials with large trade flows through the Port of Oslo. However, we must also consider materials that produce even greater environmental footprints per kilo, or that are very scarce, such as rare earth minerals and critical raw materials (CRM). An analysis by Arm et al. (2016) showed that the potential CO_2-equivalents emission cuts through material recovery of wood, metal and plastic are many times larger than for concrete and asphalt, even if these materials generate little waste. This fits well in to current debates the best material choices for buildings, a debate this paper has steered away from.

More spatialised and accurate data on in-use material stocks

There is a lack of data on materials in the building stock with a low spatial resolution and high geological certainty (Rasch, 2018). There are currently efforts in mapping this, but has as of yet not been performed at the city level (Sartori, Sandberg, & Brattebø, 2016). This complicates studies on material flows from renovation and demolition activity as it is not yet known what materials currently are stored in existing buildings. This could also potentially inform developers and waste managers of when they are dealing with composite products with hazardous content that currently complicate recycling and disassembly at site. This could also enable the wider application of material passports. Arm et al. (2016) also identify the need for *s*tandardised European statistics: “Available data on environmental quality are uncertain due to the use of diverse and poorly documented (non-standardised) sampling, sample treatment, emission measurements and content analysis methods… It was found that assessments of sustainable use of resources and environmental impact were not possible to conduct based on the current European statistical data” (Arm et al, 2016, p. 1500). This is essential for the establishment of regional secondary material markets, where quality assurance schemes, such as CE-marking, are required.

Conclusions and recommendations

Summary of findings

This study has provided a summary of the latest literature on circular economy and definitions of circular buildings as provided by international and Norwegian leading experts. Then it developed on key scholarly work on Systems Theory and developed a methodology for analysing systems in their context. I then proposed a few key metrics for analysing the circularity of the construction sector as well as assessing the environmental footprints of current practices. The method was then applied to the material flows through the Port of Oslo, defining the system of flows and stocks, tracing these stocks through the value chain and the actors operating them. Current impacts of this system were then mapped using a material flow analysis of a freight and waste generation case. A sustainability path for the system was related to current and prospective circular economy policies that were assumed to impact on the system over the coming decade. Then the study moved to a scenario analysis, identifying three contrasting pathways as either a reference-trend scenario, a high growth scenario or a circularity scenario. The different scenario input parameters were then implemented in the model which gave clear indications of the difference between the scenarios.

What role can ports play in shoring up the circular economy, through their attributes as transmitters, gateways and industrial hubs for a large quantum of material flows today? Through the scenario analysis, it was identified that in a future scenario of circular construction material flows, raw material demand from Oslo's construction sector will reduce significantly, even with increasing industry activity. Waste generation are also predicted to fall drastically. There are still a lot of unknown factors, so it is not clear from this analysis alone how total waste streams would look for the port in a fully circular construction sector. Such a transition would undoubtedly have a great impact on the operations of the port as well as the entire construction value chain. In a system where all material and residue supply chains enter closed loops, it is very possible less will have to be transported at long distances. However, most waste would likely have to be treated and it is too early to determine where such treatment will ultimately take place. If this value cycle does involve a larger regional network of actors in the current construction chain, as have been predicted by several scholars, port terminals for operating freights quite efficiently could indeed play a larger role in re-distributing these materials throughout the regional value chain.

It was also found that waste generation from the construction of new dwellings will reduce substantially, resulting in a radical shift in current waste streams leading out of Oslo. In this scenario, it is assumed that most waste streams will remain inside the municipality of Oslo, processed at repurposing terminals and reutilized locally or shipped for re-treatment in the surrounding region. The Port of Oslo is expected to be able to take the role of a materials hub, where materials loop in a circle of use, treatment, distribution to new projects and re-use. As stricter recycling and waste disposal regulations are implemented it is also expected that more actors in the value chain will shift towards waste management operations and a market for reprocessed end-of-life materials will emerge. These operations will require space and capacities within a short distance from construction activities to be viable economically as well as delivering actual emission cuts from transportation. A materials bank and repurposing terminal at the port area might prove to be a key policy leverage moving towards a circular economy.

Getting the circular construction industry to shore

Oslo has been one of the fastest-growing cities in Europe per capita over the last decade. Over the next 10 years, the population will grow with up to 100 000 new inhabitants, requiring an additional 50 000 dwellings. These must either be constructed from scratch or expanded upon the current building stock. Currently, the construction of dwellings is responsible for around 21% of total emissions in Oslo and consist of 22% of the total emissions from the activities of Oslo Municipalities. To achieve current local and national climate goals the municipality must address this sector, where there are substantial emission reductions potential. Yet, Oslo needs to place more attention to its indirect emissions, potentially 10 times higher than its territorial emissions and larger than the national average. Particular attention should be placed on the production of construction materials needed to satisfy the demand for more buildings to house Oslo’s rapidly growing population. More than 90 % of the materials bound for construction in Oslo are extracted and produced outside of Oslo, generating substantial emissions and leaving large environmental footprints in those localities.

Create material hubs for secondary materials storage, treatment and re-distribution

There are still many lessons to be learned from systems theory and the principles of the circular economy and industrial symbiosis for our urban systems. One such lesson for the city of Oslo could be the value of adding extra capacity for medium-term storage and handling of used goods and bulk material residues from the construction sector. This adds a secondary stock to its material flow system and works as a meeting place for construction industry stakeholders. Experimental and short-term projects have already proved useful, generating new business concepts and providing an important learning experience. Neighbouring municipalities are currently exploring how to better manage material flows, such as the materials bank in Bærum and a material repurposing terminal in Ås. This can be done through the Port of Oslo as a central materials hub in existing value chains and a node for industrial networks. A terminal for recycling and repurposing of bulk materials could be a key brick in Oslo's circular economy foundation as it transitions to a sustainable future.

Utilise ports' logistical connectivity and seaborne transport

The nature of the urban metabolism of Oslo and other large urban areas means vast amounts of materials are flowing into and out of their city bounds. For one, import of construction materials requires the transport of large quantities of heavy abiotic minerals, resulting in congestion and emissions from transportation nodes. Of imported material transported over 55 kilometres from Oslo, more than 50% are handled at the port area in Sydhavna. While the Port of Oslo is to reduce its emissions to zero by 2030, it expects its dry bulk handling volumes to increase 31% by the same year. This places pressures on port operations to quickly phase out fossil fuels while working to expand freight capacity. Increased capacity to handle dry bulks does, however, present opportunities for the city's high-consuming construction sector. The port can prove to become a central part of the city's circular economy ecosystem by functioning as a central node in an industrial symbiosis and transmit secondary material flows to and from more distant regions of Norway as well as neighbouring countries. For the Port of Oslo, this represents a strategic venture to recapture bulk freight market shares as imports of fossil fuels and other linear products reduce.

Implement a long-term vision for a fully circular city

While striving to achieve its ambitious climate objectives, the Municipality of Oslo also needs to start working reduce its material intensity and waste generation by transitioning to a circular economy. For the construction sector, reuse of materials is one of the biggest gaps to the 2050-vision staked out in the industry roadmap. Nationally, the construction sector generates close to one-quarter of all waste, where around 40 % is directly landfilled. This is a gross waste of vital resources, in a time when the world is running out of nature's resources, sand being one crucial example. Yet a large proportion of construction and demolition waste are fully reusable and 60 % of residues are currently prepared for re-use or recycling. Construction activity, therefore, needs to transition into a circular building value chain, where the residues from one activity form the resource base for the next. Renovation activity needs to start dominating the industry, where existing buildings are expanded, remodelled or restored to its original state. This will expand the lifetime of buildings and could ease the re-utilization of its materials.

The construction industry is but one example of where our current system operates beyond sustainable boundaries. Yet it represents a keystone to any transition to a circular economy. This paper has tried to illustrate the useful tools of material flow and scenario analysis to plan and facilitate for the circular value cycles. Mapping the origin, transportation modes, value chain operators and destination of a set of materials can be crucial information when designing policy geared towards circularity. It might highlight areas in the system that have disproportionally large environmental footprints and where to address interventions. System analysis makes seeing the whole picture, tackle root causes and avoiding burden-shifting easier. Scenario analysis helps planning for different possible outcomes and generates real policy options. While the model utilised in this paper contains uncertainties and only covers part of a contextualized, open system, relative weights and the direction of change can be generalised to other situations. It might inform organisations on the general strength of future circular flows and position themselves for new circular markets. More research is needed. Yet, that cannot excuse inaction on mitigating a pending climate catastrophe.

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Appendix 1

Table A1: Development in input parameters and total raw material demand in a high growth and high circularity scenario for the construction activities in the three periods.

High growth scenario

Input Parameters	2013-2017	2019-2024	2025-2030	Unit
Population growth (high)	42793	66449	77550	persons
New floor area growth (high)	1407560	2953289	3446667	m2
Materials				
Concrete	985292	2067302	2412667	t
Cement	208460	437382	510451	t
Sand	807236	1693711	1976663	t
Gravel	925893	1942673	2267217	t
Brick	512774	1075883	1255621	t

Circularity scenario

Input Parameters	2013-2017	2019-2024	2025-2030	Unit
Population growth (trend)	42793	44808	43604	persons
New floor area growth (trend)	1407560	1991467	1937965	m2
Materials				
Concrete	985292	1092917	807162	t
Cement	208460	235949	200909	t
Sand	807236	913685	777996	t
Gravel	925893	1047990	892355	t
Brick	512774	580393	494200	t

Table A2: Dwelling construction waste, for 2013-2030 in reference, high growth and circularity scenarios

Reference: Dwelling construction waste	2013-2017	2019-2024	2025-2030	Unit	SUM	By category
Concrete & bricks; Large	8254	9343	9091	t	18434	
Concrete & bricks, Small	1383	1565	1523	t	3088	21522
Disposal, Large	3302	3737	3637	t	7374	8609
Material repurposing, Large	4952	5606	5455	t	11060	
Disposal, Small	553	626	609	t	1235	
Material repurposing, Small	830	939	914	t	1853	12913
High Growth: Dwelling construction waste	**2013-2017**	**2019-2024**	**2025-2030**	**Unit**		
Concrete & bricks; Large	8254	13855	16169	t		
Concrete & bricks, Small	1383	2321	2709	t		
Disposal, Large	3302	5542	6468	t		
Material repurposing, Large	4952	8313	9702	t		
Disposal, Small	553	928	1084	t		
Material repurposing, Small	830	1393	1625	t		
Circularity: Dwelling construction waste	**2013-2017**	**2019-2024**	**2025-2030**	**Unit**	**SUM**	**By category**
Concrete & bricks; Large	8254	8011	4830	t	12841	
Concrete & bricks, Small	1383	1342	809	t	2151	14992
Disposal, Large	3302	1602	0	t	1602	7765
Material repurposing, Large	4952	6409	4830	t	11239	
Disposal, Small	553	391	0	t	391	
Material repurposing, Small	830	1074	809	t	1883	13122

Table A3: Dry bulk flows into the port of Oslo: Metal ores, stone, sand, gravel, clay, salt, cement, lime, fertilizer, manufactured construction materials (tonnes cargo by year; SSB, 2018)

Year	2011	2012	2013	2014	2015	2016	2017	2018
Cargo (t)	1033	985	1146	1093	1410	1562	1593	1577

Appendix 2

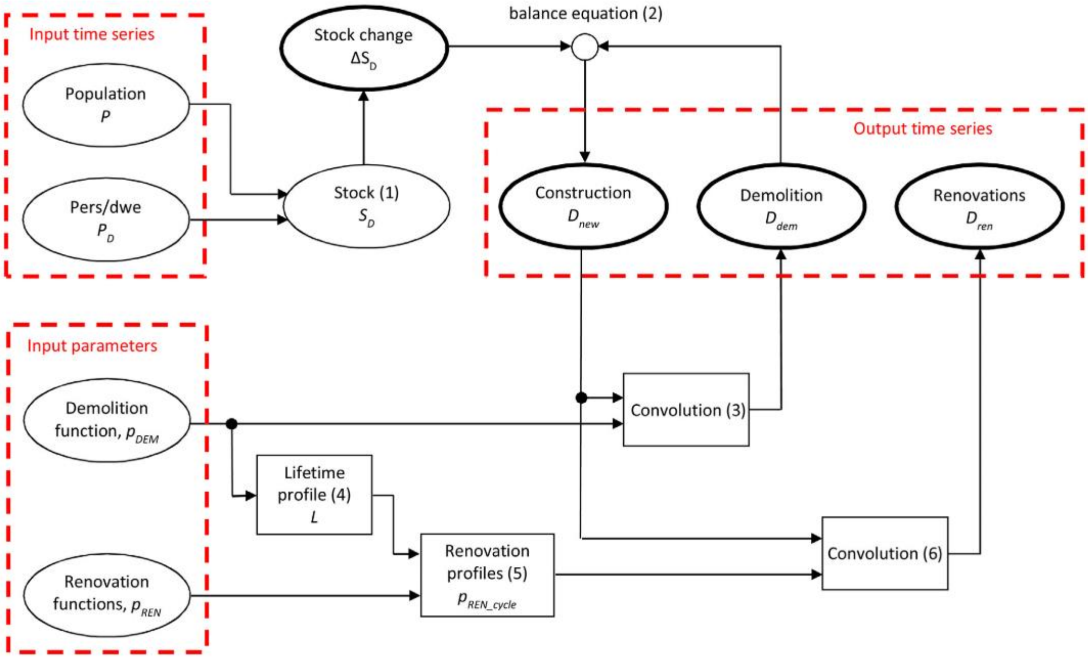

Figure A1: Schematic representation of construction system model. Describes theoretical input and output variables. Source: Sandberg, Sartori & Bergsdal (2016), p. 15

Appendix 3

Standardised interview guide

1. Din organisasjons utgangspunkt og vurderinger
    a. Hvordan ser dere markedet for sekundære byggematerialer og komponenter utvikle seg?
    b. Merker dere en reell etterspørsel etter sirkulære bygg og materialer?
2. Klimagassutslipp og utslippskutt fra byggesektoren
    a. Kan du si noe generelt om utsiktene for bransjen innen klimakutt og miljø?
    b. Rapportering av indirekte utslipp (internt)
3. Lovverk og målsetninger
    a. Hvilke krav stilles særegent i Oslo?
    b. Rapportering av oppfølging av vedtak
    c. Tilstramming av krav til sektoren/ oppfølging underveis
4. Sirkulære bygg-definisjon
    a. Hvordan vil du definere sirkulære byggevarer?
    b. Avveininger mellom indikatorer: ressursintensivitet, forbruk, livsløpsanalyse, utslipp (transport) etc?
    c. Hva mener dere er det viktigste å få definert/målt?
5. Ombruk av byggematerialer og ombrukbarhet
    a. Hvordan sikre god kvalitet (lang restlevetid) og tilgjengelighet?
    b. Hvilke materialtyper og komponenter er prioritert?
    c. Hvordan måles/vurderes ombrukbarhet?
    d. Har dere planlagt å stramme til kriteriene ettersom flere prosjekter oppfyller (minste-)kravene?
6. Logistikk og masseforvaltning
    a. Hvor stort er markedet?
    b. Hvem er tilbydere og kunder hos dere i dag? Hvor mange aktører er det?
    c. Hva er deres forhold til hverandre?
    d. Hva er mulighetene for lagring/ tilgang til lager?
    e. Hvor langt skal avfallsmaterialer transporteres?
7. Spesifikasjoner for Grønlia
    a. Hvor stor vil maks-kapasiteten være? Dekker dette etterspørselen?

8. Vurderinger for markedsutviklinger
    a. Hva er de største barrierene mot mer (sirkulær) sjøtransport og masseforvaltning per i dag, fra deres synspunkt?
    b. Hvordan spår dere dette segmentet (som andel av deres virksomhet) vil utvikle seg i fremtiden?
    c. Er det mest relevant å se dette i en verdikjede?
9. Case-studier, aktører og praktiske eksempler
    a. Har du noen gode eksempler, der dette er gjort i praksis?
    b. Vet du om liknende studier eller caser fra Oslo-området?
    c. Eller internasjonalt?

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