Thesis Paper

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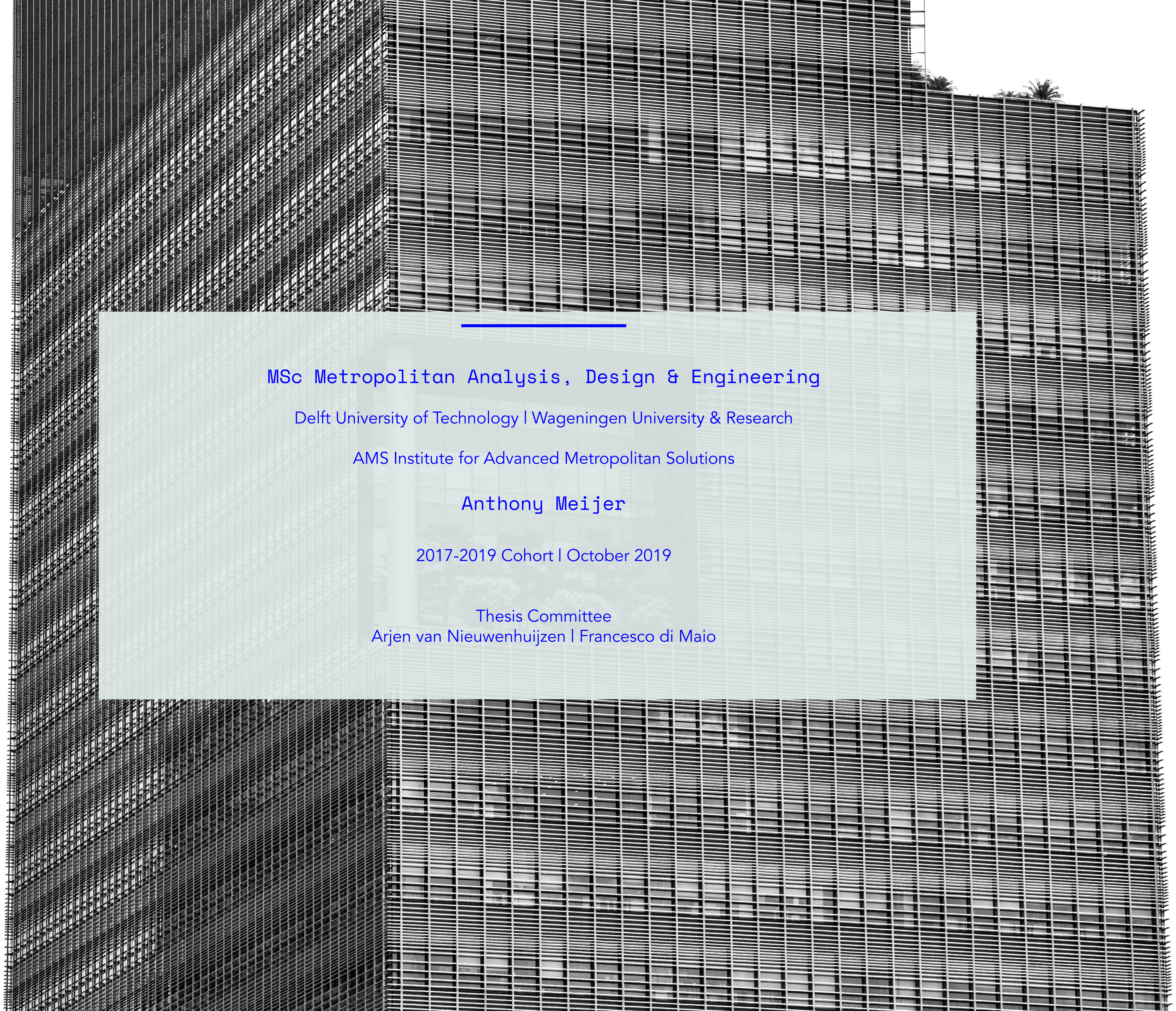
Opportunities to Close Resource Loops in the Construction Sector of Singapore



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Opportunities to close resource loops in the construction sector of Singapore

Fast urbanization has led to significant extraction of material resources, which end up stocked for a long time in the built environment. While economic growth has usually been directly proportional to trends of increasing resource exploitation, the circular economy (CE) approach is gaining increased attention in the sustainability agenda for its framework focused on decoupling economic growth from the consumption of finite resources. This paradigm shift towards a circular, resource-efficient economy requires a comprehensive knowledge of the flows and material stocks (MS) in buildings and infrastructure. In the case of an import-dependent country like Singapore, the built environment can serve as a valuable reservoir of secondary resources, underlaying fundamental importance for the nation's circular economy ambitions. Assessing the MS in cities has been the focus of several studies for insights into the in-use materials and their potential availability as secondary resources, based on the argument that such estimates will help to create mechanisms for increasing the usage of secondary resources. However, studies often are restricted to building infrastructure, despite the qualitative relevance of roads, a significant driver behind the demand for low-value reuse of construction & demolition waste (CDW) with direct effects over the overall supply and demand of secondary resources. This paper argues that linking supply and demand estimations to the drivers behind downcycling and upcycling of CDW is necessary, in order to unveil realistic opportunities for secondary resource utilization. The primary motivation in this study has been to deploy a bottom-up approach to quantify the entire stock and flows of concrete for buildings and roads within Singapore, in a quest to unveil windows of opportunity where closing resource loops is realistic. Results show that the concrete stock has grown by 21% on a 3% per year average from 2010-17, in proportion to 6% per year of GDP growth. Concrete stock is expected to grow from 220Mt in 2015 to 307Mt in 2050, which would require 13,4Mt of concrete in 2020, 43,2Mt in 2030, peaking at 310Mt in 2050. In contrast, 70,8Mt of concrete in the building stock are expected to reach their end-of-life (EOL) until 2050, with the most substantial contribution arising from the residential sector. By 2035-50 estimations suggest that local supply of EOL concrete will not be sufficient to sustain the entire construction demand by then. Nonetheless, a surplus scenario is foreseen for the next 15 years (2020-35), way beyond the yearly concrete demands for buildings and roads in the period. This oversupply creates an appealing scenario to increase secondary resource utilization. Hence, the next 15 years are a crucial period in time for Singapore to address the gaps in place for a transition towards the CE.

Keywords: Circular economy; Construction and demolition waste; Material flow analysis; Urban metabolism; Zero waste; ReCirc Netherlands-Singapore;

A.Introduction

The construction sector and the built environment consume the largest share of materials globally (Schandl et al., 2016), accounting for 40% of all extracted raw materials (Di Maria et al., 2018) and representing the highest share of local waste production (Athanassiadis et al., 2016). Fast urbanisation has led to significant material accumulation in cities, which are expected to host 86% of the population in the developed world by 2050. The material stocks (MS) of built environments in varied forms such as building infrastructure (e.g., residential, commercial, and industrial) or nonbuilding infrastructure (e.g., transportation networks, tunnels) has been shown to be the most abundant resource sink (Wiedenhofer et al., 2015; Huang et al., 2017; Liang et al., 2017; Arora et al., 2019). This accumulation remains a fundamental constituent of socio-economic metabolism from an environmental and resources point of view (Kleemann et al., 2017a; Krausmann et al., 2017a, 2017b).

One of the most significant economic, social and ecological challenges of our time is preserving the natural environment through efficient consumption of natural resources (Schiller et al., 2017). Hence, achieving sustainable levels of consumption of materials is one of the critical objectives of the United Nations Agenda of Sustainable Development Goals (SDGs). MS of built environments are of fundamental importance not only for exercising their function, such as housing and transportation but also as a reserve of anthropogenic resources. The decommissioning of these stocks through demolition creates a stream of materials which could be primarily reused or recycled into new construction materials (Hoglmeier et al., 2015; Wang et al., 2015). Krausmann et al. (2017) estimated that by 2030, 35% of the material stock in use in 2010 would be discarded, yielding 274 Gt of end-of-life (EOL) outflows, approximately the same amount of outflows of the previous 110 years combined. With the sheer magnitude of these outflows coupled with over-exploitation of natural resources and the threat of increasing carbon emissions, the role of secondary raw materials has taken centre stage in responsible consumption.

Today most of the construction and demolition waste is either recycled off-site, landfilled, or used as a foundation in road construction, which is a downcycling (or low-value) application, but more useful than landfilling at the expense of the near-complete loss in material value (Miatto et al., 2018). In the Netherlands, the reuse of construction and demolition waste (CDW) is already widespread (>95%), but often the materials are not reused at the same level. Approximately 80% of demolition waste is repurposed as the sub-base for roads (Kibert et al., 2000). Albeit the fact that road foundation is a useful outlet for recycled aggregates, it is not a sustainable application in the long run (Di Maio, et al. 2015). Hence, achieving sizeable environmental impact reductions will require an increase in the utilization of construction and demolition waste as a raw material in the manufacturing of new construction materials (Pacheco-Torgal et al., 2013; Mastrucci et al., 2017). Firstly a surplus of outflows from EOL buildings is expected while demand for road foundation might decline amid an expected decline in the net growth of infrastructure (Di Maio et al., 2016). Secondly, keeping business-as-usual scenarios of future material demand project that world-wide material use will more than double until 2050, with untoward adverse effects on the natural environment (Krausmann et al., 2017). Although downcycling applications of CDW are a necessity amid road construction demands, it is crucial to forecast when such scenarios of the surplus will come in place as opportunities to recover the full value out of CDW.

In this context, the Circular Economy (CE) approach is gaining increased attention for its framework focused on decoupling economic growth from the consumption of finite resources (Murray et al., 2017; Adams et al., 2017). Initiatives are being pursued in many countries around the world to develop the CE along with the direction of environment and finite resources preservation (Moriguchi & Hashimoto, 2016). This paradigm shift from the current linear resource-intensive, towards a circular, resource-efficient economy, requires a comprehensive knowledge of the flow and materials stocked in buildings and infrastructure (Baynes & Müller, 2016). The better understanding of waste outputs helps to anticipate planning capacity for future adequate resource management treatment. Moreover, thus helps to expand capabilities to decrease the burden over the natural environment by increasing resource efficiency towards economic opportunities (Icibaci, 2019). Material flow analysis (MFA) has gained traction as an excellent tool to systematically study the flows of materials and stocks and unveil the potentials for waste recovery and recycling (Schiller, Gruhler, & Ortlepp, 2017).

Recently, estimations of material stocks and flows at different geographical scales in the hope of enabling secondary resources have been emphasized in the industrial ecology domain (Fishman et al., 2014; Krausmann et al., 2017a; Arora et al., 2019). Schiller et al. (2017) investigated the closure of material loops for the case of concrete within the German building sector considering qualitative aspects that affect the capture and processing of CDW into new construction materials. Tanikawa et al. (2015) emphasised upon the calculation of countrywide material stocks to fully comprehend the socio-economic metabolism and the set of flows of materials and energy between nature and society. There has been a significant increase in material consumption and stock studies particularly in Europe (Kleemann et al., 2017a, 2017b; Ortlepp et al., 2016, 2018; Schebek et al.,2017; Schiller et al., 2017; Wiedenhofer et al., 2015), USA (Kapur et al., 2008; Miatto et al., 2017b; and Asia (Nguyen et al.,2019; Cao et al., 2017a;Fernandez, 2007b; Fishman et al., 2014; Hu et al., 2010; Liang et al., 2017; Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009;Vilaysouk et al., 2017; Yoshida et al., 2017). Moreover, various studies have now estimated global material stock and consumption, including hibernating stocks (Cao et al., 2017b; Krausmann et al., 2017b). MS estimations have been made for varied geographical scale from national to global, acknowledging the importance of in-usee stocks and possible outflows (Schiller et al., 2017; B. Müller, 2006; Cao et al., 2017a; Cao et al., 2017b; Kapur et al., 2008; Kleemann et al., 2017a; Krausmann et al., 2017b; Ortlepp et al., 2016, 2018). These MS studies have additionally focused on aspects such as spatial and temporal variations. Common material types analyzed include metallic and non-metallic minerals, cement, wood, and asphalt.

Though MS studies have various motivations, often the focus is on secondary resource use as one of the reasons or benefits of such an exercise. MS studies for the built environment sector often apply material intensity factors in order to estimate total material stocks (Allwood et al., 2010; Schiller et al., 2017; Augiseau and Barles, 2017; Krausmann et al., 2017a; Arora et al., 2019). These estimates provide an idea of the quantity of each material present per study area. Based on the argument that such estimates will help in creating mechanisms for increasing the usage of secondary resources, a majorly overlooked aspect has been the gap between supply and demand of recycled aggregates. When studies address this gap, it only occurs implicitly or theoretically (Schiller et al.,2017). The ratio of supply to demand, or outflow to inflow, significantly determines the potential for substitution of natural resources by anthropogenic resources (Hu et al., 2010; Ortlepp et al.,2018). Some MS studies recommended actions for improving the management of material stock and outflows in order to close resource loops and achieve a circular economy (Müller et al., 2014; Ortlepp et al., 2016; Schiller et al., 2017). However, their impact has been limited by the singular sector approach, either focused on the building or nonbuilding infrastructure. Therein studies have debated that increasing high-quality recycling to acceptable rates requires an inter-sectoral approach, to address the supply needs between drivers of demand for downcycling and upcycling applications. Roads are one of the main drivers behind down cycling of CDW; however, the number of MS studies on non-building stock, such as road networks, have been restricted despite their quantitative relevance (Nguyen et al., 2019; Miatto et al., 2017a; Miatto et al., 2017b). Roads account for the largest share among non-building infrastructure. Furthermore, modern roads are highly resource-intensive infrastructures requiring massive extraction of materials for their construction and maintenance (Miatto et al., 2017b). It is, therefore, within the interests of sustainable consumption of natural resources to keep the supply of recycled aggregates for road networks at a sufficient level.

Such knowledge gaps prevent a realistic assessment over opportunities regarding the increase of secondary resource usage. This study is a prime attempt to address this gap, including road network inflow and stock estimations along with the material stock and flow estimations for building infrastructure including residential, commercial and industrial buildings. The stock and flows of concrete set the boundaries of the analysis carried out at this moment. The production of cement, an essential part of concrete production, is the largest non-combustion related emitter of CO_2 (Olivier, Peterss, & Janssens-Maenhout, 2012). With concrete the most used construction material worldwide, it is locally the most significant stream of CDW, having the highest environmental impact.

A.1 Aim and Scope

This paper argues that linking supply and demand estimations to the drivers behind downcycling and upcycling of CDW is necessary, in order to unveil realistic opportunities for secondary resource utilization. For so, it shall comprise of both building and non-building infrastructure and its interrelations on supply and demand. On the one hand, the sectors that demand CDW downcycling (low-value) applications and on the other the sectors that could upcycle CDW into new construction materials, which is considered a high-value application. Hence the primary objective of this study is to apply an extended bottom-up method to estimate stock and flows within the residential, commercial, industrial and road sectors. A secondary objective is to analyze the short- and long-term interrelations between supply and demand across these sectors in an attempt to unveil opportunities for secondary resource utilization in new construction materials. This methodological approach has been applied for the case of Singapore. For an import-dependent country like Singapore material stock estimations and potential outflows remain crucial for matching demands and achieving resource efficiency. While the existing building stock can become a significant source of secondary materials, broad estimates remain unavailable (Arora at al., 2019). Despite Singapore ambitions within the Circular Economy, to date, there are no MS estimations for the built environment that considers the entire spectrum of buildings and road infrastructure. At present, the government focuses on the pursuit of zero waste strategies (Leng, 2010), which undermine resource and value recovery, prerequisites for the CE.

Gursel and Ostertag (2016) highlighted the need for minimizing export and accepting locally available resources for buildings in Singapore. Schiller (2017) provided an example of Germany to argue that several factors need to be addressed in densely populated urban areas for meaningfully utilizing an industrial ecology approach. Exact estimation remains key to maximizing secondary resources utilization potential (Schiller et al., 2017; Miatto et al., 2017) even though estimations and forecasts alone are not able to lead to an increase in secondary resource utilization, as other challenges are present, which are beyond the scope of this study.

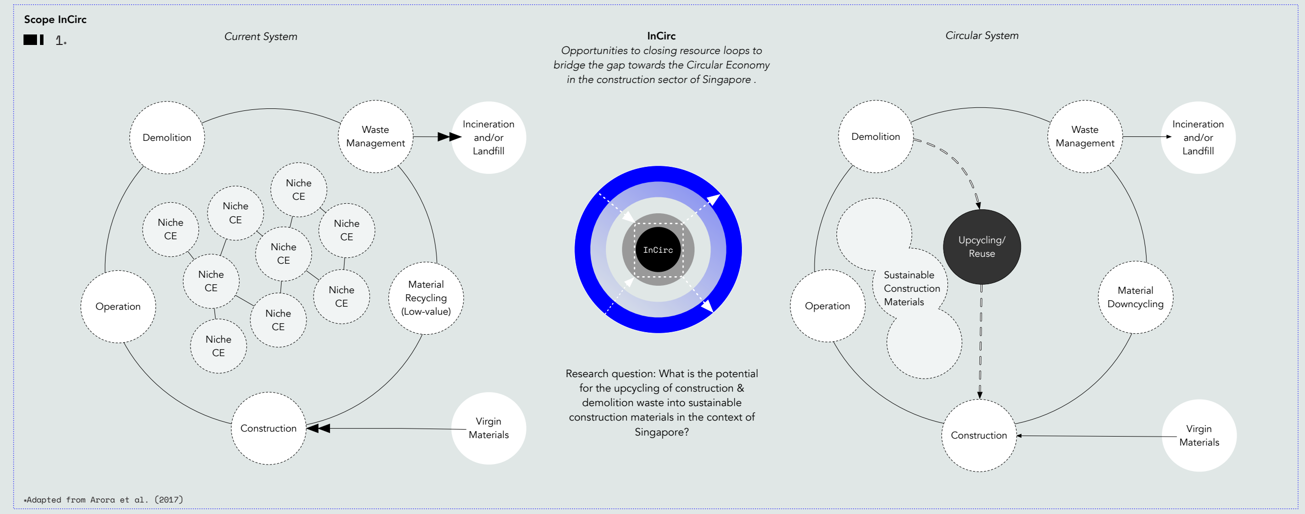
B.Methodology

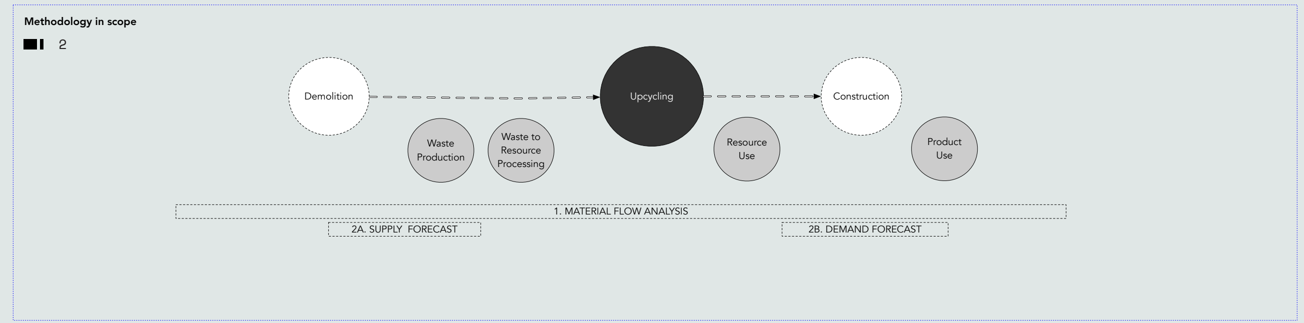
Modelling of material stocks is a standard method to assess past, present and future material reserves (Muller et al., 2014). Stocks of secondary materials are dynamic and prone to fluctuations in size (buildings added or withdrawn), by material types and techniques applied in new constructions, and yet by the speed of release from the stock according to the building's lifetime. There are various approaches to study construction material flows and stocks, according to Augiseau and Barles (2017). These approaches are determined by the combination of several components, which include: 1) static or dynamic; 2) bottom-up or top-down; 3) prospective or retrospective; 4) stock or flow driven. According to Hu et al. (2010), stock driven models are most suitable for long residence-time goods as buildings. Tanikawa et al. (2015) highlighted that most studies tend to be top-down material accounting exercises because of multiple factors. Mainly due to lack of granular data and far-reaching efforts needed for the bottom-up study, emphasizing the need for work in country-specific studies based on a bottom-up approach.

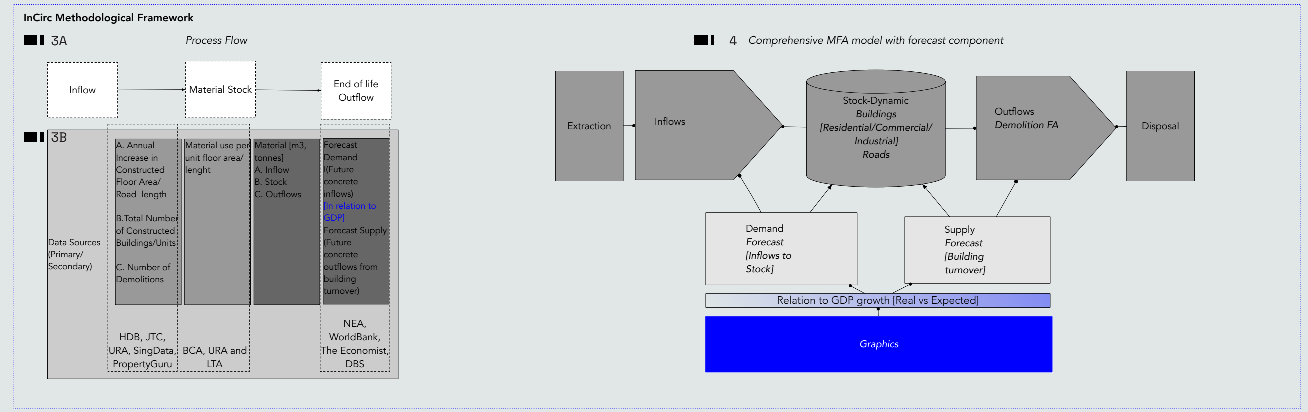
Nevertheless, bottom-up MFA is a suitable method to quantify stocks and flows of materials in complex systems, offering high flexibility in model design and the differentiation of results. Bottom-up approaches can supply more refined information about building material composition, including classification by type of material and distinction between different forms of building stock. This research applied an extended bottom-up approach to account for material stock in buildings and road infrastructure based on a general model of stocks and flows depicted in figure3. Roads have a qualitative relevance in material demand for their construction and maintenance, as demonstrated in previous MS studies (Miatto et al., 2017). Furthermore, they account for a significant share among non-building infrastructure, hence the choice for this research to consider the entire infrastructure of roads in the calculation of flows and stocks of non-building infrastructure. Based on the general model, the inflows, stocks, and outflows were estimated based on the annually constructed floor area or length of the road, the total number of buildings, apartments or total floor area and demolition data (figure 3B). This study quantifies the material stock of existing buildings from private and public sectors (residential, commercial and industrial), and road infrastructure, along with annual material inflow and material outflows associated with building demolitions (excluding renovations). Material intensity factors for Singaporean buildings are determined based on concrete usage indexes and steel to concrete usage ratios. The calculation of total material weight per layer and road type determines the material intensity factors used in this study for roads. The scope of this research is limited to concrete and steel in buildings and bitumen, quarry waste, concrete and recycled concrete aggregate (RAC) for roads, the typical materials utilised in the Singaporean road infrastructure (see figure 11). However, the extended analysis over demand and supply and its interrelations confine itself to concrete, a quantitative choice in line with the scope and time-frame of this study (figure 4). Data is entirely based on information from regulatory bodies (annual reports, statistics, material properties) and grounded assumptions through practices adopted in MS studies to fill data gaps. The inventory of material stocks and flows comprises of the entire public and private stock, and respective yearly demolitions.

C.Case study of Singapore concrete stock for sustainable construction

Singapore is a dense city-state in Southeast Asia, highly relevant for its building material stock and - potential - annual contribution to secondary resources. With 716 square kilometres of land area, Singapore supports a population of 5.6 million people (figure 5). Since land is scarce and densely occupied, it is a significant importer of building materials (Chertow et al., 2011; Gursel and Ostertag, 2016; Schulz, 2007). Three hundred eighty square kilometres out of 716 km2 is built- up with housing, industry, utilities and transport infrastructure (Chew, 2010; Yang, 2008), with an increase of underground space utilization in the coming decades expected (TODAY, 2018; Zhou & Zhao, 2016). Singapore seats high on the ladder with one of the highest cement consumptions per capita around 6 million metric tons annually. Most of the country's cement demand is met through imports with major cement terminals for unloading, zero trade tariffs and logistics. The demand for cement in Singapore has been growing from 4.4 million metric tons in 2008, 5.87 million metric tons in 2013, to 5.97 million metric tons in 2014 and it is expected to increase at 5% over the next few years. This demand is aligned with the construction sector's contribution to GDP, doubling in the last decade (Gursel and Ostertag, 2016). On its way towards a leading modern nation, Singapore has accumulated an enormous wealth of buildings and infrastructure, which consti-







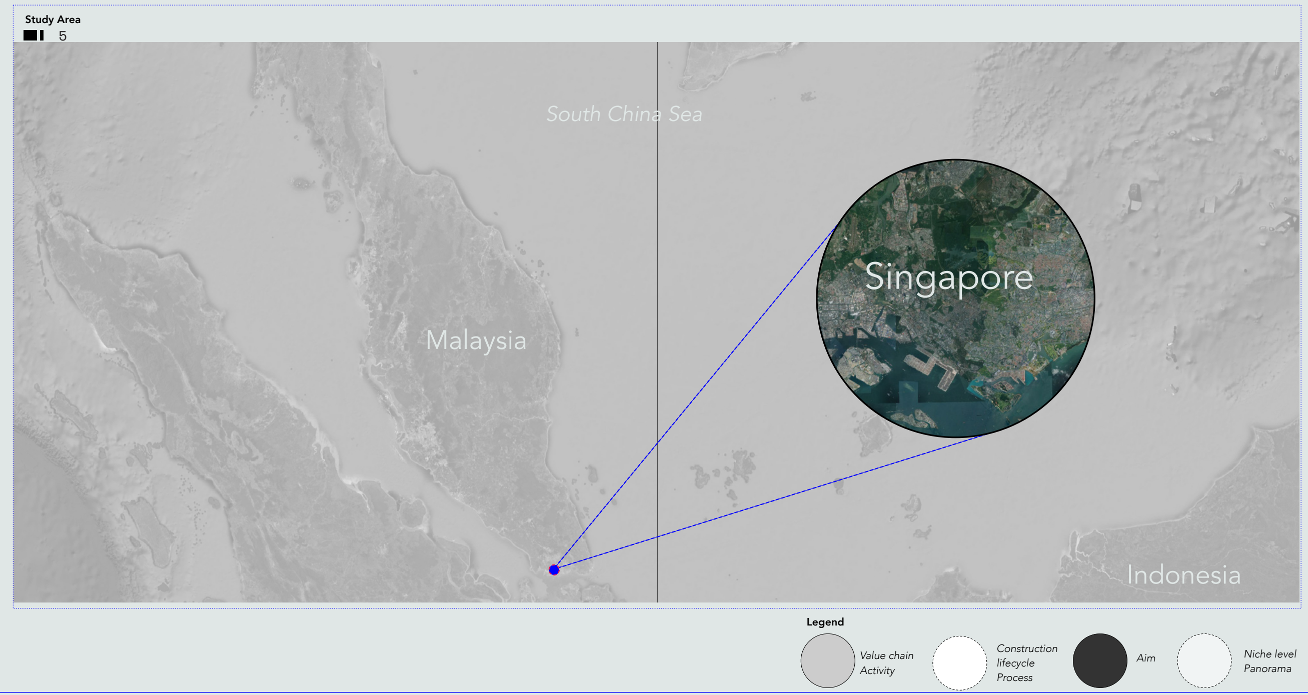


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Fig. 6: Fractions of dwelling typologies per type of building. Fig.7: Annual increase in lenght of road per category (LTA, 2019). Fig. 8: Annual increase in number of dwellings per type of building (DOS, 2019; HDB, 2019; JTC, 2019). Fig 9: Share of units and floor area per category. Fig 10: Annual demolition in units per category (HDB, 2019).

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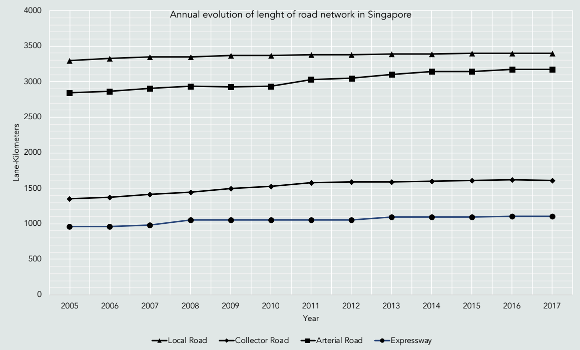

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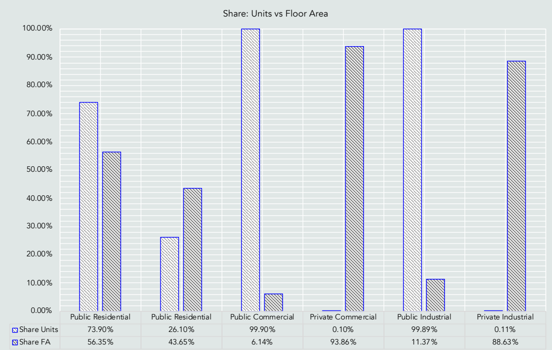

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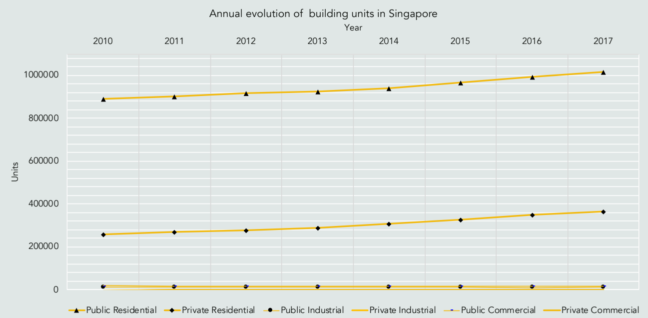

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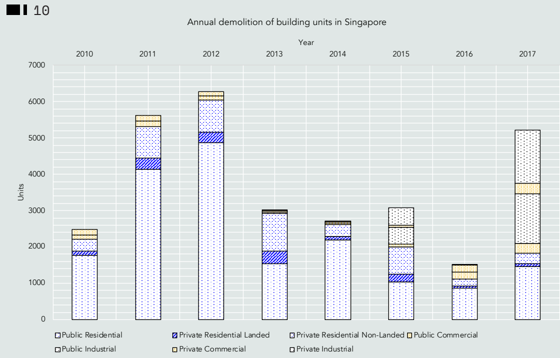

tutes a valuable reservoir of secondary raw materials - an anthropogenic material stockpile. This reserve could be approached as a representation of a capital reserve for the future, that needs to be managed systematically underlying fundamental component for its circular economy ambitions. However, the first input-dominated discussion around resource efficiency has neglected this capital reserve. Singapore's Sustainable Construction Master Plan was launched back in 2008 to reduce the strain on natural materials in construction projects, through a closed-loop zero-waste construction approach to mitigate the impact on limited landfill capacity. So far, the country is likely to continue importing cement from neighbouring countries to meet its domestic consumption (Gursel and Ostertag, 2016). Attributed partly by insufficient knowledge on material stock size, composition, as well as changes of stock over time.

Though Singapore demolition guidelines, SS 557 (2010), provide a systematic approach for building demolition to maximize resources recovery, its implementation remains mostly invisible. The primary reason is higher labour cost involved in resource recovery, absence of reuse market and strict timeline to complete demolition. Current demolition practices target metal recovery as the sole source of value. After metal extraction, debris is sent to landfill or land reclamation sites while good quality concrete from columns and beams stretch into recycling facilities towards recycled concrete aggregates (RCA). Due to Singapore's Green Mark requirements (the local building rating tool), some of the portion of concrete waste reach- es recycling plants to become RCA which mostly find low-value applications in subbase or roads. Due to lack of recycling facility and a cost for waste-to-energy plants, glass and wooden components are mostly crushed and mixed into construction and demolition debris or instead sent to an incineration/ waste-to-energy plant. Occasionally informal collectors take out good conditioned wood elements and furniture for sale in nearby cities. Various piping and air-conditioning ducts are usually treated as metals and recovered after demolition.

Research reveals that although Singapore reports a high rate of concrete and metal recycling, reuse practices are negligible. The main reason is the lack of market for reused components due to the perceived decrease in construction quality within a costly real estate market, the preference for sleek new buildings, and the concentration of construction activities in broad public and private developers (Arora et al.,2019). The process of demolition largely remains a machine intensive effort with manual sorting of low-value components. Once a building is designated for demolition, various demolition contractors participate in a bid to pay for building demolition. A qualitative estimation of metal scrap in building forms the basis for the negative or positive cost of demolition for the building owner. If the scrap/metal components are high, most likely the owner will get paid for building demolition.

Keeping heavy and voluminous nature of construction and demolition waste in mind, the National Environment Agency of Singapore follows a punitive measure for its reduction with a landfill gate fee of S$77/Ton (Arora et al. 2017). Under such circumstances, utilisation of CDW in land reclamation sites is a downcycling only application– especially Semakau landfill estimated to run out of capacity by 2035 - or as a hardcore alternative for bottom layers in road construction (see figure 1; current system). Although the National Environment Agency estimates 99% recycling of construction and demolition waste, the actual percentage of clean concrete recovered and recycled into structural concrete is hard to estimate but most likely remains substantially lower (Arora et al., 2019).

C.1 Building Infrastructure

The building infrastructure of Singapore is dominated by high-rises, followed by a smaller share of low-rise buildings and landed houses. Low-rise buildings and houses usually concentrate in heritage districts (e.g. Little India) or up-and-coming areas ongoing redevelopment (e.g. Geylang). Refer to building dynamics (growth in units). Based on the general methodological approach as described in section B under figure 3A, a case-specific methodological framework has been applied (figure 3B) for calculating public and private stocks and flows of residential, commercial and industrial buildings. The general model applied for material calculation is described in Equation (1)

*Stock = Inventory of Material * Material Intensity Factor*   [1]

BCA defines a Concrete Usage Index (CUI) for material intensity factor comparison among construction projects (BCA, 2012). CUI is an indicator of the amount of concrete required to construct a superstructure which includes structural and non-structural elements. The volume of concrete in cubic meters to cast a square meter of constructed floor area defines the CUI. Calculation of CUI does not include concrete used for external works and sub-structural works such as basements and foundations. The definition of material intensity factors for each category of building stock considers intermediate values taken from BCA's guide on concrete usage index (BCA, 2012). Intermediate values were chosen based on the assumed representativeness of old buildings (higher CUI) and newer ones (lower CUI), as well as uncertainties inherent to CUI calculations.

Where Stock represents the total volume or weight of an individual material, material Intensity Factor is defined by the material intensity by volume or weight per unit. Total stock represents the sum of individual material stocks estimated using Eq. (1). The inventory of materials accounts for the sum of all floor areas (FA) per category of stock.

HDB, the Hosing Development Board responsible for the management of all public residential buildings in Singapore, provides detailed annual information over the number of units and floor plans from each sub-category (see figures 6, 8, 9, 10) of its buildings. Reports include numbers of units per dwelling category; floor area per dwelling category; and the number of demolitions per dwelling category. That level of detail was notwithstanding for the data concerning to the private sector; therefore, data gaps needed grounded assumptions based on weighted averages and the public to private ratios. Hence, sample datasets with data from the Urban Regional Authority (URA) and the department of statistics - SingData (DOS) were made. These were structured per typology of private dwelling (landed and non-landed) and made it possible to calculate the average floor area per unit, following by public to private ratios, used to estimate demolition outflows.

The same approach applies to the calculations of the concrete inventory from commercial and industrial categories — with data from DOS, URA, JTC, and HDB. Data gaps also required grounded assumptions based on weighted averages and the public to private ratios. Total concrete and steel amounts were obtained by multiplying the pre-fined material intensity factors by the total floor area amounts. Figures 3A, 3B, and 4 illustrate the process flow and scope of the MFA applied to this study. For the calculations of material outflow, HDB provides the number of demolitions per dwelling category. HDB reports differentiate demolitions from refurbishments, although this study only considers demolitions. The sum of all floor area demolished was used to calculate the outflow of material from the stock. For the private sector demolition estimations followed the application of the respective public to private ratios, which were applied to the outcomes of total floor area demolished for each category of the public sector.

For the estimation of steel, the Ministry of Trade and Industry (ESS, 2018) provides national concrete and steel consumption. With the estimate of concrete use in public residential buildings in Singapore, the average rate of steel to concrete use was applied to estimate the overall steel stock (Arora et al., 2019). With the annual demolition data retrieved from HDB annual reports, the total number of buildings demolished was calculated. Based on demolitions data (excluding renovations/refurbishment), the overall outflow of materials was estimated for the years 2010-2017. With the annual available floor area and demolished floor area per sector and per category, the material stocks, inflows and outflows were estimated for the years 2010-2017.

C.2 Road Infrastructure

Calculations considered the entire road network maintained by the Land Transport Authority (LTA), which includes local, collector, arterial and expressways. Collector roads are built primarily to feed traffic from local onto arterial roads. It also provides access to adjacent land uses. Local access roads provide access to various types of land uses. These roads are generally smaller, in terms of width than collector roads. All public roads maintained by LTA are paved, and the annual road length in lane-km for all public roads maintained by the Land Transport Authority is available in the statistics from DOS. Technical specifications, including cross-section schemes, pavement composition including materials per layer, layer thickness, material density, and specifications of asphalt mixtures gathered in LTA reports (LTA, 201; LTA, 2010a; LTA, 2010b). Since material intensity factors for the Singaporean roads were not available, eq. (2) was used to calculate the total weight of material per kilometre of road per type of

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Material Intensity Factors							
Categories/Materials	Concrete [m3/m2]	Steel [ton/m3]	Bitumen [ton/km]	Concrete [ton/km]	Graded Granitee [ton/km]	Quarry Waste [ton/km]	RAC [ton/km]
Residential		0,125					
Private landed	0,30						
Private Non-landed	0,46						
Public HDB	0,45						
Industrial		0,122					
Multiple-User Factory	0,48						
Single-User Factory	0,48						
Business Park	*0,48*						
Warehouse Space	0,30						
Commercial		0,122					
Office Space	0,48						
Retail Space	0,30						
Roads							
Local road			25,40	785,24	1783,48	1783,48	3484,75
Collector road			29,58	858,30	1783,48	1783,48	4283,34
Arterial road			38,91	1214,39	2229,35	2229,35	4864,14
Expressway			30,87	849,07	2229,35	2229,35	4864,14
Airport							
Terminal building	0,45						
Runaway/taxiway			30,87	849,07			4864,14
Source	BCA	Arora et al. (2019)	Current study	Current study	Current study	Current study	Current study

Fig. 11: Material intensity factors deployed in this research.

road. Figure 11 describes the material intensity factors for the Singaporean roads. The sum of material weights for total road length per category determines the respective stock size.

Weight material/layer [ton/km] =
*Density of material per layer * Net volume of layer* [2]

C.3 Supply and demand forecast

The forecast of long-term supply and demand is carried out through an extension to the model (figures 3B; 4). Firstly, a concrete outflow calculation in 5-year intervals from EOL buildings is performed, founded on a cohort-based approach applied to a model stock turnover based on the public residential building stock and average building lifetime (Zhou et al., 2019). The number of dwellings is given by HDB in their annual reports with data starting from 1960. The first building cohort represents the number of buildings constructed in 1960-1965, calculations then assume that the average building lifetime will determine the year of demolition and respective EOL concrete output of that entire cohort.

The same process applies to the subsequent building cohorts, from 1965 onwards. In order to estimate average building lifetime of the Singaporean stock, which is affected by several obsolescence reasons (Langston et al., 2008), data from the HDB's Selective En bloc Redevelopment Scheme (SERS) program was used. The dataset contains 79 data-points about building names, and respective construction date and announced demolition year. Based on this data, the average lifetime of urban residential buildings in Singapore is estimated to be around 35 years, which is in line with the estimates carried in Zhou et al., (2019) for China.

Secondly, future inflows (demand) and outflows (supply) are calculated in proportion to long-term gross domestic product (GDP) forecasts, an approach inspired by Nguyen et al. (2019) and Miatto et al. (2017), depicted in equation 3. The behaviours and trends of the stock within the MFA time-frame (2010-2017) are put in perspective to GDP growth over the same period (expected and real growth).

After that, ratios of GDP growth to stock change are calculated and applied in the outlook of future growth of flows. In order to ground assumptions, long-term concrete stock growth was also estimated, providing the average "inflow to growth" ratio, which dictates the respective material inflow intensity to sustain a specific growth of stock.

GDP Ratio [A] = Avg. Expected GDP growth/ Avg. Real GDP growth
*Growth Concrete Demand Ratio [B] = GDP Ratio [A] * Avg. Grow concrete inflow*
*Future demand [Mt]= Inflow * (1+[B])* [3]

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Fig. 12: Estimated annual material inflows to road expansion, 2005 to 2017.

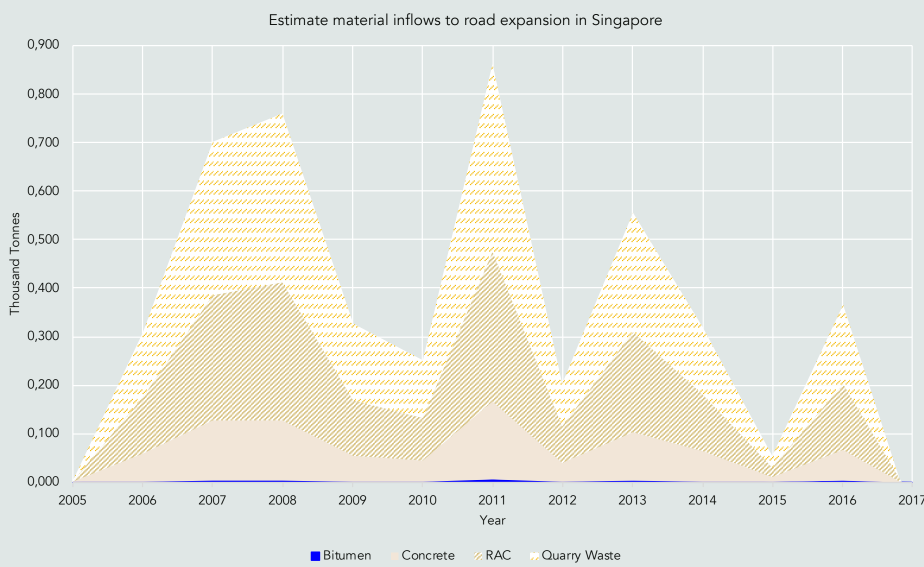

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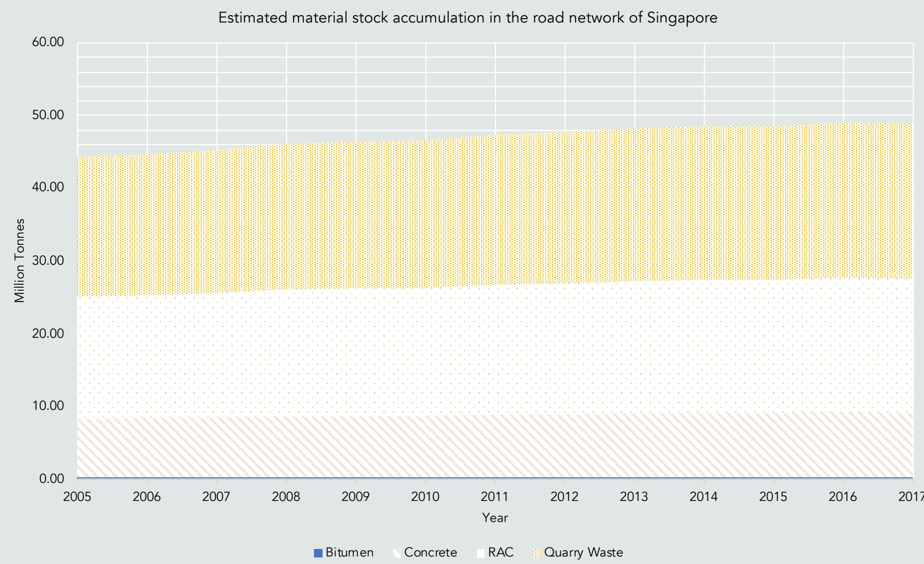
Fig. 13: Estimated road network material accumulation, 2005 to 2017.



D.Results

The results in this research comprise on the residential, commercial and industrial buildings of the public and private sectors, along with the road infrastructure of Singapore, of which regulatory agencies provided data. A spreadsheet-based model was prepared following a bottom-up approach adapted and extended based on Arora et al. (2019). Which includes all the parameters for estimating the stock, inflows, outflows and long-term outlook of supply and demand. The Sankey diagram shown in figure 16 summarizes the outcomes of the general framework of stocks and flows, covering materials inflows, stocks and outflows within the building and nonbuilding infrastructure of Singapore.

The choice of this study to focus on concrete is due to concrete's quantitative relevance within the material flow analysis, and qualitative potential to generate impact towards the Circular Economy. Total concrete stock in Singapore was estimated to be 244,2 million tons (Mt) for which 170,6 Mt covers a stock in residential buildings and 64,8 Mt in non-residential buildings. The road network accounts for 8,84Mt of the overall concrete stock, roughly 4%.

In the last seven years (2010-2017), the concrete stock has grown by 21% on a 3% average (figure 15). Buildings account for 3% annual average growth with 4% tops and 2,5% bottoms. In comparison, the concrete stock in roads has been growing on average 1% per year with a 2% peak. These numbers are consistent with the annual growth of building units - 3% per year - and evolution of road length - 1% per year - as shown in figures 8 and 7 respectively.

Annual material inflows for concrete were averaged for the past seven years. From 2010 to 2017, the average annual inflow of concrete was 6,20 million tons, on which roads were supplied with 0,12 Mt of concrete, which increases to 0,18 Mt if recycled concrete aggregates (RAC) are taken into equation (figure 12).

Annual demolition data was used to estimate total outflows, based on annual HDB reports (HDB, 2019) and statistics from DOS (DOS, 2019). From the year 2010-2017, a total of 29908 units were demolished at a pace of 391,46 units per year, as shown in figure 10. The demolition of public residential units represents the highest share with a total of 17884 units demolished over the seven years, followed by non-landed private residential units (apartment and condominium flats). However, the most concrete outflow has its source on the demolitions of private industrial units (figure 14), a category that represents 0,11% of the total number of industrial units but covers approximately 89% of the industrial floor area (figure 9).

The forecast of future concrete outflow – or supply – has been founded on the calculations of stock turnover dy-

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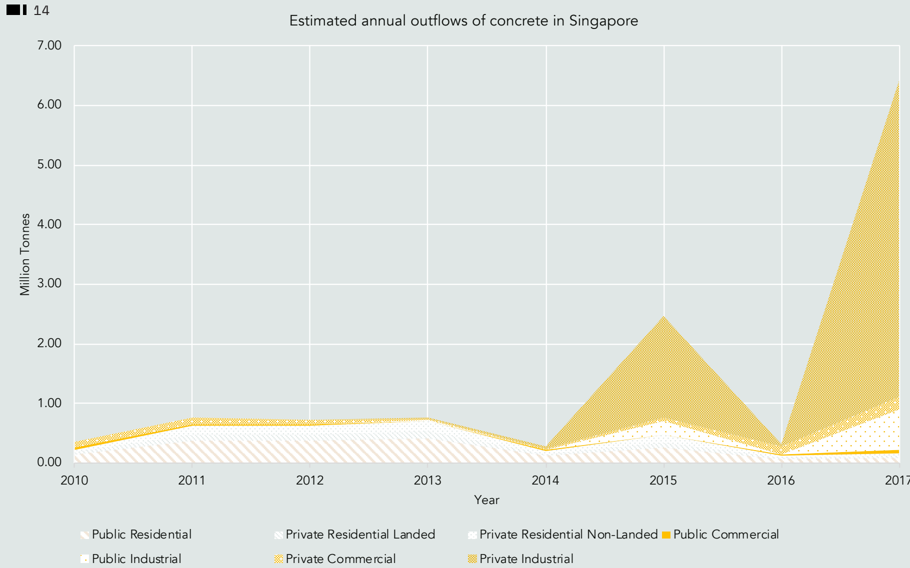

Fig. 14: Estimated annual material outflows from public and private buildings per type, 2010 to 2017.

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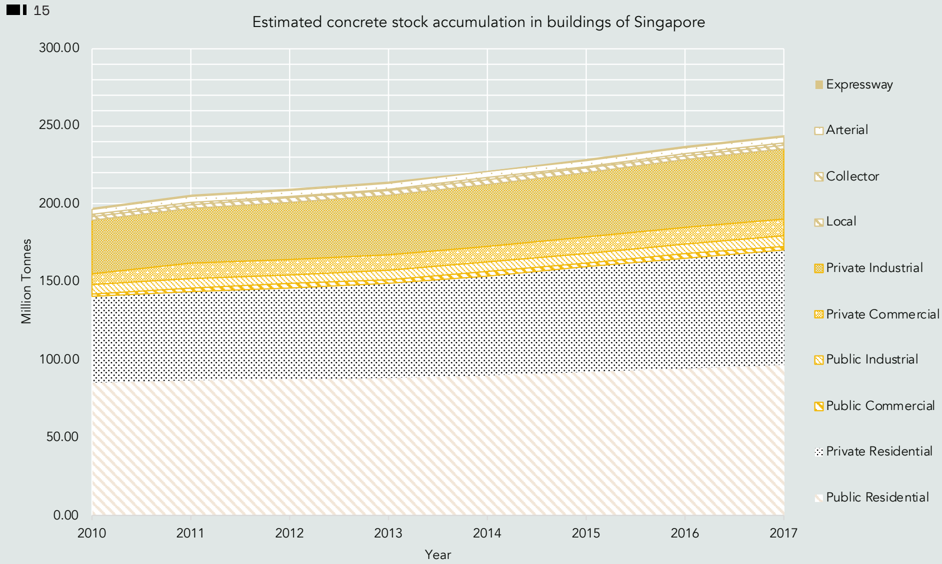

Fig. 15: Estimated concrete accumulation in roads and buildings per type, 2010 to 2017.

Material flow analysis for the Singaporean infrastructure [2010-2017]

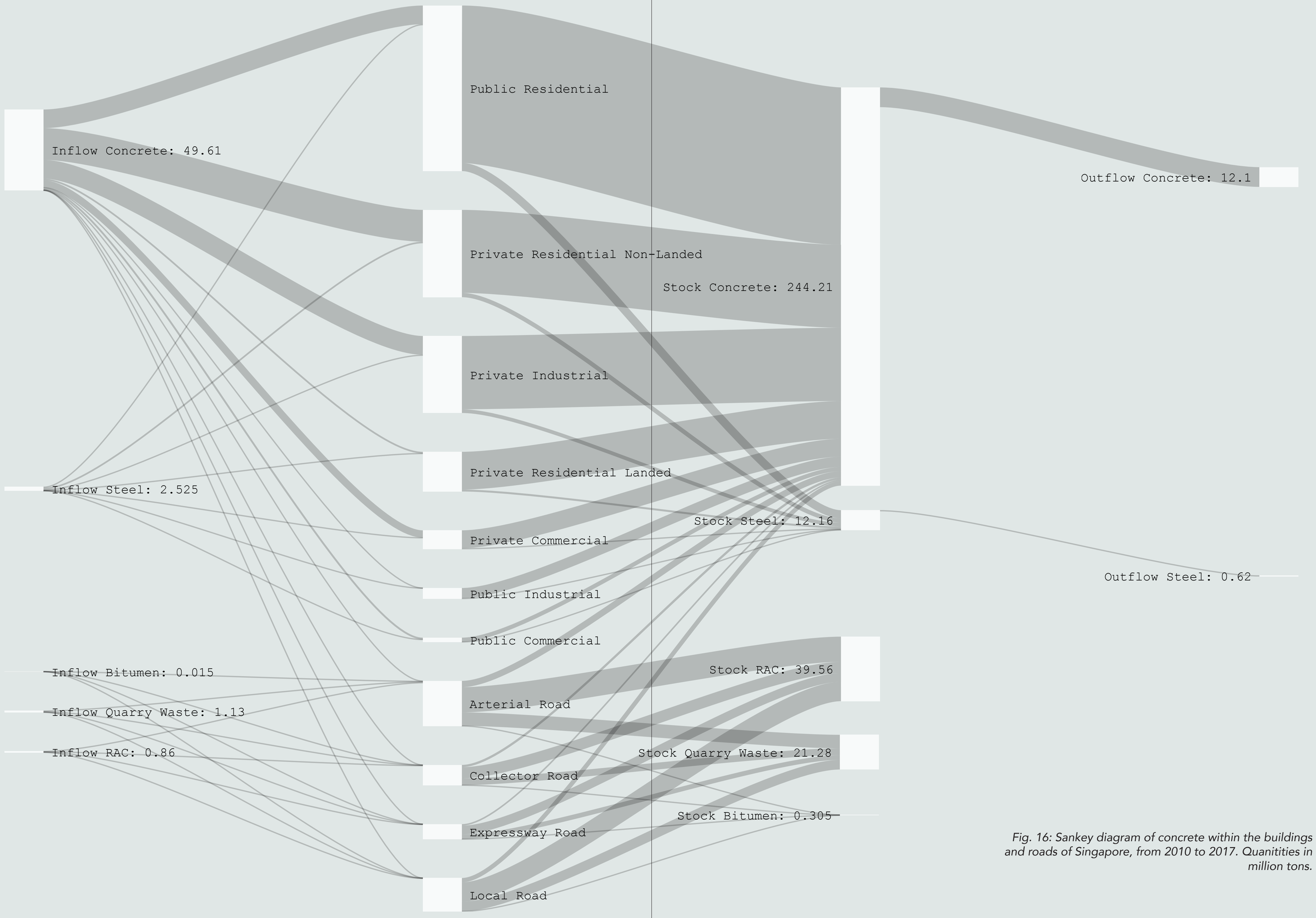

Fig. 16: Sankey diagram of concrete within the buildings and roads of Singapore, from 2010 to 2017. Quanitities in million tons.

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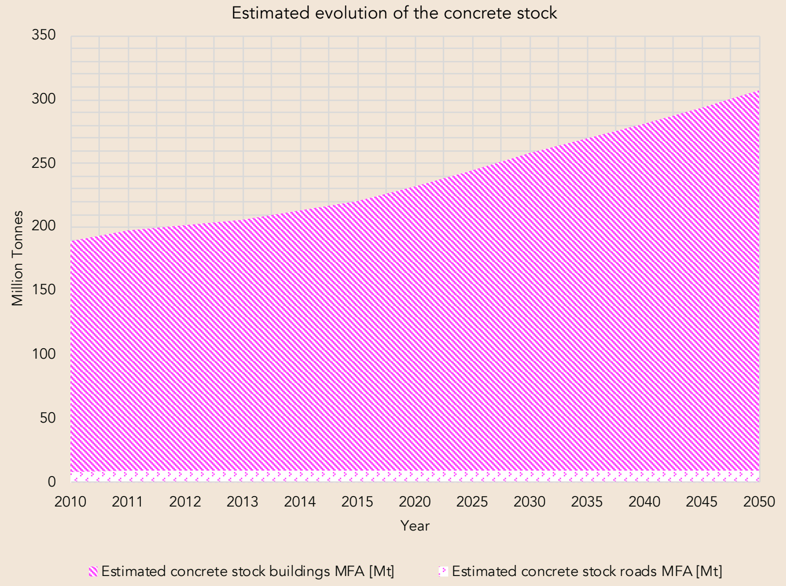

Fig. 17: Estimated long-term concrete accumulation in buildings and roads.

namics of the public residential stock in Singapore, on which building lifetime is estimated on the average survival of buildings listed in HDB's SERS program (HDB, 2019). Based on this data, the average lifetime of urban residential buildings in Singapore is believed to be 35 years, which is similar to the estimates carried in Zhou et al., 2019 for China. Therefore, buildings constructed in 1960 are assumed to be phased out in 1995, generating a concrete outflow in line with the respective calculated total floor area demolished. Calculations estimate that from 2011- 2015 12,5 Mt of EOL concrete originated from public residential turnover. From 2020 to 2050 70,8 Mt of EOL concrete is expected to be available, approximately 10,11 Mt per every five years (figure 18). If all buildings are considered, the supply from EOL concrete increases to 133,8 Mt until 2050 on a 19,1 Mt of concrete per 5-year period (figure 19).

The real average GDP growth in Singapore over the last seven years (2010-17) has been of 6%, in comparison to a 4% average concrete stock growth over the same period. Tops and bottoms indicate that GDP grows in proportion to the concrete stock, which is highly driven by the economic sector (Ofori, 1988; Business Review, 2018; MarketResearch.com, 2019). According to the long-term economic outlook (The Economist Group, 2019), real GDP growth is forecast to average 2% a year in 2019-30, before slowing to 0.5% in 2031-50. Hence, the future concrete stock has been calculated as a function of expected GDP growth for both roads and buildings. Calculations reveal that the stock in buildings is expected to grow from 220Mt in 2015 to 307Mt in 2050, with roads growing concrete stock (concrete + RAC) by 0,38Mt to 9,2Mt in 2050 (figure 17). It is estimated that sustaining such growth will require 13,4Mt of concrete for the building sector in 2020, growing exponentially to 43,2Mt in 2030 and 310Mt in 2050, based on expected GDP growth and the ratios of inflow to stock growth. In contrast, the demands for the road network will be quite modest growing from 0,25 Mt in 2030 to 2,73Mt in 2050 (figures 18; 19).

E.Discussion

It is visible that the cumulative public and private stock remains the most abundant resource sink in proportion to material inflows-outflows. In general, inflows to the existing stock are significantly more massive than the outflows, which suggest that the stocks in Singapore will continue to rise over the coming years. The concrete supply shall rise along with demand when a large cohort of residential buildings reaches either their functional obsolescence or premature obsolescence. Estimates indicate that the average public residential building in Singapore has a lifetime of roughly 35 years, in contrast to 34 years in China, which is much shorter than in Eu- European countries (Zhou et al., 2019). The short lifetimes arise from various factors, some of which imply premature obsolescence. Such as the quality of building materials, design standards, construction techniques, practices of renovation and maintenance, and inappropriately accelerated demolition as a result of rapid urbanization/city rebuilding. This high turnover in Singapore is suggestive to the fact that the building stock is replenished continuously as a result of buildings reaching their EOL and new buildings being constructed to meet growing demands. Consequently, the growth rate of the Singaporean building stock has been similar to the one of China, at 4% (excl. the 2000s where China has grown at a phenomenal pace as a benefit of joining the WTO)

Often a linear behaviour of building demolitions is adopted by MS studies, based on assumptions of expected lifetime in years (Miatto et al., 2017a). While a linear approach applies to cases where data availability is a concern, the demolition of buildings in Singapore is affected by several obsolescence factors (mentioned above). These obsolescence factors are linked to strong social-economical-urban planning inference associated with lifestyle behaviours and real estate market conditions. In Singapore, the demolitions have an independent trend from the next past year (figures 10; 14). Because of the non-linear trend in demolitions that occurred in Singapore, the outflows from stock followed a non-linear trajectory. Therefore this research utilized a blended approach to account for the encountered data gaps in the private sector infrastructure. Nevertheless, outflow estimations in this research are as close as possible to pure statistical data and not subject to the same degree of uncertainty handled by studies with dynamic models. Besides the representation of the residential building as the most massive cumulative resource sink, in terms of concrete stock, the largest share of concrete outflow has its source on the demolition of units from the private industrial sector. This Industrial stock turnover offers untapped potential and opportunities to reuse waste at higher levels. The highest floor area to unit ratio and more substantial concrete intensity factors (table 11) in the industrial stock contribute to this difference

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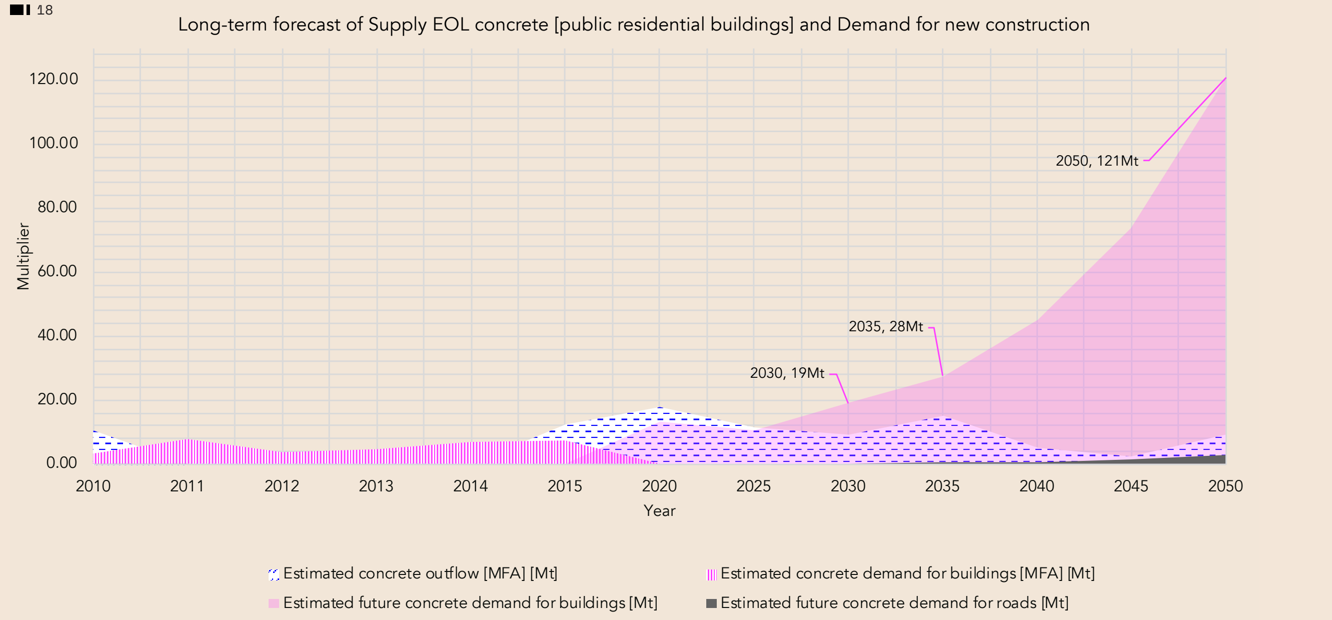

Fig. 18: Forecast of EOL concrete from public residential buildings in comparison to demand of roads and buildings. Fig. 19: Forecast of EOL concrete from all residential buildings in comparison to demand of roads and buildings.

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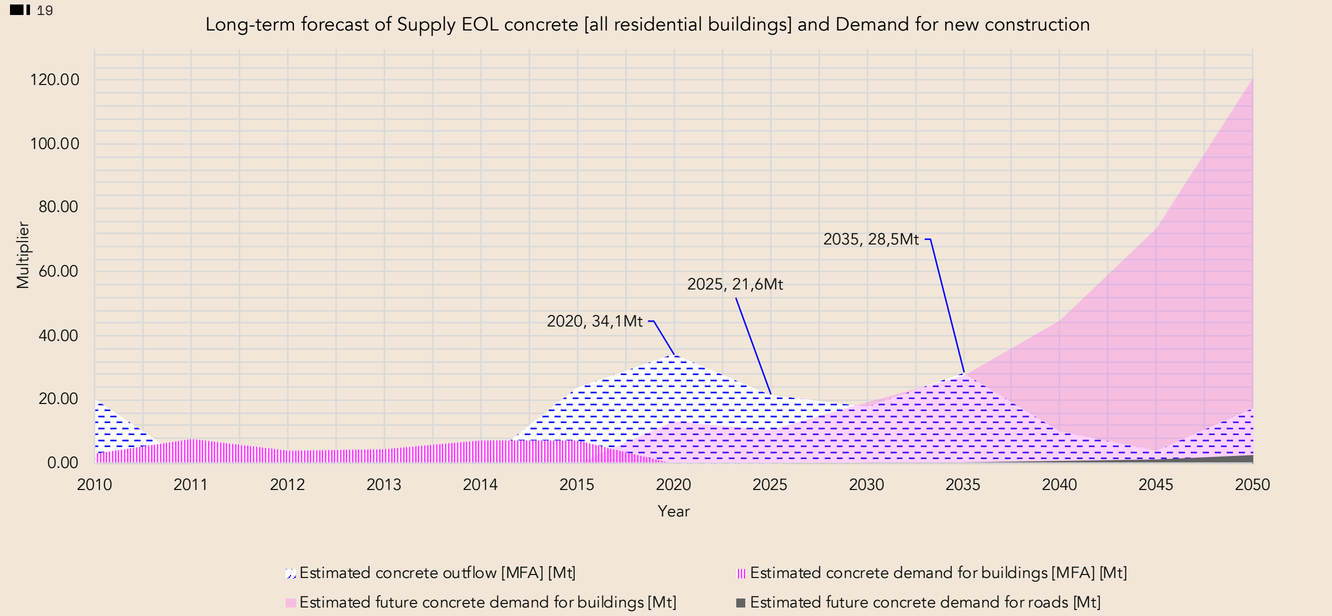

Results show that most concrete outflow in the future will come from the public residential building sector. The renewal of this ageing building stock is predicted to peak cumulative supply of EOL concrete in 2020 to 18,07Mt (34,16Mt considering the whole building stock turnover). This peak of supply is in contrast with a low demand from the road sector, considering the demand for concrete in asphalt W3B concrete mixture (LTA, 2010) and RAC as base and sub-base layers. The demand of the road sector for concrete and crushed EOL concrete has little influence on the overall supply of EOL concrete in Singapore. This expected oversupply creates an exciting scenario to increase secondary resource utilization and close resource loops under the circular economy principles. Moreover, the combination of oversupply with low demand for low-value applications could reduce the price of EOL concrete. It would also contribute to creating the conditions for the feasibility of a secondary resource market, along with the maturity of technical aspects such as state of the art concrete recycling technology although some economic feasibility aspects are to be investigated and beyond the scope of this study.

On the other hand, concrete demand is also expected to increase, in line with the growth in concrete stock accumulation, from 244,2Mt in 2017, 257,8Mt in 2030, to 307Mt in 2050. Sustaining this growth will require 19Mt of concrete by 2030 — a level beyond what EOL concrete from residential buildings can match. Although non-residential building categories could contribute to sustaining proper levels of supply up to 2035, concrete demand will require approximately 90% of virgin materials after that. Singapore currently reports that 99% of the produced CDW is recycled (NEA, 2019; Ministry of the Environment and Water Resources, 2019), although there is no distinction between how much goes into low-value applications and how much is indeed upcycled. The recycling rate is thought to be substantially lower (Arora et al., 2019). The statistics from the National Environmental Agency of Singapore (NEA) reported a total CDW output of 6,87Mt from 2011-15 with an annually consistent recycling rate of 99%, which places 687 tons of CDW to waste. However, in these estimations, the total output of

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Country level fractions of infrastructure Categories [%]			Typology			
Reference	Country/Region	Year	Residential buildings	Non-residential buildings	Roads	Other infrastructure
Huang et al. (2016)	China	1980	54,00%	36,00%	2,00%	7,00%
		1990	55,10%	31,90%	2,90%	10,10%
		2013	42,90%	38,60%	2,60%	15,90%
Fazit (2013)	China	2013	51,00%	45,90%	3,10%	
Schiller et al. (2015)	Germany		34,20%		65,80%	
Fazit (2010)	Germany		38,40%	29,00%		37,70%
Wiedenhofer et al. (2015)	EU25	2009	47,00%		52,00%	1,00%
Fazit (2009)	EU25	2009	32,00%	32,00%	36,00%	
Tanikawa et al. (2015)	Japan	2010	43,20%		26,20%	34,40%
Fazit (2015)	Japan		31,20%	31,20%	37,70%	
Hashimoto et al. (2007)	Japan	2007	33,30%		18,50%	50,80%
Current study	Singapore	2017	41,56%	16,37%	17,12%	24,95%
	Average Fractions (excl. current study)		42,03%	34,94%	24,68%	22,41%
	Average Fractions (incl. current study		41,99%	32,62%	24,68%	22,41%
Stock Growth Rate [per annum] [%]						
Reference	Country/Region	Year	Typology			Rate
Huang et al. (2016)	China	1990s	Civil engineering infrastructure			8%
		1990s	Buildings			4%
		2000s	Non-residential building [Investment]			33%
		2000s	Residential building [Investment]			27%
Country level per capita stocks [tons/capita]						
Reference	Country/Region		Typology			Material stock [Tons/capita]
Wiedenhofer et al. (2015)	EU25		Residential buildings			72,0
Fishman et al. (2014)	Japan		Residential and commercial buildings			71,0
Tanikawa et al. (2015)	Japan		Residential and commercial buildings			74,0
Ortlepp et al. (2018)	Germany		Residential buildings			45,7
Ortlepp et al. (2018)	Germany		Commercial buildings			82,9
Krausmann et al. (2017b)	Global Average		Total stock			115,0
Kleemann et al. (2017a)	Vienna		Residential buildings			130,0
Arora et al. (2019)	Singapore		Residential buildings			28,8
Current study	Singapore		Residental, commercial and industrial buildings, and roads			43,5

Fig. 20: InCirc estimations in perspective to other MS studies.

EOL concrete for the same period is as high as 12,5Mt, considering only concrete and public residential building. Hence, it might suggest that current rates of CDW recycling are in reality, around 49,47%. In comparison, the current average recycling rate of CDW for EU-27 is 47% (Di Maio et al., 2017).

As a matter of perspective, the fractions of infrastructure typologies (residential and nonresidential buildings, roads, other infrastructure) were compared with other studies on a country level (figure 20). In the current study, the residential building stock of Singapore has been estimated to represent 41,6% of the infrastructure, considering concrete stock. Non-residential buildings and roads represent 16,4% and 17,1% respectively, with the remainder attributed to other types of infrastructure. Huang et al. (2016) estimated that in China 42,9% of the stock is in residential buildings, which resembles the findings of this study, making both stocks larger than in Japan (33,3%) the average within the EU25 group (32%). In contrast, Singapore has the smallest share of non-residential buildings among the benchmarked studies, representing 16,4% of infrastructure, followed by Germany with 29% a share. Nonetheless, the data indicate that the share of stock categories within this study are realistic in accordance to the averages among the benchmarked studies.

In contrast, Singapore has the lowest per capita stock among compared studies (figure 20B). In the current study, the building stock and road infrastructure of Singapore has been estimated to be 43,5 tons per capita for mineral components, specifically concrete. Wiedenhofer et al. (2015) estimated an average of 72 tons per capita of residential building stock for EU25 countries. Fishman et al. (2014) estimated for the material stock of buildings in Japan at 9 GT, while Tanikawa et al. (2015) estimated it to be 9,4 Gt, both studies included the residential and commercial buildings for the account of material stock. Based on World Bank (2017), the population of Japan was 127 million in the year 2010 which leads to the 71 tons per capita and 74 tons per capita of building stock based on the two studies respectively. Ortlepp et al. (2018) estimated German domestic building stock at 3755,3 million tons for the year 2010, corresponding to 45,7 tons per capita of material stock. In another study on non-domestic building stock, Ortlepp et al. (2016) calculated it to be 6.8 billion tons for Germany, which is about 82,9 tons per capita. The visible differences in estimated per capita non-metallic mineral stock could be because of several of the possible reasons for differences in construction style, building typology, land area, built environment fabric, density and inclusions of other non-metallic minerals in estimations. All buildings in Singapore follow a pattern for high rises, which tends to be less reliant on the consumption of non-metallic minerals than typical European building typologies. Additionally, in most studies in Europe, the oldest buildings are as old as 120 years while the stock in Singapore is more dynamic and younger, which reflects significantly in stock. An important aspect to consider is the land density, where Singapore scores high with a population density of 7700 people per square kilometre, which contributes to lower stock per capita estimations.

E.1 Uncertainties in assesment

In pursuit of answers to the complex questions this research was designed to address, there are inherent uncertainties in the results of this study. One source of uncertainty in the methodology is associated with the floor areas. Since this research covers both private and public sector, grounded assumptions had to be made to fill data gaps encountered in private-sector data. The second source of uncertainty is associated with the material intensity factors, which are determined by relatively modern design standards. This uncertainty is pronounced in the case of roads since significant differences can arise from design specifications to their implementation, reflecting in the final weights of the materials per layer. While material intensity factors for the building infrastructure were based on the Concrete Usage Index (CUI) reported by HDB, their representativeness for older building stock is unknown, since CUI represents relatively new individual construction projects. The non-inclusion of annual material replacement due to maintenance for both buildings and roads would also lead to uncertainty in inflow and outflow rates (Stephan and Athanassiadis, 2018). The forecast of supply and demand accounts for the future stock growth as a subject of long-term GDP estimations with their influences on inflows. Outflows assumed that future outflow behaviours are a result of the EOL of buildings, which also has inherent uncertainties in regards to lifetime and net concrete output (considering the portion that meets quality requirements for new construction materials). Overall, the lack of comprehensive data at the individual level remains a significant issue for uncertainties in bottom-up stock assessments.

F.Conclusion and outlook

The built environment of urban areas requires a significant investment of material resources, which are stocked for a long time in the built environment over the buildings and infrastructure. With fast urbanization and economic growth, significant material has accumulated in cities. While this increasing economic growth has been directly proportional to trends of resource exploitation, the circular economy (CE) approach is gaining increased attention in the sustainability agenda for its framework focused on decoupling economic growth from the consumption of finite resources. This paradigm shift towards a circular, resource-efficient, economy requires a comprehensive knowledge of the flows and material stocks (MS) in buildings and infrastructure. Bringing circularity into material consumption loop has consistently been argued as an immediate need. Although there have been calls for exploiting existing stocks for material intake into newer demands, there has been little progress towards this. Considering that buildings contribute to more than 40% of total waste by volume and consume the most abundant resources (Hoballah, 2010), there should have been higher visibility of accomplished circularity in this sector.

In the case of an import-dependent country like Singapore, its enormous wealth of buildings and infrastructure constitutes a valuable reservoir of secondary raw materials and a strategic reserve for the future. However, such reserve has been primarily ignored amid current zero-waste oriented strategies summed with the lack of a comprehensive estimation of its material stocks and how they change over time.

The primary motivation of this study lies in estimating stocks and flows of concrete in Singapore and how outcomes change in the future. A quest to unveil windows of opportunity where increasing secondary resource usage trough the closure of resource loops is feasible. Despite NEA's reports on its recently achieved high rates of CDW recycling - 99% - the significant share of recycled CDW is destined into low-value applications, for covering the demands of base and sub-base applications in roads and land reclamation. Although the current situation (figure 1A) can lead to a total mass reduction (under zero-waste strategies), it is not able to keep resources circulating, requiring continuous virgin resource input amid infrastructure demand. At present, construction of buildings remain highly dependent on virgin resources, in the opposite direction of sustainable construction

Results show that from 2010-17, the concrete stock has grown by 21% on a 3% per year average, in proportion to a 6% per year GDP growth. While the stock has developed in a steady cumulative pace, the outflows have followed a non-linear trend in line with the inflows (49,6Mt), which overweight outflows (12,6Mt) considerably, suggesting that the Singapore stock will continue to grow. This assumption is confirmed by the long-term estimations, where concrete stock is expected to grow from 220Mt (2015) to 307Mt (2050). Sustaining this growth would require 13,4Mt of concrete in 2020, 43,2Mt in 2030, reaching 310Mt in 2050. In contrast, 70,8Mt of concrete in the building stock are expected to reach their EOL from 2020-50, which will create a surplus scenario for the next 15 years, beyond the yearly concrete demands for buildings and roads in the period 2020-35.

This oversupply creates an exciting scenario to increase secondary resource utilization by the construction sector. Firstly, due to the market price of secondary aggregates expected to reach lows amid excessive supply, which would make secondary resources competitive in price to virgin ones. Secondly, this scenario holds the right moment in time for the investment into the development and implementation of state of the art technologies for the recycling, which could drive prices of secondary resources down even further. If this scenario follows, the establishment of a secondary resource market and resource bank would likely follow. As 2035-50 estimations suggest, local EOL concrete supply will not be sufficient to sustain the entire construction demand by then. Hence the next 15 years are a crucial moment for Singapore to accelerate the transition towards the CE.

As trendy as the CE seems to be, it is bound to stay and establish itself as one major vector for sustainability. If the opportunities are made tangible, outcomes and innovation could turn into a factor of differentiation for the nation of Singapore. Recent research into the nation's economy and strategies (DBS Bank Ltd., 2018), states that without change "Singapore is on the road to becoming a normal developed country: from great to good". Since the country is currently at the income frontier, it will need to be driven by innovation and productivity, where resource responsibility and efficiency will be in major demand. However, current strategies have not been able to deliver, yet.

It is therefore essential to realize that the circular economy is a quest for the future, where long-term considerations are as important as the in-between steps. Inherent to its risks and uncertainties along the path of development and experimentation. A collaborative approach on both local and global scales is needed to share these risks and potentialize outcomes (Remøy et al., 2019). Collaboration could help develop new mechanisms to design, implement and measure the CE on these scales, and increase feasibility. Collaboration beyond borders also has the potential to drive the establishment of a world market for secondary resources, counteracting the effects of local undersupply of CDW. Where this research focuses on forecasting these scenarios of opportunity through the extrapolation of the current metabolism in the built environment, other aspects need to be considered to move further in the advisory ladder. Firstly, industry and government should align in understanding their mutual effects, as opportunities can only turn realistic if the government provides the conditions for the industry to do so. The public-private cross-nation consortium between The Netherlands and Singapore on resource recovery, ReCirc, its a vanguard initiative and a step on the right direction, but does not yet consider CDW in its scope within the ReCirc nexus.

Currently, there seems to be little interest to close these resource loops, which could be attributed to the perception that current recycling rates of CDW are high (NEA, 2018, Arora et al., 2018). These are misleading, especially if measured through indicators of circularity, such as the Circular Economy Index (Di Maio & Rem, 2015). On the other hand the magnitude of the term "Circular Economy" can also be misleading, because the circular economy is closely linked to every single pillar that supports a country's sector and not a mere type of economics. Instead, CE is a condition for sustainability, which is high on the agenda and well perceived as a broad term that needs to be made tangible.

Implementing the CE will require the reshuffling of various mechanisms currently in place with new ones to come. Covering technological (e.g., to capture the value from waste), environmental (e.g., to drive the sector towards green profit), governmental (e.g., policies and regulations that can drive the CE), and economic (e.g., innovation) aspects, as well as other challenges along the path. Further studies should explore the feasibility of circular economy strategies in the CDS for closing the resource loops even further and address these challenges, on both local and global scale. Feasibility studies are as a result of this paramount and require a multi-lens perspective: A collaborative effort between the academia, industry and government with the combination of various disciplines, whom are involved with analysis, design and engineering on the urban fabric.

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ReCirc Netherlands-Singapore
AMS Institute for Advanced Metropolitan Solutions
Singapore University of Technology & Design (SUTD)
SUTD-MIT International Design Centre (DEEP Lab/ Air Lab)

Appendix A. Supplementary data

Supplementary data for this paper can be found online.
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