SINGAPORE UNIVERSITY OF
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# Demolitions to Design: A Case for Circular Economy

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Engineering Product Development Pillar

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# *Abstract*


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Climate emergency demands absolute reductions in global carbon emissions while millions of marginalised people dream about decent housing and infrastructure. With the unprecedented level of consumption, urban built environment remains the largest sink for material resources, making it a top priority for achieving material efficiency and production associated emission reductions across the globe. The concept of circular economy may offer a pathway to achieve both, the socioeconomic development and ambitious emission cuts. Hence, this thesis first develops methods to investigate the status, progress and opportunities for the circular economy in cities by combining multidisciplinary data, design and sustainability methods. It then investigates the buildings sector for the urban mining of building components and end-of-life reuse driven circularity opportunities. This thesis argues that premature obsolescence of buildings in cities could drive an affordable and more sustainable supply of building components for low-cost housing in developing countries and contribute in solving the global housing challenge. With decreasing lifespan of buildings, recovery and reuse of building components at their end-of-life could be a major sustainability contributor. This research develops a systematic approach to estimate the recoverable building components, costs and environmental benefits of recovery process, and subsequent ease of designing with reuse. The challenges associated with implementation of reuse driven building construction in urban and rural settings have thus been properly identified and addressed. Overall, this research contributes in developing a roadmap for systematically upscaling the practice of end-of-life reuse and circular economy in the built environment.



**Key Words**: Urban metabolism, Material flow analysis, Building components, Sustainability, Adequate housing, Design for environment

# Publications

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**J1**: Mohit Arora, Felix Raspall, Lynette Cheah, Arlindo Silva (2020) *Buildings and the Circular Economy: Estimating Urban Mining, Recovery and Reuse Potential of Building Components*, **Resources Conservation and Recycling**, vol 154, pp 104581

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**C2**: Mohit Arora, Felix Raspall and Arlindo Silva (2018) *Transforming Industrial ecology research into practice*, **Gordon Research Seminar on Industrial Ecology**, Les Diablerets, Switzerland (Invited Speaker)

**C3**: Mohit Arora, Felix Raspall and Arlindo Silva (2018) *Realizing Science and Practice of Materials Reuse*, **CitiesIPCC Conference**, Organized by Intergovernmental Panel on Climate Change, United Nations, Edmonton, Canada (Invited Speaker)

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**Manuscripts in progress**

**M1**: Quantitative Circularity Assessment for Cities: Lessons from the Progress of Circular Economy in Singapore

**M2**: Planning, process and prospects of urban mining in buildings

**M3**: Reuse Radius: Defining embodied carbon budget for building components

**M4**: Can modularity promote enhanced reuse: Evidence from reuse-driven housing prototypes

**M5**: A bottom-up approach for material stocks and demolition waste estimation: The case of buildings and infrastructure

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**Prototypes & Design Experiments** Casa Azul, Sombra Verde, (ultra) Light Networks, vMesh

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Sitting back at home without kerosene oil to light a lamp, my daily aspirations would always be limited to a late sunset so that school assignments can be completed. Struggles to finish homework in early mornings and running to school for miles was a daily routine. Would then one dream about writing a PhD thesis in a foreign language and country? The answer is Yes, given the world is as kind and generous as it has been with me. This thesis is an acknowledgment for help and opportunities I have received from countless souls.

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*Dedicated to*
*Dr. Gajendradhar Dwivedi*
*&*
*(not just income)tax payers of India and Singapore*

# Chapter 1

# Introduction

Climate emergency, as ‘climate change’ has started to be termed, shows that the humanity is at odds with nature (Ripple et al., 2019). Arguably one of the prominent reasons behind this state of planet earth is associated with enormous material consumption since 19th century. Materials are the basis of biophysical existence of humanity and hence consumption has predominantly determined the lifestyle of modern society. All forms of commodities and services are, in one or the other way, related to materials. From home to office, infrastructure or transport, electricity or food, the entire built environment revolves around four major material categories namely biomass, metals, non-metallic minerals and fossil energy carriers. The pace of material consumption, however, has grown unprecedentedly at the beginning of 21st Century with rapid urbanisation (Krausmann et al., 2017b). Krausmann et al. (2018a) estimated 1000 Gt of materials were globally consumed from 2002 to 2015, almost 33% of the total material consumption between 1900 to 2015. Consequently, humanity has released 2500 Gt of waste and emissions over 1900-2015, 28% of this during 2002-15 alone. Results are visible in the form of alarming level of global carbon emissions, concerning the global community for the repercussions of climate change (Bai et al., 2018, IPCC, 2015).

Absolute reductions in material and energy consumption can no longer be ignored to achieve lower emissions. However, a large population across the globe remains deprived of dignified living standards (Rao and Min, 2018). Globally over 1 billion people do not have a shelter to call home (Brown, 2003, Croese et al., 2016, Mastrucci and Rao, 2019, MGI, 2014, Soyinka and Siu, 2018). Infrastructure and service growth in the developing world would require huge resources and energy which would be difficult to achieve without an environmental burden (Mark and Maarten, 2017, Solecki et al., 2018). This is evident from the material consumption patterns that OECD countries still consume a large proportion of material footprints (∼38%), yet a significant increase in the domestic material consumption of growing countries such as China, India, Brazil etc have been observed in recent years (Krausmann et al., 2018a, UNEP, 2016). On one hand, new constructions and growing material stocks provide an opportunity for low-carbon transition through lock-in of superior material efficiency practices (Creutzig et al., 2016, Ürge Vorsatz et al., 2018). On the other hand, there is a challenge for dealing with massive waste and emissions that would be released into society within the next decades. Krausmann et al. (2017b) estimate over 240 Gt of discarded and demolished waste globally, between 2010 to 2030, from overall societal stocks. This is as big a waste flow as the accumulation of the entire previous century (Hoornweg et al., 2013, 2015). This brings in another form of emergency to tap onto the opportunity for material efficiency efforts. These outflows (commonly considered as secondary materials) could potentially become available for substituting the primary materials. This has been envisaged globally as 'circular economy' where resources can almost always be re-circulated into the material consumption loop with reduced resource burden on the planet (Geissdoerfer et al., 2017, Kiser et al., 2016, Korhonen et al., 2018, Stahel, 2016). Such practice remains ingrained in the cultural practices of rural communities, for reuse and recycling, across the global south, but numerous historical evidences exist such as the practice of spolia or stone reuse in roman cities (Alchermes, 1994, Cooper and Gutowski, 2017, Frangipane, 2016). Proponents of circular economy argue that it can be one of the most efficient ways to deal with climate emergency while also ensuring that developing countries are able to provide decent living for their populations (Geissdoerfer et al., 2017, Ghisellini et al., 2016, Hertwich et al., 2019, Mathews and Tan, 2016, Su et al., 2013). But there remains numerous challenges in achieving the circular economy, low carbon growth and adequate living standards for global poor (Hart et al., 2019, Sanchez Rodriguez et al., 2018, Su et al., 2013). This is further complexed by hundreds of ways in which circular economy has been defined (Kirchherr et al., 2017) and in the variety of indicators with which it is proposed to be measured (Avdiushchenko and Zając, 2019, Krausmann et al., 2017a, Moraga et al., 2019, Saidani et al., 2019, Smol et al., 2017). This is particularly critical for cities where most of the world population lives today (UN, 2018). Cities have been responsible for the majority of global material consumption and carbon emissions as much as they are the economic centre of productivity and growth (Bai et al., 2018, Fernández, 2007b, Göswein et al., 2018b, Huang et al., 2017, Nagpure et al., 2018, Timothy Malcolm and Josephine Kaviti, 2018). Material efficiency and circular economy should and must therefore target cities. Several of the challenges raised so far are centred around near-future prospects of increased material consumption, unprecedented growth of waste and emissions as well as demand for adequate built environment for developing regions. In bringing out opportunities for the circular economy to answer these challenges, this thesis explores various aspects of built environment circularity using design research methodology. The next sections in this chapter provide a brief motivation, broader methodological framework and objectives of this thesis.

## 1.1 Motivation

The United Nations predicts over 1.1 billion urban population increase in the next 14 years, equivalent to nearly all of global population from 2016 to 2030 (Cohen, 2015), if one were to account for urban migration. It further suggests that higher resource consumption, energy use and greenhouse gas emissions associated with urban lifestyle would intensify the burden of climate change. There is, hence an immediate need of concerted efforts to reduce urban resources and energy consumption to achieve sustainable development goals (Sanchez Rodriguez et al., 2018). On similar lines, the Intergovernmental Panel on Climate Change (IPCC) estimates an absolute necessity for reductions in global greenhouse gas emissions by 50–85% by 2050 in order to stay within 1.5°C to avoid severe climate repercussions (IPCC, 2015, 2018, 2019). This however seems unlikely with business as usual material and energy consumption, with expected waste and emissions reaching 112 Gt/year, potentially exceeding available cumulative global carbon budget for 2°C temperature increase (Krausmann et al., 2017b, 2018a, Rogelj et al., 2019). This

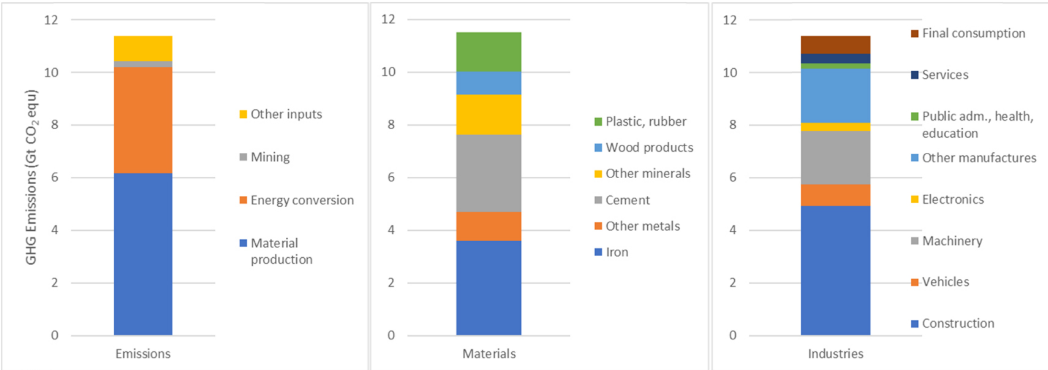



FIGURE 1.1: Emissions associated with material production (Hertwich et al, 2019)

brings in the priority of material efficiency in one of the biggest resource consuming sector of built environment- buildings and infrastructure.

The United Nations Environment Program argues buildings remain one of the largest contributors to greenhouse gas (GHG) emissions so any target for global emission reduction cannot be achieved without attempting resources efficiency in the building sector (UNEP, 2018b). Large proportions of materials consumed for stock building are non-metallic minerals such as sand, gravel and rock (Fishman et al., 2014, UNEP, 2016). In addition, building construction uses cement, metals, wood and various materials in complex building components which account for over 3.3 Gt of carbon emissions, close to 40% of overall material production emissions (Fig. 1) (Hertwich, 2019, Hertwich et al., 2019). In addition, of 1 Gt of annual steel production, 40% is consumed in buildings and 15% in infrastructure, making the construction sector its largest beneficiary. This is important from the point of view of typically 50-100 years of expected building lifetimes. However, the rapid urbanization and technological advancement has led to high rate of building obsolescence causing huge loss of resources and materials embodied energy (Cabrera Serrenho et al., 2019, Cooper and Gutowski, 2017, Göswein et al., 2018b, Miatto et al., 2017b).

Building obsolescence has contributed to significant building demolitions causing resource depletion and heavy waste generation. Construction and demolition waste so generated, contributes to about 40% of global waste at landfill (Huang et al., 2018, Kleemann et al., 2017b, Miatto et al., 2017b, Wu et al., 2014, Yuan and Shen, 2011). Construction and demolition (C&D) waste, as it is commonly referred to, accounts for approximately 30% of solid waste stream in U.S. and about 50% of overall landfill volume in the UK and 23% of the total solid waste generated in Hong Kong (Duan and Li, 2016, Huang et al., 2018, Sealey et al., 2001, Wiedenhofer et al., 2015, Wu et al., 2014). Langston et al. (2008) defined various forms of premature obsolescence as physical obsolescence, economic obsolescence, functional obsolescence, technological obsolescence, social obsolescence and legal obsolescence. Various forms of obsolescence generally render buildings unfunctional before their intended lifespan (Kaveh et al., 2018, Langston et al., 2008, Shen et al., 2013, Wuyts et al., 2019). This brings in the importance of production associated emissions in the overall emissions associated with a building's lifetime. Energy demand for buildings can be divided into materials embedded energy and operational energy such as electricity, heating etc (Cabrera Serrenho et al., 2019, ?). Generally embedded energy of building materials were not taken into consideration when compared to operational energy demands over building life cycle (Rauf and Crawford, 2015, Yohanis and Norton, 2002). Several studies have now highlighted that the average life of buildings has consistently decreased and often in Asian cities demolished buildings age could be lesser than 30 years (Cao et al., 2017a, Huuhka et al., 2015, Mah et al., 2016, Wuyts et al., 2019, Zhou et al., 2019). Though embodied energy may typically account for up to 20% of total building life cycle energy, studies have found it can be as high as 67% of total (Dixit et al., 2013, Mastrucci and Rao, 2017, Rauf and Crawford, 2015, Yohanis and Norton, 2002). With decreased building life, embedded energy forms a considerable amount of total energy consumption in building life cycle (Dixit, 2019, Mastrucci and Rao, 2019). This offers an opportunity for low-energy material efficiency strategies to be applied for a circular economy in building sector. Over 20 Gt of demolition waste was produced by building demolition in 2015 and has been growing at 4.2% of annual growth rate (Krausmann et al., 2018a). Such a huge waste stream shows the importance of developing systemic solutions for this challenge. C&D waste majorly include the debris generated during the process of construction, renovation, and demolition of buildings, roads, and bridges and includes concrete, wood, asphalt, gypsum, metals, bricks, glass, plastics, building components like doors, windows, plumbing fixtures, stumps, earth, and rock from clearing sites. There can be variations in the composition of C&D waste materials. According to the Environment Protection Agency of United States of America, the composition of C&D waste materials is given in Table 1.1.

Table 1.1: Typical composition of construction and demolition waste

| **S. No.** | **Components** | **Percentage** |
|---|---|---|
| 1 | Concrete and mixed rubble | 40-50% |
| 2 | Wood | 20-30% |
| 3 | Drywall | 5-15% |
| 4 | Asphalt roofing | 1-10% |
| 5 | Metals | 1-5% |
| 6 | Bricks | 1-5% |
| 7 | Plastics | 1-5% |

Various studies have emphasized reuse of building parts in order to save embodied energy, to minimize waste and its environmental impact (Cooper and Gutowski, 2017, da Rocha and Sattler, 2009, Dunant et al., 2017, Jin et al., 2017, Nußholz et al., 2019). Recycling of demolition waste remains an energy consuming process and hence may provide low embodied energy savings (Allwood and Cullen, 2012, Thormark, 2002). Instead, reuse with minimal or no processing offers low-energy building components and could save as high as 95% of embodied energy (Allwood and Cullen, 2012, Cooper and Gutowski, 2017). Though there have been significant efforts on demolition waste recycling, the majority of it has been used as backfilling materials with inferior applications (Haas et al., 2015, Mayer et al., 2019). To achieve low GHG emissions and resources efficiency in the building sector, Allwood and Cullen (2012) argued that the most important steps are to reuse old components before recycling and extend the life of products through a second life. However, several challenges, such as costs of transportation and recovery, have been cited as major hurdles. Nonetheless, reuse practices will not only eliminate energy needs for further processing but also enhance materials availability to support its demand (Allwood and Cullen, 2012, Cooper and Allwood, 2012, Dunant et al., 2017). Looking at the global material demand for providing decent living standards (Rao and Min, 2018), material and components reuse can play a crucial role in solving this challenge. There have been efforts in identifying pathways for building components reuse and challenges associated with it. But most commonly, such challenges for sector-specific circular economy vary with local stakeholders and practices (Petit-Boix and Leipold, 2018). First a comprehensive approach needs to be developed to look at macro-scale circular economy so that most material intensive sectors can be identified for circularity. Following such a prioritisation, sector-specific opportunities for the promotion of reuse can be identified. In principle, there is a need of systemic efforts to re-assess the concept of reuse, discuss its limitations and evaluate conditions under which reuse becomes a sustainable approach for climate change mitigation and adaptation in material world. Further, the challenges and opportunities for reuse-driven construction must be investigated for securing a supply of building components from the demolition site, scale of availability, acceptance in construction and underlying design process associated with each step.

## 1.2 Objectives

Considering the complex inter-connected material consumption patterns and importance of system-wide interventions, this thesis aims to identify opportunities and challenges associated with circular economy in the urban built environment. The specific objectives of this thesis include:

- Developing a methodology to assess the quantitative circular economy status and apply it to highlight circular economy progress in a city.
- Assessing the building demolition process to identify roles of various stakeholders, limitations for circularity and potential design interventions to overcome the limitations.
- Estimating the material and component inflows, stock and outflows for urban buildings to identify a potential scale of reuse-driven circularity.
- Assessing challenges associated with urban mining of building components, through experimental settings, such as labour costs, timelines, process and efficiency of recovery.
- Developing a methodology to assess the scale of urban mining and reuse potential of building components along with the scale at which low-cost houses can be supported with such a practice.
- Developing embodied carbon budget for building components and estimating the reuse radius- a transportation distance within which carbon savings exist for reuse of reclaimed building components.
- Developing the construction process and building prototypes for a proof of concept demonstration of design with reuse in construction sector

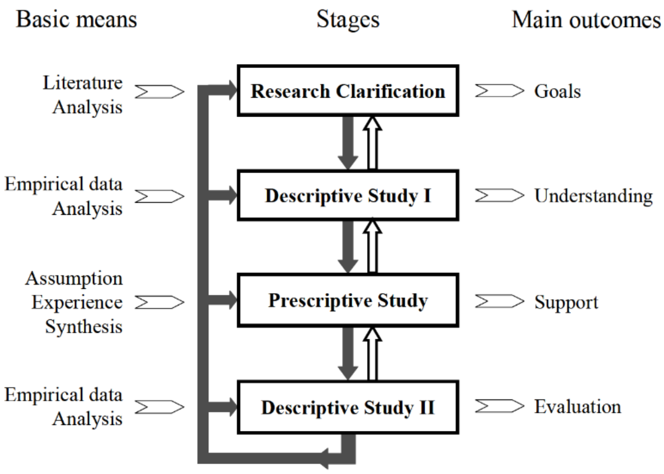



FIGURE 1.2: Design Research Methodology Framework (Blessing and Chakrabarti, 2009)

## 1.3 Methodological framework

This research majorly follows the Design Research Methodology framework (Blessing and Chakrabarti, 2009). Design research methodology (DRM) aims to support a more rigorous approach for design research and ensure its effective and efficient nature. DRM categorises (design) research into four major stages namely- Research Clarification (RC), Descriptive Study-I (DS-I), Prescriptive Study (PS) and Descriptive Study-II (DS-II) (Fig 1.2). Each stage is interconnected so that newer insights can inform each stage for effective research. The objective of the Research Clarification stage is to identify the goals of research, focus of the project and formulation of research questions. It includes the identification of the existing situation, known as Initial Reference Model and of the desired situation described as Impact Model. Research Clarification provides focus for the DS- I stage of the project for identifying factors that contribute, obstruct or prevent the realization of desired outcomes. The DS- I stage provides increased understanding of the phenomenon and success factors through empirical research and reasoning. The deliverable of DS-I include a clear and complete picture of existing situation highlighting the problems, relevance of research and factors that must be addressed to achieve the desired improved situation. Prescriptive study focuses on developing design support and/or solutions to act on the identified crucial factors or enablers of transformation while Descriptive Study-II evaluates the success of design support and/or solutions in achieving the desired goals.

Based on the identified research problem, seven types of design research projects are possible under the DRM framework (Fig 1.3). A research project may initiate with a review-based Research Clarification followed by comprehensive, initial or review based DS-I and PS stage in some combination. Evaluation of DS-I and PS can by initial or comprehensive depending on the timeline of a research project, availability of resources and feasibility of evaluation. The appropriate research methods may include empirical studies, analytical studies, experiential setups along with design support development. The design support to achieve desired impact model can be in the form of prototypes, proof of concepts, frameworks, products, software and/or decision tools, guidelines etc. The evaluation of such support tool can be at times difficult but can be ensured based

| Research Clarification | Descriptive Study I | Prescriptive Study | Descriptive Study II |
|---|---|---|---|
| 1. Review-based → | Comprehensive | | |
| 2. Review-based → | Comprehensive → | Initial | |
| 3. Review-based → | Review-based → | Comprehensive → | Initial |
| 4. Review-based → | Review-based → | Review-based → Initial/ Comprehensive | Comprehensive |
| 5. Review-based → | Comprehensive → | Comprehensive → | Initial |
| 6. Review-based → | Review-based → | Comprehensive → | Comprehensive |
| 7. Review-based → | Comprehensive → | Comprehensive → | Comprehensive |

FIGURE 1.3: Types of design research projects under DRM

on user feedback, customer acceptance, workability and success in satisfying the initial objectives. Broadly, the research in this thesis can be considered to fall under category 5 of Figure 1.3 where the design research projects which takes a review-based Research Clarification followed by a comprehensive DS- I, a Prescriptive Study followed by initial DS-II. Due to the inter-connected nature of research objectives in this thesis, different chapters have contributed, in part or fully, to one or more DRM stages.

DRM has been successfully applied in several domains of engineering design, including computer science, software development, product and service delivery. However, this thesis expands its applicability for urban sustainability and circular economy research in cities. Certain chapters of this thesis, hence, demonstrate a complete DRM based project on a standalone basis where a Research Clarification, DS-I and Prescriptive Study has been carried out for a specific design research objective with initial DS-II.

## 1.4 Organization of thesis

Overall, this thesis provides a comprehensive literature review, analytical and empirical studies, development of support tools and their evaluation in achieving the objectives. Though the overall implementation plan can be divided into distinct stages, in practice, this research project execution followed a partly parallel approach. The thesis is divided into nine chapters which contribute to the seven broad objectives identified in section 1.2. Each chapter develops a set of sub-objectives and contributes to one of the four stages of the DRM framework discussed in section 1.3. This thesis is organised as follows:

1. Chapter 2 provides a comprehensive framework for assessing the quantitative scale of circular economy in a city. The methodology so developed has been applied to Singapore to evaluate city-wide progress of circular economy from 2003 to 2016. This provides a comprehensive DS-I within a circular economy context, highlighting the status quo of urban material consumption and circularity. It further identifies a target sector for increasing material efficiency and circularity in cities.

2. Chapter 3 investigates the practice and status of building demolitions for end-of-life materials circularity in Singapore. It identifies potential design interventions for building components reuse, thus contributing to DS-I and directions for PS.

3. Chapter 4 develops a bottom-up material flow accounting framework for estimating building materials and components stock. Building material and component inflows, stock and outflows have been estimated in a city over 2010-2016.

4. Chapter 5 demonstrates urban mining experiments carried out in residential buildings for estimating the timelines, labour skills, cost and processing efforts required in recovering building components for reuse. It contributes to DS-I and PS by creating a building components inventory, as a support tool, to tackle market and information associated challenges in reuse.

5. Chapter 6 proposes linking of building demolitions with low cost house construction. It provides the scale of urban mining, recovery and reuse potential for Singapore. It further presents a case study of construction practices in Indonesia for low-cost houses and provides annual housing supply potential of building components from Singapore, contributing both to DS-I and PS.

6. Chapter 7 has been dedicated to estimating the reuse radius for salvaged building components for comparative transportation associated emissions with embodied emissions savings in reuse of building components. This decision tool for reuse of building components provides another support under PS for realisation of reuse driven circularity.

7. Chapter 8 provides design experiments and construction of reuse driven functional house Casa Azul to showcase the applied feasibility of the framework proposed in chapter 5, contributing towards DS-II. It further develops lessons from designing with reuse for a more circular built environment and thus expands on the PS.

8. Chapter 9 details the conclusions of this thesis with a discussion on the overall evaluation of the support tools developed in this thesis. It also highlights the direction for future research as a way forward.

For a non-expert reader, Table 1.2 provides a simplified overview of this thesis. It provides an overarching research question that each chapter attempts to answer and its contribution towards different phases of DRM. It is important to note that the basic research questions, as identified in Table 1.2, do not completely capture the complexity and details for each step in this thesis. Nonetheless, it provides a crucial and coherent structure for the research carried out in this thesis.

TABLE 1.2: A non-expert view at the research in this thesis

| **Chapter** | **Basic Research Question** | **RC** | **DS-I** | **PS** | **DS-II** |
|---|---|---|---|---|---|
| Chapter 1 | Objectives and the research framework | ✓ | | | |
| Chapter 2 | How can we measure the scale of Circular Economy in cities? | ✓ | ✓ | | |
| Chapter 3 | What are the existing barriers and opportunities for CE in construction sector? What are the prospects of reuse in construction? | | ✓ | | |
| Chapter 4 | How much stock of building components exists in residential buildings? What is the annual scale of building demolition? | | ✓ | | |
| Chapter 5 | How much will it cost to recover? What can be recovered without damage? | | ✓ | ✓ | |
| Chapter 6 | How much can be urban mined annually? How many low-cost houses can be built from it? | | | ✓ | |
| Chapter 7 | How far can we sustainably transport building components for reuse? | | | ✓ | |
| Chapter 8 | How can we design with reuse? What would change in the construction process and acceptability among clients? | | | ✓ | ✓ |
| Chapter 9 | Evaluation, scale up and way forward for this approach | | | | ✓ |

# Chapter 2

# Quantitative circularity assessment for cities: Status and progress of circular economy in Singapore

## 2.1 Synopsis

Circular Economy (CE) has become a top research and policy agenda within sustainability science for resources efficiency and climate mitigation. With focused dematerialization ambitions of cities and increased institutional investment, assessing the quantitative urban circularity has become an imminent priority. This chapter adpats an established economy-wide material flow analysis approach to develop an urban circularity assessment framework and analyses Singapore, a trade driven economy with a set of quantitative CE indicators during 2003-2016. Results highlight considerable socioeconomic metabolism expansion with highest material flows accumulating in societal stocks, a key sign of urban growth. The input circularity increment from 1.1 to 4.6% and output circularity rate increase from 8.5 to 13% over 14 years demonstrates little progress with long way to absolute circular economy. Results highlight that construction materials and fossil energy carriers have predominant effects on overall consumption and stock building.

## 2.2 Introduction

Hosting over 4.2 billion people, cities have become an epicenter for material and energy consumption, emitting over 75% of global carbon emissions (Allwood et al., 2011, Bai et al., 2018). Rapid urbanization, predominantly in Asia and Africa, would see an additional 2 billion people in cities, reaching a global average of 68% by 2050 (UN, 2018). Associated global material consumption and expected demands for near future would certainly lead to more emissions (Bai et al., 2018, Krausmann et al., 2017b, 2018a). Such resource requirements for urban growth have led to calls for sustainable development and low carbon transition in cities (Bai et al., 2018, Creutzig et al., 2016, Liu et al., 2015, Mark and Maarten, 2017, Mathews and Tan, 2016, Sanchez Rodriguez et al., 2018, Stahel, 2016, Ürge Vorsatz et al., 2018). There is an emerging consensus that growing material consumption and associated carbon emissions can potentially be reduced by achieving circular economy (Geissdoerfer et al., 2017, Kiser et al., 2016, Mathews and Tan, 2016, Stahel, 2016, Ürge Vorsatz et al., 2018). The concept of circular economy has, therefore, been applied at various scale from products and processes to systems, with significant research efforts and investments for circularity improvement across cities (Abu-Ghunmi et al., 2016, Arora et al., 2020, Bocken et al., 2016, Haas et al., 2015, Hertwich et al., 2019, Mathews and Tan, 2016, Schiller et al., 2017, Su et al., 2013, Ünal and Shao, 2019). The real challenge, however, has been assessing the progress towards circularity at a city and/or economy level.

In recent years, a variety of indicators have been developed to scrutinize the extent of circular economy at micro, meso or macro level of product, process and systems (Moraga et al., 2019, Saidani et al., 2019, Smol et al., 2017). Global circular economy momentum, however, requires city and nation-wide monitoring of progress. City-level monitoring of circular economy is crucial for policy makers and global scientific communities to assess its productivity and contribution to sustainability and ability to limit consumption within global carbon budget of 1.5°C as highlighted by Solecki et al. (2018). It goes beyond a product or process-level analysis to encompass a systems of system perspective in determining if CE does play a role in reducing the societal resource burden or promise of environmental benefits through material loop closing. Until recently available indicators couldn't provide the ease and scale for assessing city-level circularity due to several reasons including data availability and complexity of such a task. This challenge was resolved by Haas et al. (2015) by developing a monitoring framework to assess the scale of global circular economy. Haas et al. (2015) used varied datasets to combine global material consumption, waste and emissions to determine the scale of global circular economy for 2005. This framework has been further modified and adopted to quantitatively estimate the CE status for European Union and Austria by Mayer et al. (2019) and Jacobi et al. (2018) respectively. However, due to challenges associated with city-level datasets, these approaches still reach to a national-level monitoring.

Fundamentally, economy-wide material flows comprise four primary material categories namely biomass, metals, non-metallic minerals and fossil energy carriers. Consumption of these resources for food or developing societal stocks such as buildings, products, infrastructure and eventual generation waste and emissions helps sustain the bio-physical existence and wellbeing of society. A city can be modelled as a system in which materials are consumed and wastes are released after processing while a sizable portion of these materials contribute to the socioeconomic stock. Measuring the extent to which circularity exists in these flows for a City and how can it be maximized remains the major objective of this chapter. The biggest challenge in measuring the status of a circular economy remains the availability and sourcing of data. In case of a country or a group of countries, readily available datasets can be utilized which are either maintained by trade organizations or national registers and statistics offices. The challenges for finding such datasets for a city are significant. Data from surveys or bottom-up approaches of material flow estimates can be crucial but may not provide the comprehensiveness needed for complete resource consumption, in addition to stocks, waste and/or emissions.

To solve this challenge, this study adopts and advances the monitoring framework developed by Haas et al. (2015) to assess the circular economy status and progress of a city. Singapore has been chosen as a case study to assess its circular economy status and progress from 2003 to 2016. Singapore, known for its advanced built environment and near absolute house ownership, remains a global model for cities for smart, sustainable and high quality life (Chew, 2010, Henderson, 2012, Marshall, 2016, UNEP, 2018c). However, being a land limited nation, Singapore remains a resource limited city with significant dependence on trade flows (Arora et al., 2019, Chertow et al., 2011, Gursel and Ostertag, 2016, Schulz, 2007). High quality of built environment and local resource scarcity makes Singapore a typical example of growing cities. Assessing the historical progress towards circular economy will help in tracking resources consumption, waste generation, emissions and extent of circular loop closing through reuse, recycling and/or downcycling. This chapter further discusses the challenges in realizing practice oriented circular economy and opportunities for incorporating circularity in existing material consumption patterns of cities.

This chapter is organized into a section detailing the methodological framework and data sources, followed by results and a discussion considering the global circular economy debate.

## 2.3 Methodology

Overall societal resource consumption can be aggregated into four major material categories- biomass, metals, non-metallic minerals and fossil energy carriers. Fundamentally, these resources are consumed either for energy such as biomass for food, animal feed, coal and petroleum for electricity and heat etc; or for material usage such as wood and concrete in buildings, metals for infrastructure and vehicles to name a few. Total resources consumption, hence, can be categorized into material usage and energetic usage denoted as mUse and eUse.

Systems boundaries are an important aspect of an economy within socioeconomic systems. In this study, the physical boundary of a city serves as the economic system boundary while outflows include trade with the region and waste and emissions into the natural environment. A city can be considered as a system of systems which receive inflows of resources to sustain its activity, accumulate some resources to maintain its productivity and creates outflows after resources transformation. Inputs comprise of domestically extracted primary materials, denoted as DE and Imports from neighboring cities and/or economies. In a traditional economy-wide material flow analysis, these indicators have been well established (Krausmann et al., 2017a, 2018b). Figure 2.1 provides a systemic methodological framework where a city is represented within the dotted system boundary.

Direct Material Input (DMI) is the sum of DE and imports while domestic material consumption (DMC) reflects the proportion of DMI excluding exports. DMC provides for material and energetic requirements of society. In the case of a city, exports themselves may be processed and transformed before export and hence can contribute in socioeconomic activities. Inclusion of exports in Processed Materials (PM) require further debate and consensus for circularity considerations. The processing of raw materials from sectors such as mining may lead to significant extractive waste which directly becomes an outflow, however, such a major activity within a city may or may not exist. Processed materials used for energetic purposes would lead to gaseous emissions and solid and/or liquid waste which can directly be attributed as an outflow. However, processed material with material usage may have varied service life within socioeconomic systems. For circularity assessment, material usage with an expected life of 1 year or less has been considered as throughput materials. These include products and packaging materials with a very short life span of one year. Materials with service life longer than one year such as concrete, metals in buildings and infrastructure, electronics and electronic equipment, vehicles, furniture are typically added to the existing societal built stock as long-lasting manufactured artifacts. As materials are added into the stocks, they are also discarded and demolished. This is accounted for in the circularity assessment framework as demolition and discard. Balance of gross added materials into stock and demolitions and discard denotes the net stock addition which highlights the growth of urban material stock. All the outflows in this system are intermittently called interim outputs which include all emissions, solid and liquid wastes. Together they account for overall system outflows from which a fraction of materials can be recovered for functional applications through all kind of further processing such as reuse, recycling, remanufacturing and/or downcycling. Such fraction, called secondary materials (SM), contributes back as input to create a circular economy. The proportion of SM in outflows and/or inflows helps create a variety of CE indicators, as highlighted in Table 2.1, which have been used to further assess the circular economy in Singapore city. Outflows finally leave the system boundary as domestic processed output (DPO) in the form of emissions or solid and liquid waste. The overall mass balancing for energetic and material usage to emission and end-of-life waste has been achieved through Eq. 1 and 2 (see SI - A.1).

$$\text{DPO emissions} = \text{eUse} - \text{solid and liquid wastes} \tag{2.1}$$

$$\text{Demolition and discard} = \text{EoL waste from mUse} - \text{throughput materials in waste} \tag{2.2}$$

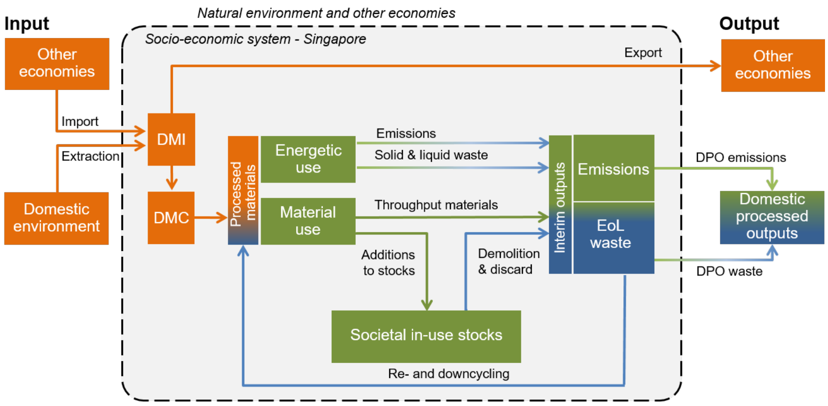



FIGURE 2.1: Methodological framework for quantitative circular economy monitoring adopted from Haas et al. (2015); Mayer et al. (2019). Colors indicate data sources: orange represents official data from the IEA, FAO and UN Comtrade, blue represents official waste data from data.gov.sg, and green represents mass-balanced modeling with the shift from green to blue color indicating a combination of statistical data and modelling

## 2.4 Data sources and validation

Singapore, being a city-state has clear urban boundaries, allowing all material flows to be accounted as international trade flows. Due to natural resoutrces scarcity, domestic extraction is limited to biomass such as vegetables, seafood, meat etc. To build a systems and material circularity perspective, this study combines statistical data available from various international data sources and national data reporting system of Singapore. Singapore's import and export data for metals and nonmetallic minerals was accessed from United Nations International Trade Statistics Database (UN Comtrade). Even though UN Comtrade provides data for biomass and fossils energy carriers, better quality databases are maintained by Food and Agriculture Organization (FAO) and International Energy Agency respectively. Hence, the FAOSTAT database was used for all biomass related trade and production, while IEA database was used for all fossils energy carriers such as coal, natural gas, petroleum and petroleum products. Waste and emissions data was collected from Singapore National Data Repositories (data.gov.sg) and Singapore's Department of Statistics. The datasets were processed and cleaned based on the procedure recommended by Krausmann et al. (2018a). Datasets from various sources were combined for all biomass, metals, fossils and non-metallic mineral flows to align with the proposed CE monitoring framework (see Fig. 2.1) through systematically mass-balanced material inputs with waste flows. A crucial data challenge remains in identifying data for distributing stock building materials under mUse. The exact share of stock-building materials in mUse for a specific city could be very hard without a thorough bottom-up assessment. Shares used in this study are based on previous studies such as Mayer et al. (2019) and Singapore specific literature, statistics and assumptions. This was further validated with a mass balanced approach used for the data and material stream specific strategy. To validate the fossil energy carrier consumption, associated emissions were estimated using a stoichiometric mass balance approach recommended by Krausmann et al. (2018a) and compared with national greenhouse gas emissions reported by Singapore. Non-metallic minerals consumption was validated based on total demand for cement, asphalt and land reclamation.

Table 2.1: Various Parameters and Indicators for Circular Economy

| **Parameter** | **Definition** |
|---|---|
| Processed materials | PM = DMC+secondary materials |
| Interim outputs | IntOut = EoL waste+DPOemissions |
| Input socioeconomic cycling rate | ISCr = Share of secondary materials in PM |
| Output socioeconomic cycling rate | OSCr = Share of secondary materials in IntOut |
| Input ecological cycling ratepotential | IECrp =Share of DMC of primary biomass in PM |
| Output ecological cycling ratepotential | OECrp = Share of DPO biomass in IntOut |
| Input non-circularity rate | INCr = Share of eUse of fossil energy carriers in PM |
| Output non-circularity rate | ONCr = Share of eUse of fossil energy carriers in IntOut |

## 2.5 Results and discussion

With a negligible proportion of local produce (DE), Singapore's trade dependence on gathering primary resources can be seen from Figure 2.2. With only 0.329 million tons

(MT) of biomass as DE, processed materials (PM) within the city are predominantly driven by 270.3 MT of import and 173.5 MT of export in 2016. A large proportion of imports being fossil fuels (187.2 Mt, 69%) followed by non-metallic minerals (65 Mt, 24%) highlights the importance of fossil and construction industry in Singapore. Even though the DE has been stagnant over the years from 2003 within 0.3 MT range, imports and exports have seen a major growth. Comparatively in 2013, the imports were roughly half at 136.6 MT with 84.4 MT of exports. An overwhelming majority of exports are fossil energy carriers and products (160.8 MT). As a major oil trading and refining hub, most of the fossil fuels it imports are in the form of crude oil, which is traded or refined into other petroleum products for export.

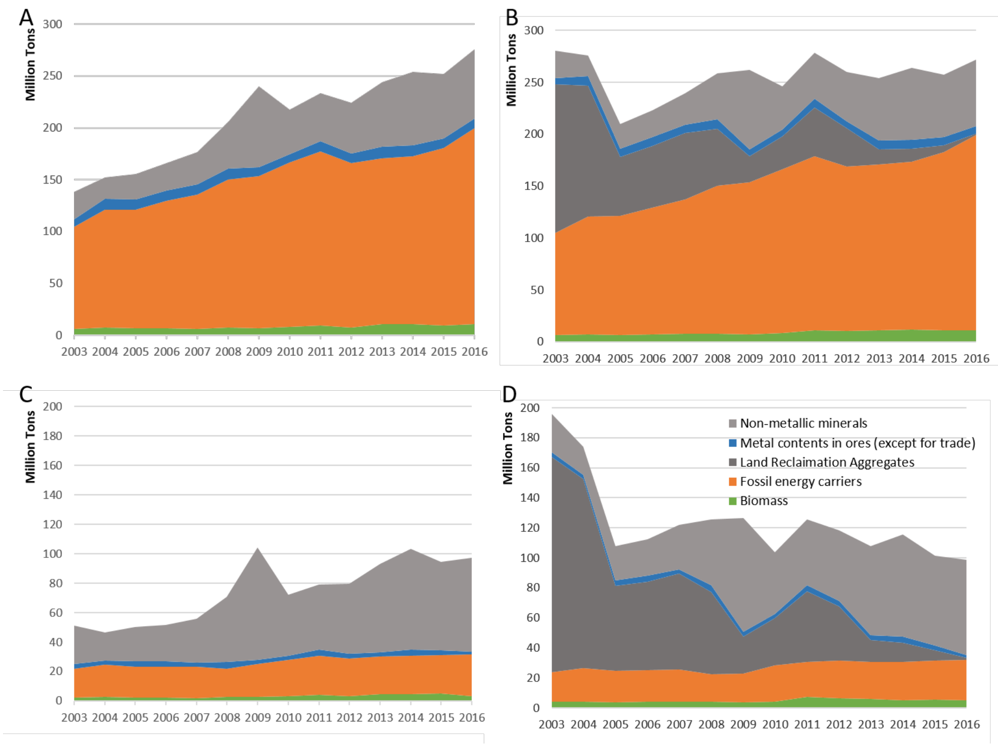



FIGURE 2.2: A. Direct material input (DMI) without land reclamation, B. includes land reclamation flows, C. domestic material consumption (DMC) without and, D. with land reclamation

DMI and DMC have seen similar increasing trends based on their dependence on DE, import and exports (Figure 2.2). It is important to highlight that the construction sector remains one of the largest sinks for annual DMC in the form of non-metallic minerals. This is compounded with non-metallic minerals needed for land reclamation. Singapore's land scarcity has seen targeted efforts on making more land. However, not all the non-metallic minerals are captured by the UN Comtrade data on construction minerals import. Based on geotechnical studies on land reclamation in Singapore (Arulrajah et al., Bo et al., 2005), and previous estimation of required materials (Schulz, 2005, 2007), demand of annual land reclamation was matched with the excess of non-metallic minerals required for all construction activities. Unmet demand for land reclamation has been then assigned into inflows as shown in Fig. 2.2, however, discussion here refers to Fig.

2.3 which doesn't include the land reclamation flows. Fig. 2.4 highlights the true state of material flows and includes demand of non-metallic minerals for annual land increase.

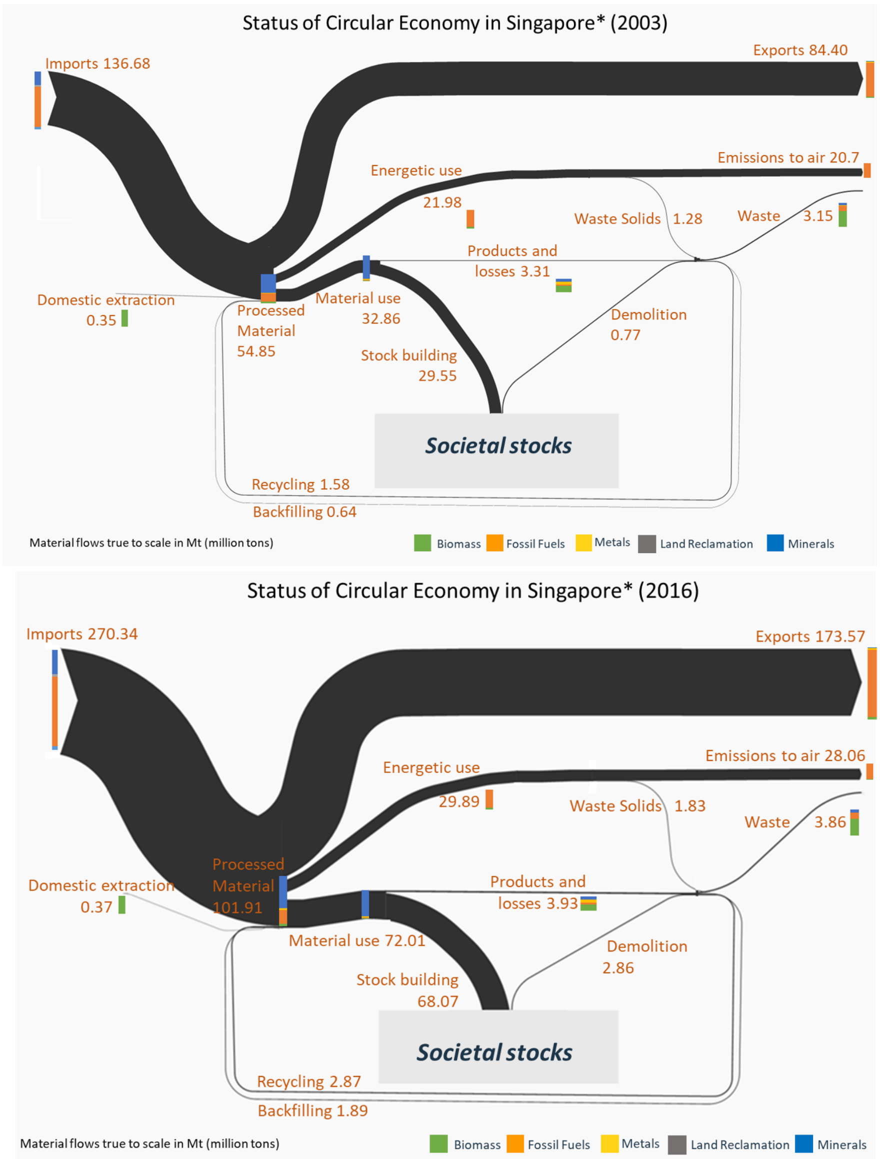



FIGURE 2.3: Status of the circular economy in Singapore (*excluding the land reclamation flows)

Processed materials have increased from 54.8 MT to 101.9 MT over fourteen years. A large proportion of this has been used for stock building activities through mUse and the rest serving the energy demands for societal need such as food, feed, electricity, vehicle fuel etc. mUse grew from 32.8 MT in 2003 to 72 MT in 2016, highlighting the ever-increasing growth of the city. eUse has also increased from 21.9 MT to 29.89 MT over the years but not as significantly as mUse. In 2016, eUse helped produce 48.6 TWh of electricity which is consumed by manufacturing industry (38%), followed by businesses in the commerce and services sector (36%), and households (16%) (Singstat, 2019a).

Further eUse helps provide fuel for 956,430 motor vehicles (LTA, 2018) in addition to the food for 5.6 million residents.

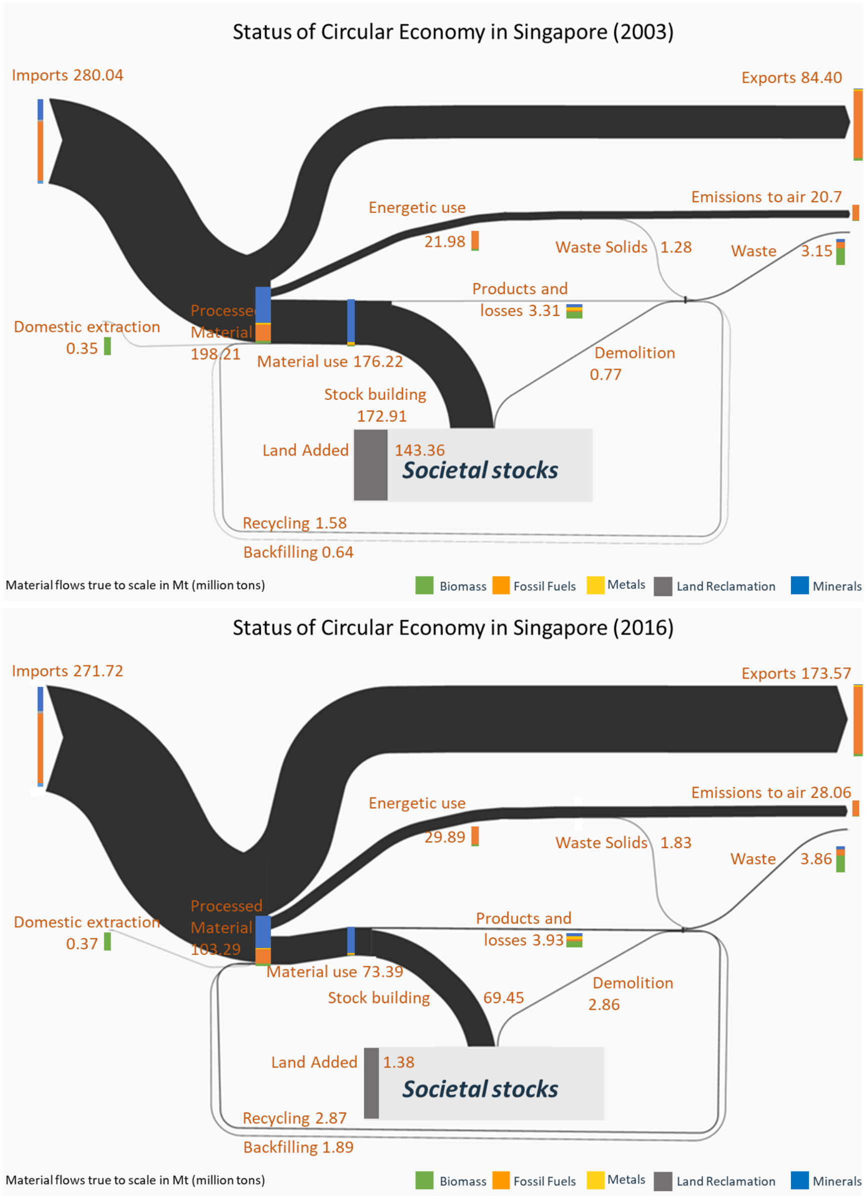



FIGURE 2.4: True scale of material flows and circularity with land reclamation flows

The process associated losses and short-lived products contributed 3.9 MT of outflows along while 2.9 MT of materials from existing stocks that were discarded and demolished. eUSe contributed to 1.7 MT of solid and liquid waste. Oxidation and/or consumption of energetic materials released 28 MT emissions into atmosphere while 3.8 MT of solid waste was generated as processed outflow for disposal through incinerators and/or landfill. Demolition and discard have significantly grown from 0.8 MT in 2003 while the overall disposed off waste only grew by 0.7 MT. In comparison to 29.5 MT in 2003, 68 MT of materials were used in stock building in 2016, over 30fold more than the demolition and discards.

Secondary materials recovered from Interim Outputs have been distinguished into recycled and backfilled materials. Backfilling primarily accounts for material usage in low quality applications such as concrete used as base materials in road or land reclamation. Out of total PM, secondary materials accounted for 1.9 MT of down cycling and 2.9 MT of recycling in 2016 compared with 1.58 MT and 0.6 MT of recycling and backfilling respectively in 2003.

Data validation, as discussed in the methods section, helped in identifying the data gaps and making sure that the results are robust. Validation of construction minerals DMC with the expected demand highlighted the need to capture unreported flows. Figure 2.4 shows a significant contribution of unreported flows on the overall socioeconomic metabolism and circularity. The PM for 2003 increased from 54.8 MT to 198.2 MT with accounting of land reclamation. This resulted in significant increase in DMI and DMC (as shown in Fig. 2.2). Further 143.3 MT of total 172.9 MT of stock building mUse helped in creating new land which is a permanent stock. Over the fourteen years of this assessment, land reclamation activity has consistently decreased which has resulted in very low impacts on later years. This is visible from only 1.3 MT of addition PM and stock building mUse for 2016. To validate eUse flows, overall equivalent carbon emissions associated with eUse were estimated and compared with total energy associated carbon emissions for Singapore reported by International Energy agency (https://www.iea.org/statistics/). For example, we estimate energy associated emissions to be 43.9 Gg and 43.6 Gg in comparison to 44.16 Gg and 45.27 Gg reported by IEA for year 2015 and 2016 respectively (Fig 2.5B). These estimates match satisfactorily with Singapore's reported total Greenhouse gas emissions of 51.7 Gg and 51.3 Gg for each year. Overall there has been a slight increase, from 85% to 89%, in energy associated emissions from city.

As described in Table 2.1, circularity rates used in this study and proposed by Mayer et al. (2019) measure material flows in relation to interim flows namely PM and Interim Outputs. The ISCr (socioeconomic cycling rates) measure the contribution of secondary materials to PM, OSCr, output socioeconomic cycling rate measures the share of IntOut diverted to be used as secondary materials. The share of biomass DMC in PM estimates the input ecological cycling rate potential (IECrp) and while the share of DPO from biomass in IntOut measures the output ecological cycling rate potential (OECrp). eUse of materials lead to emissions which can not be recovered in material form and hence, the noncircularity indicators measure the share of eUse of fossil energy carriers in PM and IntOut. These indicators detect and monitor city-wide improvements and trade-offs for circularity. Enhancing circularity for one material has an impact upon the use of other materials and energy due to transport, labor and energy investments in process associated with circularity. The shares of socioeconomic, ecological, and noncircular flows in PM and IntOut as circularity indicators, hence, can monitor system-wide implications of circularity initiatives (Mayer et al., 2019).

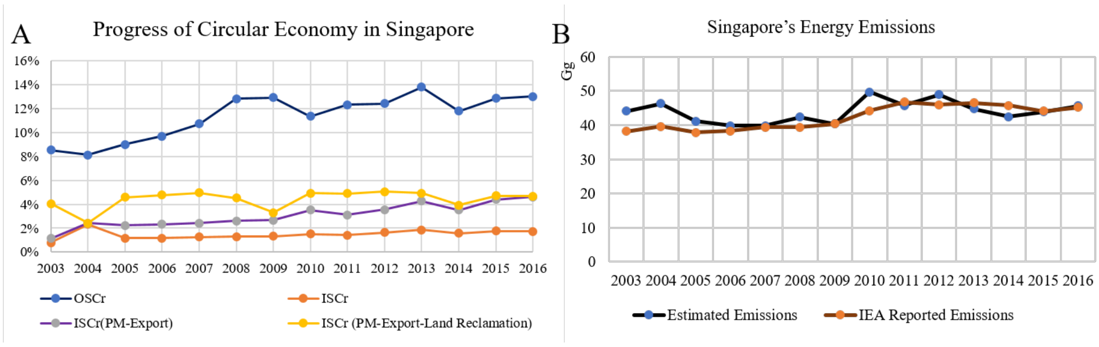



FIGURE 2.5: (A) Progress of Input and Output Socioeconomic circularity rates (B) estimated carbon emissions associated with eUse in comparison with IEA data.

Fig. 2.5A highlights the citywide circularity change over fourteen years from 2003-14. It is crucial to highlight, though, that PM, for a trade dependent city with major processing of exports involved in its territory, can also become the sum of DMI and Secondary Materials. Likewise, flows associated with permanent stock i.e. land reclamation can also influence the overall circularity rates. To account for these two aspects, ISCr has been calculated for all three possibilities. ISCr for Singapore city varied from 0.8% in 2003 to 1.72% in 2016 with highest level of 2.3% in 2004. Ignoring exports, ISCr was lowest at 1.1% in 2003 and reached highest level of 4.62% in 2016. Excluding permanent stock flows resulted in high ISCr rates in early years and became similar at 4.68% in 2016 due to very low share of permanent stocks share. Input non-circularity rates have decreased from 35% in 2003 to 25% in 2016. While IECrP rates have decreased from 9% to 6% in 2016. Input Socioeconomic cycling potential, however, has increased from 56% to 68% of the total PM in 2016. On output circularity, OSCr has grown over the years in quantity and share from 8.52% to 13% over fourteen years. Output noncircularity rates (ONCr) decreased from 74% to 70% while OECrP decreased from 14.5% to 13.4% in 2016. If one were to exclude emissions in accounting for circularity and only look at the share of SM in total non-emission Interim Outputs, OSCr would have 29.3% in 2003, reaching the highest level of 35.6% in 2016. In comparison for EU28 group of countries, Mayer et al. (2019) estimated OSCr at 14.8%, ISCr at 9.6%. IECrp at 24.6%, the OECrp at 35.3%, Input noncircularity rate (INCr) of 21.2%, and an output noncircularity rate (ONCr) of 32.8%. Singapore's circularity, both OSCr and ISCr, is much lower than EU. Input circularity rates of 4.68% in Singapore, in comparison to 9.6% in EU, highlight a much smaller scale of input circularity rate into societal consumption. Higher Non-circularity rates demonstrate greater dependence on fossils which makes it difficult to achieve a circular economy. For a more comprehensive comparison, Table 2.2 compares the scale and circularity indicators of Singapore with global, European union and Austrian average estimated.

To look at the progress of Singapore's material consumption since independence in 1965, Schulz (2005) estimated imports, exports, DMI and DMC at 6.8 tons, 5 tons, 8.2 tons and 3.2 tons per capita respectively. After 52 years, these have grown to 48.2 tons, 31 tons, 48.3 tons and 17.3 tons per capita. This highlights the growth in resources demand as Singapore became a developed city in Asia. This growth however has fueled the per capita GDP from S$5800 in 1965 to over S$77000 now. This leads to a very important point that even though cities struggle on self-sufficiency for their material

Table 2.2: Comparative positioning of Singapore's circular economy

| **Indicator** | **Global average in 2005, Haas et al. (2015)** | **EU28 average in 2014, Mayer et al. (2019)** | **Austria average in 2014, Jacobi et al. (2018)** | **Singapore average in 2014 based on this study** |
|---|---|---|---|---|
| DMC (Tons per capita) | 12.2 | 13.2 | 22.6 | 21.1 |
| PM (Tons per capita) | 13 | 14.6 | 24.7 | 21.9 |
| PM mUse (Tons per capita) | 8.8 | 8.4 | 18.2 | 16.5 |
| PM eUse (Tons per capita) | 4.2 | 6.2 | 6.5 | 5.3 |
| Socio-economic input circularity ISCr | 0.061 | 0.096 | 0.083 | 0.039 |
| Socio-economic output circularity OSCr | 0.093 | 0.148 | 0.166 | 0.118 |

demand, they are epicentres for creating economic productivity and services for society which must also be looked at in this discussion on material productivity.

This assessment highlights several possibilities for monitoring circularity status of a city. Typically for resource rich countries, as shown by Haas et al. (2015) and Mayer et al. (2019), processed material differ from DMI or DMC significantly. For cities like Singapore, where imported materials are typically processed before exporting into other economies, distinguishing DMI with PM or DMC becomes a matter of discussion. If exports were to be accounted in PM, the circularity rates will accordingly change. In addition, lack of detailed data on existing stocks, demolition rates from buildings, vehicles or manufactured artifacts as well as the extent to which a material is used for material or energy purposes, all can lead to uncertainties in CE assessment. Bottom-up assessments of sector-specific stocks and stock building extent of material categories can also help in bringing additional robustness into CE assessments.

The practice of waste management and aspirations to be a circular economy can be at odds with end-of-life treatment practices such as incineration. Singapore relies significantly on incineration processes for end-of-life management due to lack of enough land or labor. Annual waste incineration ranged from 2.3 million tons to 2.87 million tons annually over 2003-2016. Even though incineration produced annual electricity in the range 0.9-1.2 million MWh, it replaces ecological cycling with non-circular emissions. Another important aspect related to circularity indicators and the circular economy remains the trade of secondary materials. Intention to recycle secondary materials does not ensure recycling within the city boundary. This study assumed secondary materials for Singapore city were processes and used again within the the city. But massive trade flows of waste across countries suggest that such a circularity may not always exist within a city. It is becoming increasingly important in an era of trade wars and ethical issues associated with developing countries becoming a scrapyard of waste (Liu et al., 2018, Qu et al., 2019). This has led to countries such as China banning the import of recyclables and several countries returning the shipments back to source country from their port of entry (Göswein et al., 2018b). More robust data on recycling and reuse locations will help ascertain if the SM collection and/or recycling contributes to the circularity of same city or it goes to another city and/or country for processing and ends up contributing to an open economy of circularity.

Land reclamation remains one of the major sinks for non-metallic minerals in Singapore. Over the period covered in this study Singapore's land increased from 693.4 $km^2$ in 2003 to 719.7 $km^2$. Based on a conservative estimate in this study, such a scale of land reclamation would require over 786 million tons of non-metallic minerals. In comparison, Singapore produced mere 14 million tons of non-metallic mineral waste i.e. demolition waste over this period. This highlights the extent to which the land reclamation activity consumes demolition waste for backfilling, making concrete recycling, for higher applications, a completely demand driven process. This suggest that a closer look at demolition practices of buildings and infrastructure can bring about opportunities for non-structural components circularity. Based on the overall non-metallic mineral PTB, it is possible to validate if the imports alone can match such a huge demand. Documented non-metallic mineral flows, however, suggest a gap of over 678 million tons in trade flows which may have been met through alternative sources. This study however assigns flows to landfill directly as a proportion of total flows. Addition of material inflows to land reclamation brings in a newer aspect to the traditional societal 'stock' in Industrial ecology. Typically, stocks are expected to become obsolete after a service life and lead to outflows through demolition. However, in the case of Singapore, a fraction of stock becomes permanent stock with an infinite service life and hence provides an exceptional example, diverging from hibernating stocks.

## 2.6 Summary and outlook

This chapter contributes in increasing objectivity of targeted circular economy in societal material consumption based on the investments already in place for end-of-life waste management. Case study like the one offered here can help assign the financial capital needed for growing unit percentage point towards absolute circularity. This study provides several insights for city-level circularity. With no-apparent domestic extractions, cities predominantly rely on neighboring regions for their primary consumption. The contemporary debates on urbanization and rural migration may benefit from resources contribution of neighboring communities to cities. The extent to which circular economy can be achieved is limited by non-circularity rates for material consumption for energetic purposes. Achieving circularity has its own energy requirement, e.g. recycling consumes energy, transport and infrastructure which affects consumption and so the overall circularity rates. Hence promotion of less-energy intensive circularity modes such as material reuse and resource efficient designs hold key. Overall an absolute circular economy cannot be imagined without elimination of fossil energy carriers from consumption stream. A world with fossil energy may then be best both for planet and the absolute circular economy. This further opens the opportunity for evidence-based policies on circular economy targets for city authorities and national governments.

This chapter provides a firm basis to investigate circular economy in buildings and construction sector in much detail. With the largest share of DMC and stock addition, circularity in the buildings sector can have a significant impact on the overall circular economy. To investigate sector-specific grassroot opportunities and challenges associated with realization of circular economy, further assessment of local practices, conditions and stakeholder's role remains necessary (Petit-Boix and Leipold, 2018). The CE assessment in this chapter could not differentiate between circularity forms such as reuse, recycling or backfilling in greater detail due to data constrains. This highlights the need for assessing end-of-life buildings, their demolition process and fate of materials to identify opportunities for downcycled materials to be reused.

# Chapter 3

# Design interventions for linking demolitions to design[1]

## 3.1 Synopsis

A traditional way of looking at the urban sustainability has been from the perspective of the environmental sciences and waste management methods. Analyzing urban areas with design science perspectives could provide novel insights to improve existing resource consumption patterns and transform sustainability growth in cities. This chapter focuses on the problem of demolition waste arising from the premature building obsolescence in cities. It applies design research methodology framework for identifying existing problems associated with demolition waste and generating strategies to transform cities into more sustainable urban systems. In the research clarification phase, a detailed literature review and semi structured interviews were used to identify stakeholders involved and their responsibilities in the building demolition process. Research was further extended to carry out a demolition case study (DS-I) and generate support tools to enable transformation in the existing scenario for achieving reuse of building materials. Singapore has been taken as a case city in this research. Results highlight lack of noticeable reuse and significant downcycling of end-of-life building materials. Low-cost housing demand in neighboring regions have been proposed as a potential reuse market. The challenges associated with realization of material reuse practice needs significant efforts. This chapter concludes with the strategies on creating a reuse market through entrepreneurial innovation and an alternative material supply chain of secondary materials for regional housing demand. Methodologically, results highlight the role of design research methods for tackling complex systems problem in cities.

## 3.2 Introduction

The high pace of alteration, renovation and demolition of buildings has led to significant construction and demolition (C&D) waste. Such scale of waste generation has created an alarming imbalance in inherent resilience of urban metabolism (Hoornweg et al., 2013). To tackle this challenge, various resource efficiency concepts have been developed though the applicability of those concepts remains a subject of detailed scrutiny (Duan and Li,

[1]Partially published as Mohit Arora, Felix Raspall and Arlindo Silva (2018) *Identifying design interventions in cities for urban sustainability, Proceedings of ASME IDETC/CIE Conference on Design for Manufacturing and the Life Cycle*, Quebec, Canada (DETC2018-85808)

2016, Lu et al., 2017, Mah et al., 2016). For Simon, the first step in identifying a satisficing solution to a complex systems design problem would be to unearth the underlying situation followed by defining the problem we seek the solution of (Simon, 1988). Points of intervention can only be identified after forming a clear picture of the existing system. For resource constrained urban systems, finding alternative approaches for minimizing the supply-demand gap of building materials has become rather immediate (Miatto et al., 2017a, Ugochukwu and Chioma, 2015). Consistent construction and increased real estate GDP have caused huge demand for building components and materials, while premature building obsolescence has caused significant decrease in a building's average life (Aksözen et al., 2017, Duan and Li, 2016, Dwaikat and Ali, 2016, Hoornweg et al., 2013). Such premature obsolescence leads to the discard of excellent quality building components which could have been utilized for a longer life cycle. This is not merely a waste of material, but it also represents embodied energy which becomes significant compared to operational energy demand in a reduced lifespan of a building (Crowther, Langston et al., 2008). Various cultural, economic and/or planning reasons cause such building demolitions leading to resources and landfill burdens. The extent at which demolition waste contributes to the global waste stream makes this problem furthermore significant.

Instead of material compositions, buildings can also be categorized in the form of structural components such as columns, beams, roof and non-structural components such as doors, windows, kitchen and toilet accessories, appliances, flooring etc. Though materials are hard to bring back into the next use phase, components have an advantage of being able to be reused as such with little or no additional processing which makes them interesting from the resource's efficiency point-of-view. This chapter focuses on resource constrained cities as a model urban system for identification of design interventions. Singapore relies on importing construction materials and building components from other countries and thus has been taken as the case study. Land scarcity and a single available landfill to accommodate solid waste are major concerns for Singapore which require interventions.

Design science has been associated with sustainability research and can help in targetted efforts for the circular economy. Papalambros (2009) noted lack of environmental sustainability focus in design research studies and highlighted that only few studies looked at sustainable design or the possible environmental consequences in engineering designs. Following this call, sustainability in design efforts emphasized on the need for engineering designers to consider environmental consequences as well as sustainability attributes for artifacts (Ramani et al., 2010b). Ramani et al. (2010b) suggested to go beyond individual design's sustainability and support every economically viable design which may significantly reduce environmental and societal concerns. In first of its kind study, Ramani et al. (2010a) linked sustainable thinking with traditional design methods for the life cycle environmental performance of designs to provide designers with a perspective of eco-design and product performance. Devanathan et al. (2010) discussed products end-of-life management issues at length and concluded that disposal can no longer remain a primary strategy for product retirement. Authors discussed processes for end-of-life management, primarily the product take-back option and highlighted that better information about product design, quality and timing can improve the end-of-life opportunities. Study further summaries previously established design strategies, including modular design, Design for disassembly, Design for reuse and re-manufacturing and

Design for material recovery, for cradle to cradle product life management highlighting the challenges that remain unsolved in achieving close loop management.

In line with previous assessments, Behdad et al. (2012) also argued that disposal can no longer remain only strategy and recycling, repair and reuse must be explored as an alternative end-of-life strategy. Authors highlighted the uncertainty involved in the end-of-life products return for remanufacturing industry. However, it is important to highlight that products such as electronic items, equipment as well as sold goods are inherently different from commercial or residential buildings. The uncertainty in end-of-life product flows do remain crucial in real estate building renovations and demolitions though there is no product ownership at end-of-life of buildings. Similar to the e-waste stream as discussed by Kwak et al. (2011), the variability in the demolition waste streams are significant. The issues of age, size, quality and quantity are highly uncertain for materials coming out of demolitions for each building primarily because of the differences in construction method, timing, typology and geographical locations. Several studies have also considered market influence of waste products, primarily considering take back programs in which manufacturing firm is responsible for managing the end-of-life phase of sold products, for profitability as well consumer preferences for designers to consider at early design phase (Shiau and Michalek, 2008, Zhao and Thurston, 2013). In order to provide coherent early design phase guidelines, Telenko et al. (2016) analyzed 6 strategies and 72 guidelines on design for environment to reduce overall environmental impacts.

There has been a significant consideration for end-of-life management strategy at studies focusing on early design phase (Arlitt et al., 2017, Cardin and Hu, 2015, Chung et al., 2013, Kishita et al., 2010, Sabbaghi and Behdad, 2017, Withanage et al., 2016). However, some studies have focused on end-of-life product management, second hand markets, profitability and remanufacturing (Kwak and Kim, 2016, Kwak et al., 2012, Sabbaghi and Behdad, 2017, Woo Kang et al., 2013, Zhao and Thurston, 2013). Studies like Capen and Capen (2014) and Odonkor et al. (2016) have considered, in detail, the operational energy consumption in an urban and suburban context, highlighting various energy consumption patterns. In addition, there has been an effort to initiate design for disassembly and modularity in constructions for reuse at the end-of-life or deconstruction in previous decades (Kozminska, 2019, Rios et al., 2015). Their remains a lack of literature on building demolition processes and demolition waste in design focused community. With renewed interest in achieving circular economy, the waste management community has scrutinized construction and demolition waste for challenges in its reuse or recycling (Burlakovs et al., 2017, Huang et al., 2018, Jin et al., 2017, Kleemann et al., 2017b, Sakata et al., 2002, Wu et al., 2014, Yuan and Shen, 2011). Due to large differences in stakeholder interactions, construction methods, choice of materials and typologies, bottom-up assessment of demolition waste situation remains extremely crucial for identifying opportunities for achieving resources efficiency. To assess end-of-life buildings management, this chapter investigates residential building demolitions in Singapore city.

Literature on the state of the art of construction and demolition waste in Singapore is limited. During 2007-08, Singapore faced a construction material crisis due to an Indonesian export ban on sand and granite (BCA, 2007). To answer to such challenges, Singapore initiated its focus on waste recycling and optimum utilization of construction materials through a Sustainable Construction Master Plan (BCA, 2015). The Master plan started with two targets a) ease the impact on limited landfill capacity and b) reduce dependency on imported construction materials through initiatives on recycling and efficient concrete usage. Though website data on the National Environment Agency, Singapore shows 99 % recycling of total 1,269,700 tons of C&D waste generated in 2015 (NEA, 2017), there seems to be some ambiguity in estimations. It seems that everything that does not reach official landfill has been considered as recycled waste while based on the case study, most of the C&D waste ends up at the land reclamation sites in Singapore.

This research focuses on identifying design interventions to achieve resources efficiency in the urban built environment primarily focusing on end-of-life building demolitions. It aims to develop a clear understanding of building demolition process and the fate of end-of-life materials in Singapore. This will help in identifying crucial factors affecting the overall end-of-life material circularity. This chapter aims to answer the following research questions:

1. Q-1: What is the status of construction and demolition waste management in Singapore?
2. Q-2: What are the key stakeholders in construction and demolition waste management?
3. Q-3: How significant are the reuse practices for construction and demolition waste?
4. Q-4: What could be the potential opportunities for resources efficiency and reuse?

Though hypothesis can be developed for these research questions based on the literature review, research clarification with open research questions may provide broader insights and perspectives (Blessing and Chakrabarti, 2009).

## 3.3 Methodology

This chapter focusses on the DS-I phase of the Design Research Methodology (DRM) framework to look at the end-of-life buildings management (Blessing and Chakrabarti, 2009). It includes the identification of the existing situation known as Initial Reference Model and of desired situation described as the Impact Model. A comprehensive literature review was followed by semi-structured interviews with major stakeholders including government regulatory bodies like National Environment Agency, Building and Construction Authority, Housing Development Board; and private stakeholders primarily building demolition contractors and waste recyclers. This empirical study was aimed at achieving the better understanding of the existing situation and the crucial factors influencing reuse patterns of building materials. For increased understanding and clarity on the C&D waste management practices, an empirical approach was taken. Based on mutual agreement with a local demolition contractor, a demolition case study was carried out at 371 Beach Road, Singapore. The process of building demolition was observed, and documentations were made for 45 days on-site. Results document the existing practice of demolition and potential opportunities for circularity.

## 3.4 Results and discussion

For the research clarification, literature review and semi-structured interviews helped in creating an initial reference model, highlighting the existing status of material flow in the urban built environment (Fig. 3.1). Currently, significant quantity of virgin materials is consumed in construction activities with little contribution of recycled materials such as metal scrap in steel production. The circularity loop in reference model through material recycling is predominantly closed at a geographically different location due to waste exports and lack of significant recycling facilities. Waste arising from annual demolitions lead to significant built environment outflows with negligible direct contribution towards material inputs.

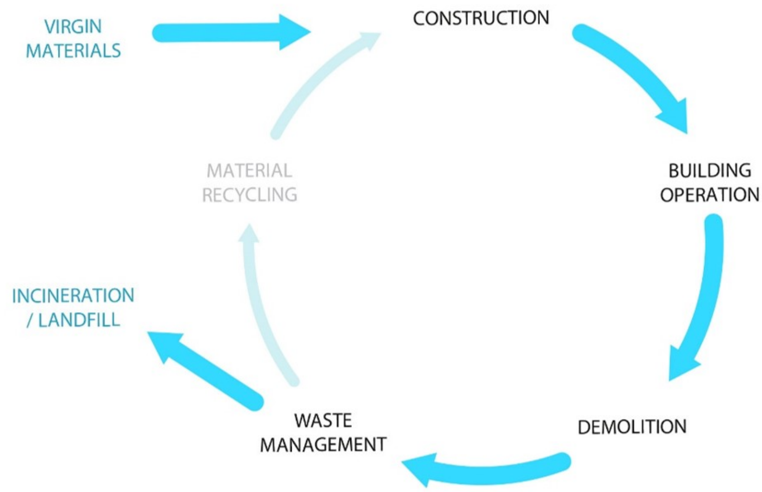



Figure 3.1: Existing building material flows in Singapore

At the demolition phase of buildings, everything goes into waste where existing waste management practices either transfer materials to landfill or incineration plants. The only recycled products are metals such as steel and copper which brings in the material circularity, potentially in another country.

The existence of centralized institutions such as the National Environmental Agency (NEA), which monitors and regulates waste management, the Building and Construction Authority (BCA), which frames guidelines and provides construction and demolition permits, and the Housing and Development Board (HDB), which plans and manages a large proportion of the building stock in Singapore, facilitates the diagnosis of existing C&D waste management (Fig. 3.2). Various stakeholders have different responsibilities in ensuring the handling of C&D waste in Singapore. Building and Construction Authority, being the main regulatory body, frames policies associated with building construction, alterations and end of life demolition. Developers need a permit from BCA to carry out any function related to buildings in Singapore.

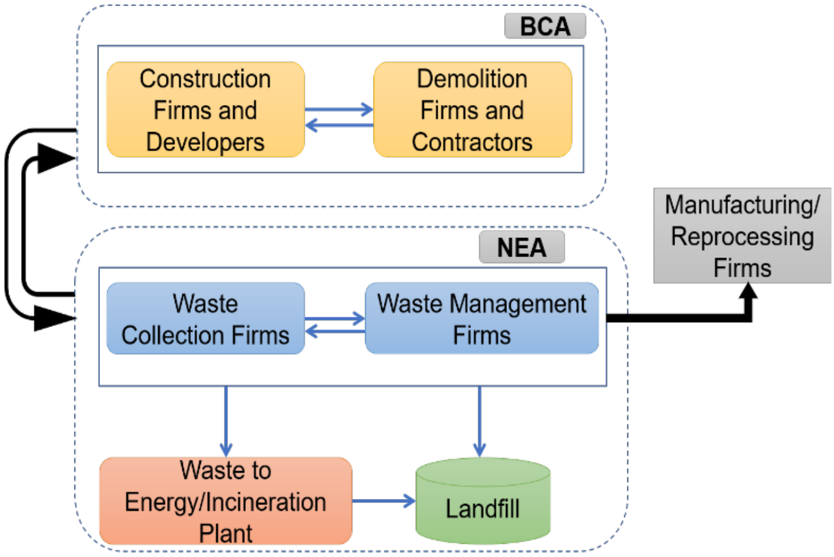



FIGURE 3.2: Stakeholders relationship for C&D waste management in Singapore

The National Environment Agency sets the overall environmental vision for Singapore and, in practice, acts as a facilitator to BCA in controlling the waste materials flow and its minimization at disposal sites namely Semakau Landfill, the only dumping site of Singapore or at Waste-to-Energy/Incineration Plants. NEA controls and maintains both the landfill as well as the waste to energy plants. Demolition firms and contractors play the major role, once any real estate developer plans for a development project. Various demolition firms compete through a tendering process to get the demolition project. Real estate development firms have a major role in deciding the fate of building components. Demolition firms take out the resources and transfer it to waste collection firms or waste recyclers. Based on associated value, recyclers and waste collectors decide the final fate of materials.

In Singapore, on average about one thousand demolition projects are carried out per year which generates more than one million tons of C&D waste per year. Singapore adopts a punitive measure with a waste disposal charge of 77 dollar per ton for incineration and/or landfill. Large portion of waste from these demolition projects comprises crushed concrete which has caused major emphasis on its recycling. Low value components like ceramic tiles, insulation materials etc and components with least recycle possibility end up at landfill. C&D waste, being heavy, becomes a liability for contractors to recycle. Sarimbun recycling park is a dedicated site for C&D waste recycling in Singapore. Recyclers crush concrete waste into recycled concrete aggregates (RCA). The process of concrete recycling is purely market driven. Users of recycled aggregates make it possible to achieve high recycling rate. RCA is majorly used as non-structural concrete for road curbs and temporary constructions. For structural application of RCA, a professional engineer must provide a detailed test report and get it approved from BCA. Most of the waste management companies in Singapore are involved in waste collection and segregation while for recycling most of the materials like paper, metals, plastics, glass are sent abroad. Materials which cannot be exported are handled locally.

Material recovery from demolition waste is purely market driven. Table 3.1 describes current fate and key driving factors for various materials at demolition site. Components like steel, copper, and other metals have high value, so its segregation remains a priority at demolition sites. Timber, glass, flooring etc do not really have high values, there are usually mixed waste collection bins from which waste collectors segregate the useful materials and send the rest of it to waste to energy plants. Timber and wood components usually reach biomass plants for reprocessing into pellets and ply boards. Concrete is sent either to concrete recyclers or to land reclamation sites for dumping. Concrete recyclers produce Recycled Concrete Aggregates, used as alternative to granite in buildings, which is usually 10-20% cheaper than virgin materials.

TABLE 3.1: Fate of materials at end-of-life through demolition

| **S. No.** | **Material** | **Current Fate** | **Driving Factor** |
|---|---|---|---|
| 1 | Demolition Concrete | Recycled Concrete Aggregate and/or Landfill | Punitive Measure (S$77/ton at Landfill) |
| 2 | Doors / Windows (Wood) | Reprocessing and/or Incineration | Time Need/Absent Market |
| 3 | Steel Rebar | Recycled | High Value/Market Driven |
| 4 | Copper | Recycled | High Value/Market Driven |
| 5 | Glass | Disposal | No Recycler/No Market |

The demolition case study helped in detailed analysis of a building demolition process and eventual fate of materials listed in Table 3.1. The process of demolition largely remains a machine intensive effort with manual sorting of low value components (Fig. 3.3). 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 a building forms the basis for 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 landfill gate fee of SGD 77/Ton. Under such circumstances, the construction and demolition waste is downcycled for application at land reclamation sites or as hard core alternative for bottom layers in road construction. 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 within 10% or lower.

Figure 3.3: Observations from demolition case study

Though, Singapore demolition guidelines, SS 557 (2010), provide a systematic approach for building demolition to maximize resources recovery, its implementation remains largely ignored. The major reason is higher labor cost involved in resource recovery, absence of a reuse market and the strict timeline to complete demolition. Lack of market in many ways seems a big hurdle in achieving efficient reuse of building components. Current demolition practices target metal recovery as sole source of value. Due to Singapore's Green Mark requirements (the local building rating tool), some of the portion of concrete waste reaches recycling plants to become recycle concrete aggregates (RCA) which mostly find low value applications in temporary construction. 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 a 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-condition ducts are usually treated as metals and recovered after demolition.

For demolition, hydraulic breakers and excavators are landed on the top floor of the building using a crane. A top down approach is followed to minimize the space requirement for logistics. Lift holes serve as a passage for building debris to be thrown to the ground floor where debris is crushed to remove metal rebar and other metallic components. To extract smaller magnetic metal components, a hydraulic magnet is used in the presence of workers who remove any non-magnetic metal that may remain at the pile of debris(Fig. 3.3). After metal extraction, debris is sent either to landfill or land reclamation sites while good quality concrete from columns and beams is sent for recycling into RCA. Current practice of demolition remains largely focused on site clearance instead of deconstruction and/or material recovery for resources efficiency.

To achieve resource sustainability, an ideal ecosystem would incorporate strategies to extend the life of quality materials which are currently being incinerated and/or dumped at landfill (Devanathan et al., 2010, Telenko et al., 2016, Woo Kang et al., 2013). This provides a major opportunity for design intervention to rethink and transform the existing urban material consumption patterns. Though there are possibilities of recycling, reuse at component level would save processing energy, labor and time, thus becoming a preferred pathway (Arlitt et al., 2017, Woo Kang et al., 2013). Based on these assessments, an impact model has been developed which highlights the desired material flow regime for urban sustainability (Fig. 3.4).

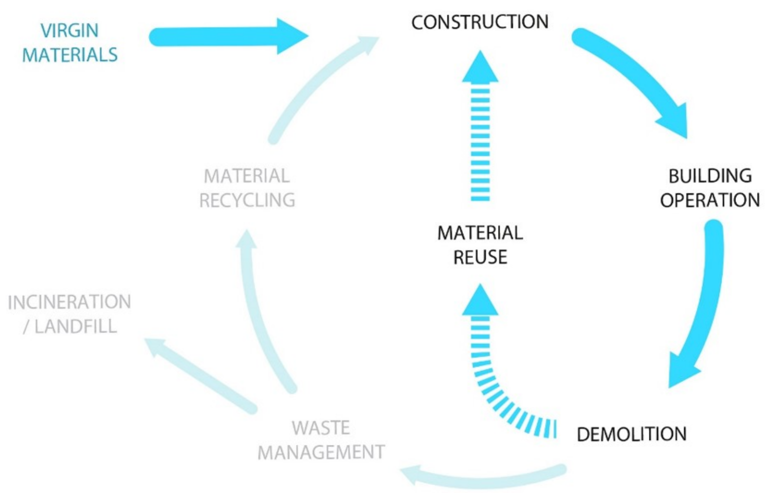



Figure 3.4: Desired material flow for urban sustainability

The Impact Model highlights a reduced input of virgin materials and supplement of building components through material reuse from the demolition phase of existing building stock. Design intervention at the end-of-life of buildings could help in achieving sustainability in this sector. To enable this design intervention, buildings need to be first assessed for availability of quality building components which could be reused for the new construction in cities and/or regional peri-urban-rural region. Such a strategy would eliminate significant amount of materials going to landfill. Existing demolition practices may provide an opportunity to salvage building components for high level applications in construction. An ideal consumption of these components could be in developing low-cost housing. Such opportunities remains crucial for achieving growth towards providing decent living standards for marginalized society of the developing world (Huang et al., 2018). At a large scale, building components recovered from demolitions in developed cities can greatly support the efforts for achieving adequate urban housing in developing countries, however the emissions associated with transport must be assessed for sustainability.

Lack of noticeable reuse in Singapore makes it an appropriate urban system to understand various issues associated with reuse of building components. Singapore's ambitious sustainability goals, pro-climatic stand and need for self-reliance in construction materials sums up into an ideal case for promotion and acceptance of reuse.

Descriptive study-I helped in identifying a number of challenges associated with such an approach of reuse to realize the impact model. Based on the demolition case study and comprehensive DS-I, many of the challenges have been identified.

1. Absence of interest in reclaiming building components is driven by lack of market where salvaged building components could be sold.

2. The scale of building components stock and annual availability remains unclear at a city level. There is little information on the quantity and type of components that could be recovered from a city each year. Despite good records on the number of buildings and amount of floor space that is demolished, current practice does not link that to any information about what components were in a demolished building or that are in a building to be demolished.

3. Even if the market can be created, there are strict timelines of demolition which limit the opportunity to carefully assess, record and salvage building components before demolition.

4. Lack of information on sizes, availability and quality of salvaged components to a potential buyer is another major concern. With uncertainty on scale and timing of availability, construction projects with salvaged building components may not be completed in a time bound manner.

5. Incorporation of uncertainty into the design process for new construction must be minimized. Often materials are purchased based on designs in building construction practices, but reuse will require a design paradigm which is driven by available materials. In such a case, design guidelines on efficiently incorporating reused components into new construction remain absent.

6. For acceptance of material reuse in organized sector real estate development, quality certification of these components remains a legal and often building code associated requirement.

These challenges are similarly identified in varied context in other studies (Gorgolewski, 2008, Kozminska, 2019, Rios et al., 2015). Challenges associated with creating a reuse market for building components are driven by lifestyle, building regulations and consumer acceptance for reuse. The decision to demolish a building in an urban setting is influenced by several of the obsolescence reasons which may include a financial, regulatory or functional basis. However, there remains an opportunity to mine functional building components which could then be used for an extended life in another building and/or construction setting. Considering the housing sector alone, adequate and affordable housing is at the centre of Sustainable Development Goal 11 (Sustainable cities and communities), with direct or indirect contributions to several other. Lack of adequate housing has far reaching consequences, yet it remains a major challenge for the global community (Brown, 2003). In south-east Asia alone, there remains a shortage of 38 million housing units to match the UN standard for decent living. A McKinsey report estimates about 330 million urban families living in inadequate conditions and cited the cost of construction materials alone as one of the prominent barriers with construction cost alone to be as high as 9 trillion to 11 trillion USD (MGI, 2014). In such a scenario, cities offer a surplus of used, functional building components, which can be instrumental to low-cost housing solutions and/or supply for urban construction. This approach, however, requires several steps in order to be implemented at a single building to a city scale (Fig. 3.5).

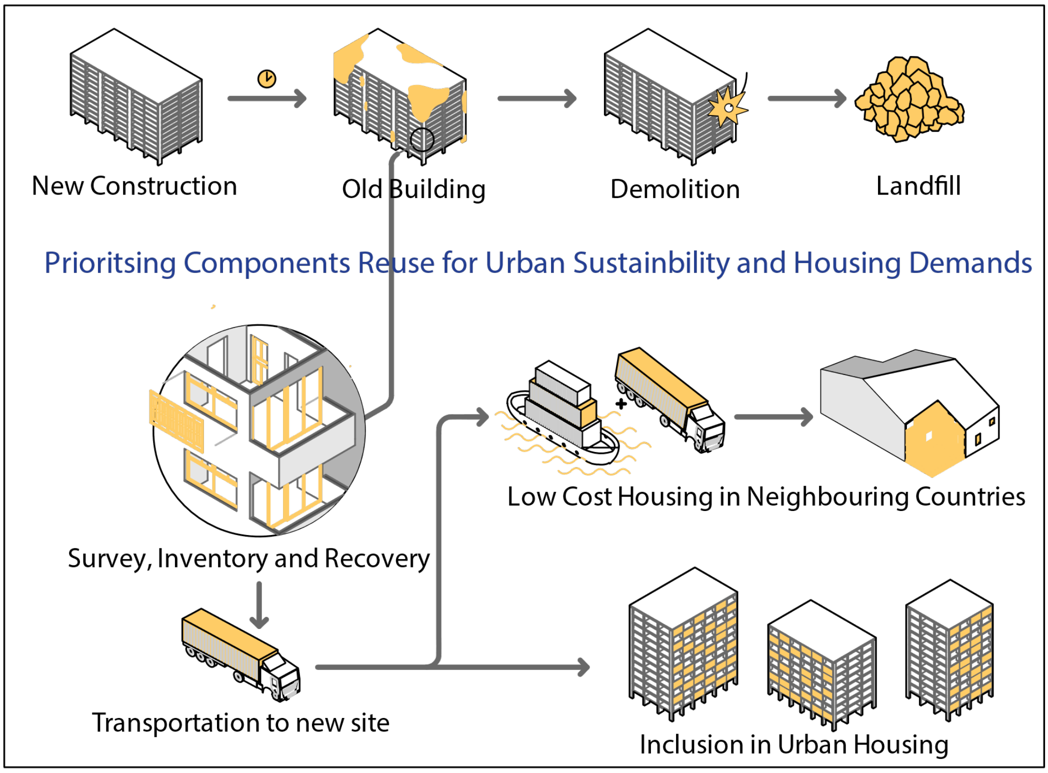



FIGURE 3.5: Building components reuse framework for linking demolitions to design

To implement this strategy, several of these identified challenges require design interventions. Looking at the building components salvage, there is no incentive for demolition companies to deconstruct instead of demolition. The green building certification process do not distinguish between recycled and reuse, nor is any incentive for enhanced reuse. On the contrary, certification of building components, in certain tightly regulated building code regions, may become a bigger bottleneck. With the advent of circular economy, recycled products have started to get regulatory validation, however, reuse specific certification remains a major requirement. If building components are not replacing the structural components, within a national boundary, reuse in construction primarily requires stakeholder's initiative. A bigger challenge, however, remains on transboundary movement of salvaged, functional building components. The distinction of second-life building components from both waste and new components, puts this commodity in a grey zone of import-export regulation and taxes. As the push for circular economy continues, there is a need for global consensus on reusable second-life components to be distinguishable from waste so that these can contribute to a consumer-base in need. This primarily broadens the debate within circular economy on closing the loop within national boundaries or extending to an international consumption point.

Consumer behavior is at the center of reuse and circularity. Though developing countries and often marginalized subsection readily accept reuse driven material systems, developed economies with high-end life style tend to distance themselves from old until its antique (Cooper and Gutowski, 2017, Huang et al., 2018, Huuhka et al., 2015, Jin et al., 2017, Ng and Chau, 2015). However, the trend of sharing economy and service-based business models have highlighted a shift in mindset and increasing acceptance. Empirical research in Singapore has highlighted the lack of building components salvage and absence of building components reuse due to lack of market. Acceptance of old building components in a newly constructed, high cost apartment remains a skeptical proposition within real estate developer's perspective. Though sustainability has taken a major leap in terms of green product acceptance within commodities, it will still need a greater motivation for reuse acceptance within the formal, high cost urban construction. In contrast, marginalized families living in poor housing conditions, prefer a better quality component even if its old. The low-cost housing sector however remains financially dependent on public funds or non-profit organizations which require close stakeholder participation and institutional support. An unconventional sustainability approach necessitates an innovative business model adoption (Geissdoerfer et al., 2018), which often requires consumer, market and supply factors to be clearly taken into account (Bocken et al., 2014, 2016). It is important to highlight that several possibilities exist for an ideal financial strategy for reuse driven construction which should be specific to target consumer and geographical preferences. The focus on low-cost housing sector for reuse would benefit through public-private partnership and/or social entrepreneurial ventures in which local governments can play catalytic role. Bases on field work and overall understanding developed so far in this thesis, following design interventions may help create a building component reuse ecosystem in cities:

1. Material and building components stock and flow estimate should be developed to assess the scale of resources availability in a city.

2. Challenges associated with demolition timelines and urban mining of building components should be looked through experimental exercises to ascertain local parameters such as cost, time and recovery scales.

3. Building components inventory needs to be developed at a project and city level. Further, advanced technologies for building scans such as 3D-point cloud scanning could be used for surveying which creates a 3D model with high granular data on building components. Recovery of these components could follow soon afterwards.

4. This can be further scaled to a digital reuse platform. At such a digital reuse platform, various salvaged components can be sold or bought based on clear information on their quality, age, size specifications, quantity and location. This support tool will help in enabling demand for old building components as well as initiation of reuse acceptance into current building materials flow. Materials will be diverted from demolition phase of buildings to the construction phase and a material bank would support the temporary storage for consistent supply.

5. To help designers and architects with uncertainties arising due to different size and shape of reclaimed components, design guidelines can be prepared based on full scale prototype construction with reused components. Such design guidelines should include the opportunity of aesthetic innovation in incorporating material reuse and flexibility of design layouts to accommodate slight variability. Design guidelines will further include material selection approaches to facilitate suitable components prioritization.

6. The challenge of quality assurance can be solved through certification guidelines on salvaged material quality which has previously been utilized in cases of natural disaster re-building codes. Though the design interventions and support tools to tackle market associated practical barriers have been addressed above, it is also crucial to scientifically assess the environmental and economic basis of such a practice. A detailed environmental and economic scrutiny will provide strong academic foundation for such a practice to be accepted and promoted by all stakeholders and policymakers.

## 3.5 Summary and outlook

Urban systems have rarely been assessed through the design research methods though these systems provide an excellent opportunity to identify challenges which could be solved through design interventions. This study applies design research methodology framework to an urban resources efficiency problem and identified several design intervention opportunities to achieve urban sustainability. It first develops an initial reference model which highlight huge resource wastage which end up at landfills or incineration plants. Through literature review, case study and stakeholder interviews, it provides a detailed current state-of-art and roadmap to achieve the desired impact model. It provides a comprehensive research clarification as well as descriptive study-I looking at the key factors that play an important role in realizing material reuse. To achieve urban resources efficiency, there is a need of strategic design interventions in the current building demolition practices as well as reuse market. Research highlighted that the reuse of end-of-life building components will not only lead to embedded energy savings, resources efficiency and environmental sustainability but could also provide resources for low-cost housing to support urban poor in growing cities.

This chapter highlighted the demolition waste ecosystem, stakeholders, process and their interaction in a city. It further suggests linking building demolitions with construction for realizing material circularity. Looking at huge housing shortage across the globe among urban-poor, material reuse strategy may have far reaching impacts on low-cost affordable housing. With increasing pace of premature building obsolescence in cities, reclaimed materials for reuse could shape an alternative supply chain for cheap housing construction which will help urban policy makers to reduce waste and create homes. Sector-specific targeted design interventions require system-wide multi-stakeholder efforts. Application of these design interventions could play a significant and decisive role in achieving sustainable built environment.

## Chapter 4

# Residential building material stocks and component-level circularity: The case of Singapore[1]

## 4.1 Synopsis

The residential built environment plays a crucial role in supporting many human activities. In urban areas however, high-rise residential buildings require significant investment of material resources, which are stacked for a long time over the building's lifetime. Assessing the Material Stock (MS) of buildings has been the focus of several studies for insights into in-use materials and their potential availability as secondary resources. The study of material circularity, or the potential to reuse materials emerging from end-of-life buildings, has so far been mostly limited to metals. This chapter argues that material stock analysis at individual material or material categories e.g. mineral, or metals, need to be complemented with building component stock estimations to enhance the potential for secondary resource recovery. Based on a bottom-up stock analysis approach, this chapter estimates both the material and component stock of public housing developments in the city-state of Singapore and associated annual in- and out-flows. Results show that public housing in this city, which accommodates over 80 percent of its residents, accounts for 125.7 million tons of non-metallic minerals, 6.52 million tons of steel, 6.45 million windows, 8.61 million doors, 1.97 million toilet accessories, 15.33 million lighting fixtures, 0.99 million kitchen accessories (such as cookstove, kitchen cabinets) and 52.54 million $m^2$ of tiles. The average stock of materials for these residential buildings is estimated at 27.4 tons of non-metallic minerals per capita and 1.4 tons of steel per capita. The average annual inflow of materials has been estimated to be 1.94 million tons for concrete and 0.1 million tons of steel, with a considerably low outflow of 0.31 million tons concrete and 0.02 million tons of steel, implying growth in these material stocks. This chapter provides a methodological approach to quantify building material and component stock and flows, which can be used by policy makers, urban planners and designers to consider responsible resource consumption. In particular, material and component stock estimations like that reported in this study contribute towards component-level circularity in the built environment.

[1] Published as Mohit Arora, Felix Raspall, Lynette Cheah, Arlindo Silva (2019) Residential building material stocks and component-level circularity: The case of Singapore, Journal of Cleaner Production, vol 216, pp 239-248

## 4.2 Introduction

Fast paced urbanisation has resulted in significant material accumulation in cities. The material stock (MS) of built environments in various forms like residential, commercial, industrial buildings, public infrastructure and transport networks has been shown to be the biggest resource sink (Huang et al., 2017, Lin et al., 2017, Ng and Chau, 2015). From environmental and resources point of view, this accumulation remains extremely important constituent of socio-economic metabolism (Kleemann et al., 2017a, Krausmann et al., 2017a,b). In recent past, industrial ecology has emphasized upon estimations of material stocks and flows at different geographical scales in hope of enabling secondary resources utilisation (Fishman et al., 2014, Krausmann et al., 2017a). Tanikawa et al. (2015) emphasised upon the calculation of country wide material stocks to fully comprehend the socio-economic metabolism – 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,b, 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., 2017c) and Asia (Cao et al., 2017a, Fernández, 2007b, Fishman et al., 2014, Hu et al., 2010, Ng and Chau, 2015, Tanikawa and Hashimoto, 2009, Tanikawa et al., 2015, Vilaysouk et al., 2017, Yoshida et al., 2017). In addition, several 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-use stocks and possible outflows (B. Müller, 2006, Cao et al., 2017a,b, 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/or temporal variations. Common material types examined include metals and non-metallic minerals, cement, wood, asphalt, etc. However, there is a lack of focus on building components stock assessment which might aid resource circularity in built environment.

Though MS studies have various motivations, most studies cite secondary resource use as one of the reasons or benefit of such an exercise. From studies focusing on the built environment material stock, however, there is an apparent gap on secondary resources exploitation and/or acceptance into newer construction practice. The building sector is known to be responsible for significant resource consumption and greenhouse gas emissions, emphasizing the need of policy efforts to be directed towards minimising the overall resource burden of the built environment (UNEP, 2018a). Material stock studies for the building sector often apply material intensity factors to arrive at total material estimates (Allwood et al., 2010, Augiseau and Barles, 2017, Krausmann et al., 2017a). These estimates provide an idea on how much quantity of each elemental material each study area has. Based on the argument that such estimates will help in creating ways of secondary resources utilisation, a majorly overlooked aspect has been the shape and/or form in which estimated materials would ideally be accepted into the material loop with upcycling prospects. When accounting for MS, studies often look for elementary materials and neglect the nature and/or physical state of these materials in the built environment. Several of MS studies have recommended actions on the efficient utilisation of material stock and outflows for closing the material loop or the circular economy (Augiseau and Barles, 2017, Müller et al., 2014, Ortlepp et al., 2016, Schiller et al., 2017, Vilaysouk et al., 2017). Material stock studies have often overlooked how to make the secondary applications of these in-use or end-of-life stocks more efficient. Therefore, the impact of MS studies has not been realised to measurably contribute in secondary resources acceptance for cleaner production (Augiseau and Barles, 2017, Kalcher et al., 2017, Krausmann et al., 2017b, Ortlepp et al., 2016). Krausmann et al., (2017) estimated that by 2030, 35% of the material stock in use in 2010 will be discarded, yielding 274 Gt of end-of-life outflows, about the same amount of outflows in the previous 110 years combined. With such a massive outflow coupled with over-exploitation of natural resources and threat of global warming, the role of secondary resources in responsible consumption has become critical (Cao et al., 2017b, Gursel and Ostertag, 2016, Kalcher et al., 2017, Krausmann et al., 2017b, Lin et al., 2017, Yoshida et al., 2017).

For the building sector, most of the material stock outflows would emerge either at the time of retrofitting or at the end-of-life of buildings (Huang et al., 2018, Kleemann et al., 2017b). Since materials involved in buildings, other than concrete and steel, are often presented in complex assemblies of a material mixture, their efficient recovery into the material loop is more difficult (Fernández, 2007b, Göswein et al., 2018b). Often materials cannot be isolated as they are integrated within components or are part of composites for example, windows typically consist of an aluminium extension, rubber gasket, glass sheet and an iron handle. To tackle this issue, there is a need for material stock estimation methods to consider building components circularity in addition to materials circularity. Fernández (2007a) highlighted that buildings of 21st century have adopted newer and complex composite materials in various layers- structural to exterior enclosures and interiors, such as smart materials, superior coatings, advanced insulations, fibre reinforced concrete to name a few. Fernández further assessed that incorporation of novel complex materials into construction industry will expand with acceptance among construction engineers. With increased future inflow of complex materials into built environment, it remains ideal that the secondary applications of such materials be made at the component level without energy and labour-intensive processing. Rose and Stegemann (2018) discussed in detail the need for construction industry to move beyond traditional waste management approaches to component management strategies to achieve end-of-life upcycling and reuse in building sector. Authors emphasized upon lack of information on the scale and failure to identify building components for functionality as one of the major barriers in realizing components upcycling. From embodied carbon perspective, Göswein et al. (2018b) highlighted the role of structural components choices within existing residential building stocks of Johannesburg, a rapidly growing city from developing countries perspective. Looking at the importance of components, Göswein et al. (2018b) emphasised on interventions on existing stocks for secondary resources utilization. Stephan and Athanassiadis (2018) provided a comprehensive analysis of non-structural material replacement flows during the building service life for 13075 buildings of Melbourne city. Stephan and Athanassiadis (2018) highlighted the need for more qualitative information on existing material stocks and exiting flows to understand secondary resources availability in terms of what, where and when, so that prospects of reuse could be improved. Under informal settings of developing world, secondary resources utilisations have been significantly higher than the organised formal markets of developed world (Huuhka et al., 2015). This practice of component level reuse contributes to material input through informal markets (Raspall and Arora, 2016). The concept of Design for Disassembly and Modular Design in construction remains primarily motivated by ease of taking components apart and efficiency of component level circularity after first end-of-life (Arora et al., 2018, Fernandez, 2006, Salama, 2017). This strategy to reuse components without breaking or separating into material form has several benefits in terms of stronger artefact supply chain through secondary streams, reduced labour for time consuming disassembly, possibility of machine-enabled separation and/or processing through advent of automation, and energy savings. Though an efficient secondary resources utilization at component level remains feasible in formal markets, it will require certain additional enabling efforts in terms of flexible design strategies and operational modifications. Ideally, an information platform (potentially virtual) and storage space with descriptive component information, where designers of new buildings can source for materials, will lead to smooth execution (Arora et al., 2018). Hence, the current study includes component stock and outflows estimations along with the material stock calculations for residential built environment. To account for these developments in material trends of built environment, it is of importance that the MS estimations for the built environments to be made based on both at material level for non-complex materials such as concrete and steel, and at component level for exterior enclosures and interior construction. There have been strong recommendations for accepting the materials into the circular economy at the component levels in order to minimize the efforts involved in processing, cost, energy as well as environmental considerations for prolonged secondary life (Addis, 2006, Allwood et al., 2010). To provide realistic stock estimates which can directly be utilized by either policy makers or by designers and/or planners for efficient inclusion into resources input stream, better representation of results would be to include the materials for steel, concrete and the components for assembled materials.

In this chapter, we argue that it is important to additionally consider the potential for building component reuse, and not just material reuse/recycling. Hence the primary objective of this is to propose a bottom-up method of estimating the availability of used building components, which may help in estimating supply to the secondary market. A secondary objective is to apply the proposed bottom-up methodology to estimate the material as well as component stock and flows in the residential built environment of a city. The methodological approach developed in this study has been applied for the case of Singapore. For an import-dependent country like Singapore, material stock estimations and potential outflows remains crucial from matching demands and achieving resource efficiency. While the existing building stock can become a significant source of secondary materials, accurate estimations of material and building components stock remain yet unavailable. Gursel and Ostertag (2016) highlighted the need for minimising export and accepting locally available resources for buildings in Singapore. Augiseau and Barles (2017) provided an example of Paris region to argue that several factors need to be addressed in densely populated urban areas for meaningfully utilizing industrial ecology approach. Exact estimation remains key to maximising secondary resources utilization potential (B. Müller, 2006, Stephan and Athanassiadis, 2018).

## 4.3 Methodology

In general, material stock accounting has typically used four types of methods which are bottom-up material accounting, top-down material accounting, demand driven modelling and satellite driven remote sensing methods (Tanikawa et al., 2015). Based on a short review of MS studies in the past decade, Tanikawa et al. (2015) highlighted how most studies tend to be top-down material accounting exercises because of multiple factors – primarily due to lack of granular data and extensive efforts needed for bottom-up study, emphasizing the need of efforts for country-specific studies on the basis of bottom-up approach. This research primarily applies a bottom-up approach to account for material stock accounting in buildings based on a general model of stocks and flows depicted in Fig. 4.1A.

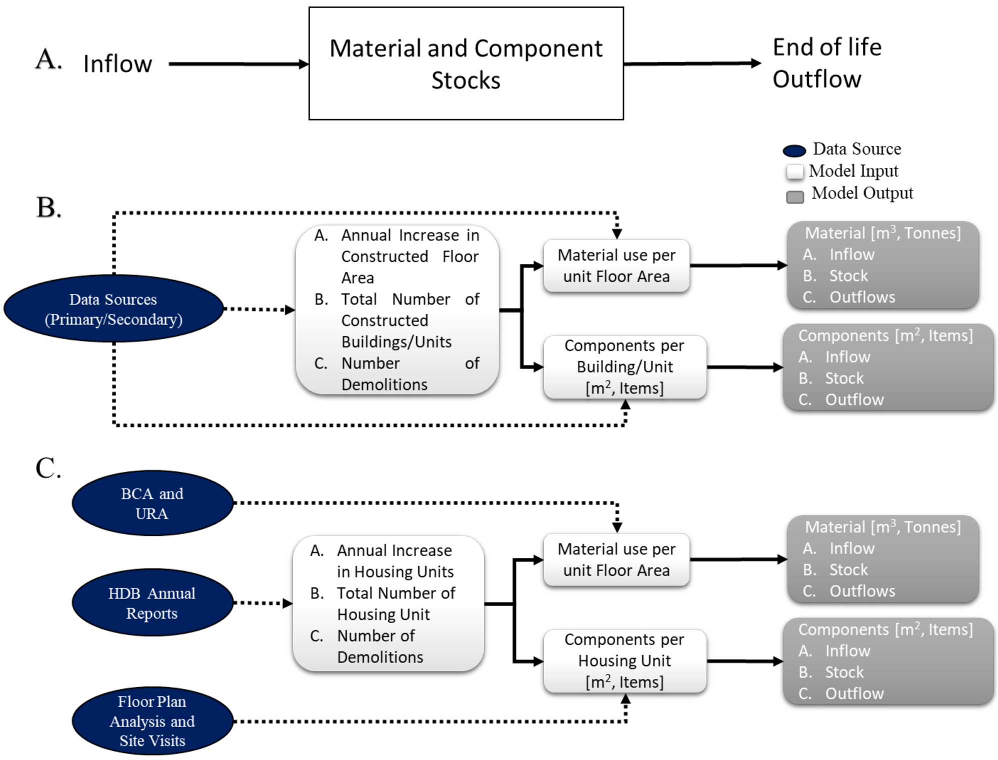



FIGURE 4.1: Stock and flows assessment framework: A. General model of building material stock and flows where inflow is denoted as addition of materials through new construction activities while end-of-life (EoL) outflows are result of demolitions; B. Generic model

Based on the general model (Fig. 4.1B), the inflows, stocks and outflows were estimated based on the annually constructed floor area, total number of buildings, apartments or total floor area and demolition data (see Fig. 4.1C). Using this model, this study quantifies existing public housing stock, annual material and building components inflows and material outflows associated with building demolitions. The scope of this study is limited to the estimation of concrete and steel in building materials while for building components, it includes doors, windows, floor tiles, toilet accessories (wash basin, toilet bowl), lighting fixtures (LED and CFL bulbs) and kitchen accessories (cookstove, hob and cabinet). These components remain the major proportion of building service life materials and interiors excluding the structural materials. The universal need and acceptance of these components in newer construction remains a major motivation for their estimations. In addition, there is potential for these components to be salvaged and efficiently reused which may help achieve resources circularity. Though some of the components have limited lifetime, usually most of them do not complete their functional lifetimes and so could serve as material input for next application. Using available data from regulatory bodies, we account for the existing public residential building stock and yearly building demolition to estimate an inventory of material and component outflows.

## 4.4 Case study of public residential building stock in Singapore

In this study, we analyse Singapore, a dense city-state in Southeast Asia, for its residential building material stock and potential annual contribution to secondary resources. With a land area of 716 $km^2$, Singapore supports a population of 5.6 million people. Being a small island nation, Singapore is a major importer of building materials (Chertow et al., 2011, Gursel and Ostertag, 2016, Schulz, 2007). Singapore has one of the highest cement consumptions per capita with annual consumption around 6 million metric tonnes. The construction sector's contribution to GDP has doubled in the last decade (Gursel and Ostertag, 2016). 380 $km^2$ hectares out of 710 $km^2$ is built-up with housing, industry, utilities and transport infrastructure (Chew, 2010, Yang, 2008). Through its Housing Development Board, a government agency for ensuring housing for Singaporeans, Singapore has achieved near-complete access to adequate housing. 82% of the total Singapore population lives in public housing maintained by Housing Development Board (HDB). Today, there are about 1.2 million housing units, of which 0.9 million are HDB flats which is about 75% of the total residential dwellings, while the rest are private apartments and landed property (Fig. 4.2A). Additionally, public housing follows a similar construction practice and building typology, all these reasons led to the focus of this study on public housing.

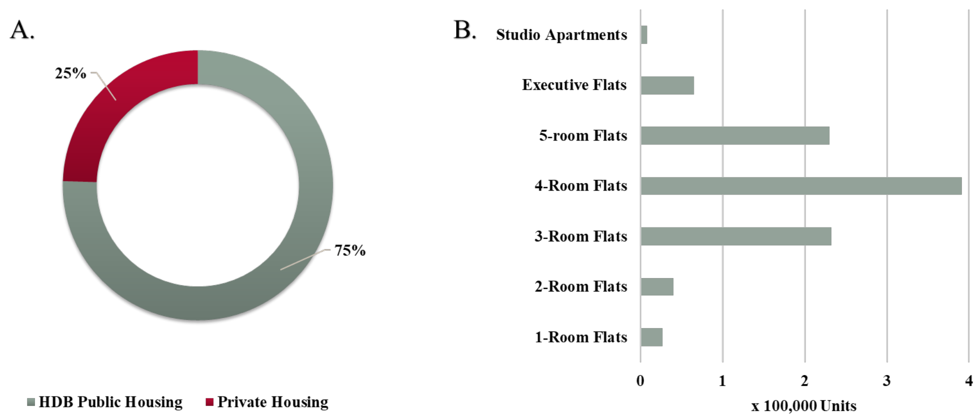



FIGURE 4.2: Residential building dynamics of Singapore: A. Share of public and private housing; B. Dwelling type distribution for public housing (HDB, 2018)

Based on the general methodological approach as described in section 4.3, a case-specific methodological framework has been developed (Fig. 4.1C). Total building stock is calculated from the number of total housing units according to annual housing reports (Brown, 2003, HDB, 2018). Housing unit drawings and layouts were used to calculate the building components. For individual materials, the data was assimilated from the

Building and Construction Authority (BCA), Singapore. 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. CUI is defined in Eq. 4.1 as volume of concrete in cubic metres to cast a square metre of constructed floor area.

$$\text{Concrete Usage Index} = \frac{\text{Concrete Volume}(m^2)}{\text{Constructed Floor Area}(m^2)} \tag{4.1}$$

Calculation of CUI does not include concrete used for external works and sub-structural works such as basements and foundations. The general model applied for material calculation is described in Eq. 4.2.

$$\text{Stock} = \text{Inventory of Material } \times \text{Material Intensity Factor} \tag{4.2}$$

Where Stock represents the total volume or weight of an individual material, Inventory of Material is defined by the number of total unit while the 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. 4.2. For estimation of concrete, CUI provides for the required Material Intensity Factor for stocks.

The Concrete Usage Index was averaged over 5 construction projects as listed in Table 4.1. These five projects have been selected to represent the variety of typologies in which the CUI of HDB constructions ranges from 0.42 - 0.47, covering gross floor area construction from 2,000 $m^2$ to 224,500 $m^2$. To accommodate older constructions with less efficient concrete application and sub-structural works, an average CUI value of 0.5 has been used in this study. Total Floor Area was calculated for residential buildings and was used to estimate the amount of concrete used.

Table 4.1: Concrete Usage Index of recent construction projects (BCA, 2012)

| **Project Name** | **Building description** | **Gross Floor Area ($m^2$)** | **CUI (m)** |
|---|---|---|---|
| Education Resource Centre, National University of Singapore | 4-storey university building | 21910 | 0.47 |
| Tiong Seng Prefab Hub | 5-storey industrial building | 19606 | 0.46 |
| Woh Hup Building | 4-storey commercial building | 2000 | 0.46 |
| Punggol Waterfront Terrace | 19-storey residential building, 1074 units of dwelling apartments | 224500 | 0.46 |
| Hundred Trees Condominium | Six blocks of 12-storey and two blocks of 11-storey residential buildings, 396 units of dwelling apartments | 43751 | 0.42 |

For the estimation of steel, national concrete and steel consumption data was obtained from Economic Surveys of Singapore developed by the Ministry of Trade and Industry (ESS, 2018). Table 4.2 provides the amount of concrete and steel use. 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.

Table 4.2: Concrete to Steel Consumption Rate

| **Year** | **Concrete (million $m^3$)** | **Steel (million Tonnes)** | **Average Rate (Steel/Concrete)** |
|---|---|---|---|
| 2014 | 15 | 1.8 | 0.12 |
| 2015 | 16 | 2 | 0.125 |
| 2016 | 14 | 1.7 | 0.121 |
| | | **Average** | 0.122 |

To account for various building components, dwelling construction plan and layouts were studied to list each component in a specific dwelling type. With the annual demolition data retrieved from HDB annual reports, total dwellings demolished were calculated. Based on demolitions data, overall outflow of materials and building components was estimated for the years 2011 to 2016.

## 4.5 Results and discussion

The results in this research are based on residential buildings of Singapore for which the data was obtained from regulatory bodies and available building layouts. A spreadsheet-based model was prepared with all the parameters for estimating the stock. Total concrete stock was estimated to be 125.7 million tons for public residential buildings in Singapore (Fig. 4.3B). Based on the average steel to concrete consumption ratio, the steel stock of residential buildings was estimated to be 6.52 million tons. The total stock for concrete has increased by 10.2% in the past 6 years while the steel stock has increased by 10.3%, both with a combined annual growth rate of 1.64%. This is consistent with the residential dwelling number growth in recent years as shown in Fig. 4.3A. Annual material inflows for concrete and steel were averaged for past 6 years. From 2010 to 2016, average annual inflow of concrete was 1.94 million tons while the steel inflow into residential building stock was 0.1 million tons (Fig. 4.5).

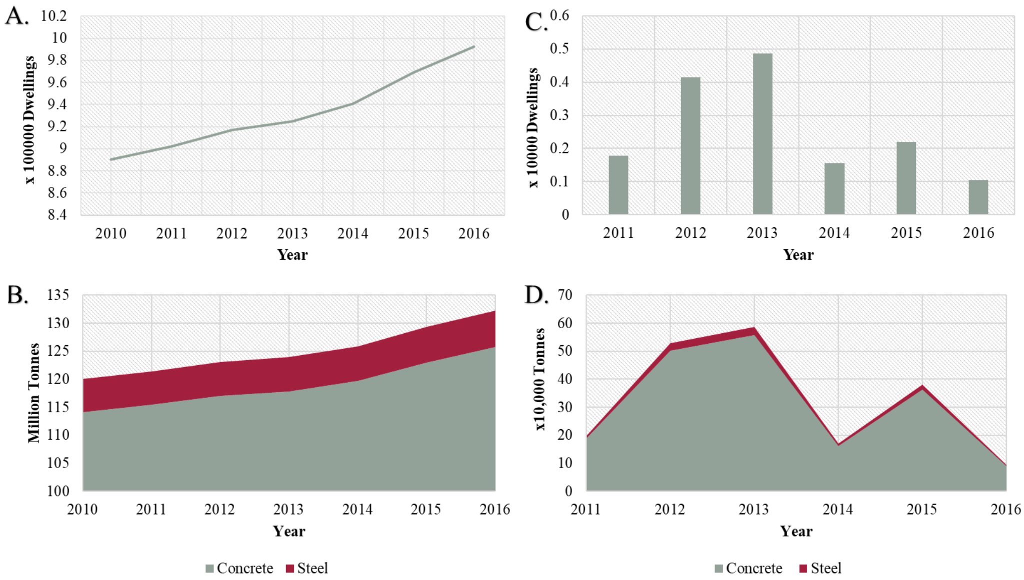



FIGURE 4.3: Building material stock and flows: A. Growth of public housing units in recent years (HDB, 2018); B. Estimated public housing material stock accumulation, 2010 to 2016 ; C. Annual residential dwelling unit demolitions in Singapore (HDB, 2018); D. Estimated annual outflows of concrete and steel from public residential buildings

Based on the housing unit layouts, 7 different apartment/dwelling types were analyzed for number of building components within. Table 4.3 summarizes building components in a typical model of each dwelling type in public housing.

Based on the estimations on total number of units, total stock of building components includes 6.45 million windows, 8.61 million doors, 1.97 million toilet sets, 15.33 million lighting fixtures, 0.99 million kitchen accessories and 52.54 million $m^2$ of floor tiles (Fig. 4.4A). In comparison the annual average inflow of building components was estimated to be 0.1 million window sets, 0.14 million doors, 0.03 million toilet sets, 0.25 million lighting fixtures, 0.02 million kitchen accessories and 0.86 million $m^2$ floor tiles (Fig 4.6). To estimate total outflows, annual demolitions data was used from annual HDB reports (Brown, 2003, HDB, 2018). From year 2011 to 2016, a total of 15,549 dwelling units were demolished with annual average of 2,754 units over 5 years (Fig. 4.3C).

TABLE 4.3: Assumed building components in each dwelling type

| **Type** | **Units** | **Floor Area** | **Window Sets** | **Doors** | **Toilet Sets** | **Lighting Fixtures** | **Kitchen Accessories** |
|---|---|---|---|---|---|---|---|
| 1-Room Flats | 26840 | 33 | 2 | 2 | 1 | 7 | 1 |
| 2-Room Flats | 39894 | 45 | 3 | 3 | 1 | 11 | 1 |
| 3-Room Flats | 232144 | 65 | 5 | 4 | 2 | 13 | 1 |
| 4-Room Flats | 390901 | 90 | 7 | 6 | 2 | 16 | 1 |
| 5-room Flats | 229829 | 110 | 9 | 7 | 2 | 18 | 1 |
| Executive Flats | 65082 | 130 | 9 | 7 | 2 | 19 | 1 |
| Studio Apartments | 7782 | 37 | 2 | 2 | 1 | 8 | 1 |

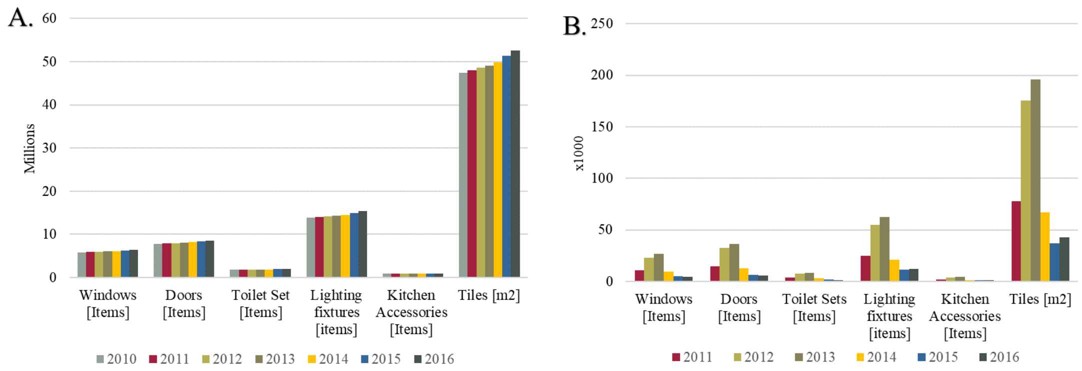



FIGURE 4.4: Building components stock and flows: A. Total stock of building components in Singapore public residential buildings; B. Annual outflows of building components from Singapore public residential buildings

Several MS studies assume a streamline behaviour of building demolitions and assign an assumption of annual rate based on expected lifetime in years (Miatto et al., 2017b). While such an approach could be applied in cases where data availability is a concern, in actual scenario, the decision for building demolitions is affected by several obsolescence reasons (Langston et al., 2008). These obsolescence drivers could be mutually dependent or exclusive, depending on strong social-economical-urban planning inference associated with life style behaviours and real estate market conditions. In real scenario over a brief period, it is apparent that the demolitions would have an independent trend from adjacent past year (Fig. 4.3C). Because of the apparently non-linear trend in demolitions that occurred in Singapore, the outflows from stock followed a non-linear trajectory (Fig. 4.3D). The outflows of building components highlight that over the past 5 years, the highest outflows were in the year of 2013 with 196000 $m^2$ of floor tiles, 26662 windows, 36212 doors, 8620 toilets set, 62735 light fixtures and 4501 kitchen accessories (Fig. 4.4B).

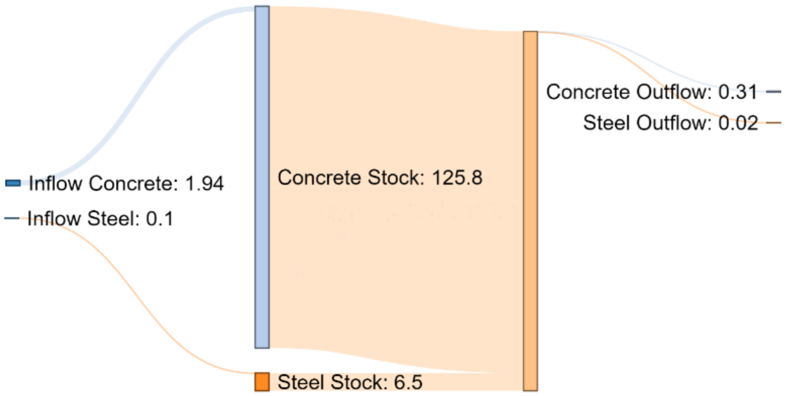



FIGURE 4.5: Sankey diagram of concrete and steel flows for Singapore public residential buildings in year 2016 (quantities in million tonnes per year)

Based on the general framework of stocks and flow estimations, the results have been summarised with the help of Sankey diagram shown in Figure 4.5 for materials inflow, stock and outflows while for components inflows, stock and outflows in Figure 4.6. It is visible that the cumulative residential building stock remains the largest resource sink in proportion to material as well as components inflows- outflows. Inflows to the existing stock are significantly larger than the outflows which suggest that the stocks in Singapore will continue to rise over the coming years until most the residential buildings reach either their functional obsolescence or premature obsolescence due to additional factors.

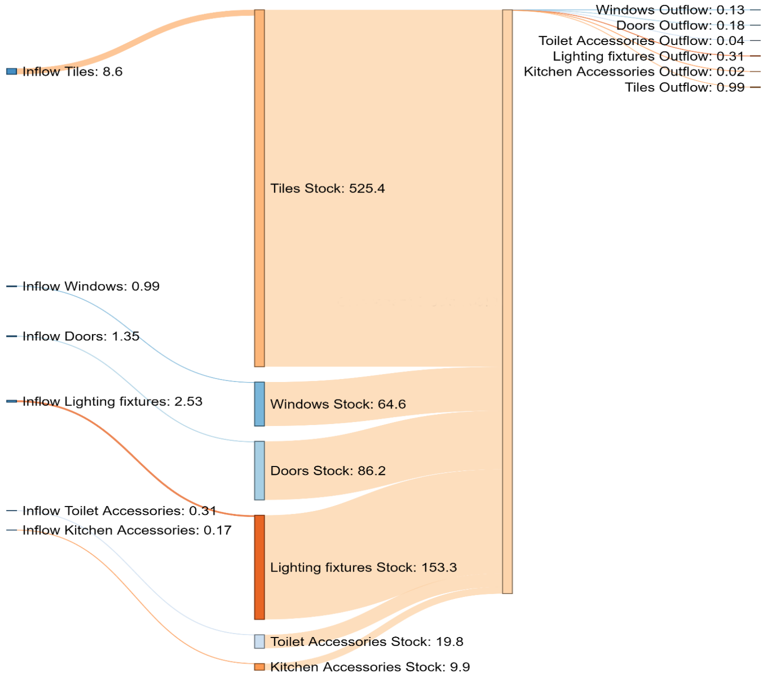



FIGURE 4.6: Sankey diagram of component flows for Singapore public residential buildings in year 2016 (tiles are in x100,000 $m^2$ while other components are in x100,000 Items)

To put the MS estimations in perspective, one can compare the results of Singapore with recent MS studies (Table 4.4). In the current study, the residential building stock of Singapore has been estimated to be 27.4 tons per capita for mineral components, specifically concrete. The average steel stock in residential buildings has been estimated at 1.4 tons per capita. These estimations are based on an assumption that 82% of the total Singapore population lives in public housing. 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 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 account of material stock. Based on World Bank (World, 2017), 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. Kleemann et al. (2017a) calculated building stock of Vienna using GIS and arrived at the conclusion that average per capita building stock is 210 tons per capita which is composed of 96% mineral components. Their study further estimated an average of 3.2 tons per capita of steel. Study highlights that of the total gross volume, 62% accounts for residential buildings, which results to 130 tons per capita residential building stock in Vienna.

TABLE 4.4: Country level per capita stocks reported in past studies

| **Material Stock (Tons/capita)** | **Country/Region** | **Typology** | **Reference** |
|---|---|---|---|
| 72 | EU25 countries | Residential buildings | Wiedenhofer et al. (2015) |
| 71 | Japan | Residential and commercial buildings | Fishman et al. (2014) |
| 74 | Japan | Residential and commercial buildings | Tanikawa et al. (2015) |
| 45.7 | Germany | Residential buildings | Ortlepp et al. (2018) |
| 82.9 | Germany | Commercial buildings | Ortlepp et al. (2016) |
| 115 | Global Average | Total stock | Krausmann et al. (2017b) |
| 130 | Vienna | Residential buildings | Kleemann et al. (2017a) |
| 28.8 | Singapore | Residential buildings | Current Study |

The visible difference in estimated per capita non-metallic mineral stock could be because of several of the possible reasons – differences in construction style, building typology, non-inclusion of non-metallic minerals other than concrete in estimations. All residential buildings in Singapore follows a pattern for high rise buildings so the entire building stock has been distributed in multi-storey dwellings which has often been cited as less non-metallic mineral consuming than typical European typologies. In most of the European studies, the oldest buildings are as aged as 120 years while Singapore public housing efforts initiated in early 1970's which makes a significant difference in stock. Additionally, methodology in this research focuses on categorising different building components as separate entity for inclusion in inventories of secondary utilisation after end-of-life. The overall material estimations would have to discount for the components such as tiles, etc. for their weight. Another key factor in looking at per capita stocks remains the population density across a country and/or city. With population density of more than 7700 people per $km^2$, Singapore remains one of the densest countries in the world, which also contributes to the lower material stock per capita estimated in this study. A significant factor for per capita stocks assessment has been the resident population in a city which may or may not include the non-resident population. Looking at the official data on resident population in public housing, stock increases significantly to 38.9 tons and 2.0 tons per capita for concrete and steel respectively. Hence, inclusion of non-resident population can significantly influence the per capita stocks.

## 4.6 Uncertainties in assessment

In pursuit of developing a relatively simpler material and component stock assessment approach, there are inherent uncertainties in the results of this study. One source of uncertainty in proposed methodology is associated with Concrete Usage Index which has been assessed for recently completed individual construction projects. CUI values have inherent measurement uncertainties which have been superimposed with the uncertainty associated with the annual average concrete to steel ratios approach in current study. The uncertainties associated with the floor plans assessment for components stocks are due to representative sample sets which do not capture renovation and/or alteration works. Non-inclusion of annual material replacement due to maintenance would also lead to uncertainty in inflow and outflow rates (Stephan and Athanassiadis, 2018). The lack of comprehensive data at a building scale remains a major issue for uncertainties in bottom-up stocks assessment.

## 4.7 Summary and outlook

This chapter presents a relatively simpler yet efficient methodology for estimating building stocks in such a way that the estimations could help decision makers on how to accommodate building stocks and outflows as potential material resource stream. The general methodological framework proposed in this chapter can be applied at a neighbourhood or city-level to fully understand the building resources availability in stocks and potential outflows. The data requirements for components intensity can be met by surveying representative building typologies while the material intensity factors can be obtained through construction data. Availability of these two datasets can help in smooth replication of this approach for any city.

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. MS studies could demonstrate the potential for harnessing this stock and capturing outflows which would otherwise eventually end up in landfills. Considering that buildings contribute to more than 40% of total waste by volume and consume largest resources (UNEP, 2018b), there should have been higher visibility of accomplished circularity in this sector. Accounting for individual materials, realizing that those materials cannot be recovered and used as such, makes less of a difference in existing situation of waste driven dynamics. In a comprehensive recommendation for more circular building sector, Stephan and Athanassiadis (2018) argued that design for disassembly in close architects-manufacturer collaboration and shift in construction material ownership system to Product-Services-System could potentially enhance efficient reuse and/or secondary resource utilisation. Yet the information on modularity and availability in qualitative and spatially distributed manner is a key enabling factor. Accounting for building components could be more easily appreciated and understood outside the research community, therefore, it would be vital to represent MS estimations in terms of material as well as components stocks. For realisation of resources reuse in built environment sector, achieving a component level circularity could become more feasible than materials level circularity. Except for metals, which have intrinsic market value, resources reuse has thus far remained limited to individual examples. For non-metallic mineral, glass, wood and plastic, achieving upcycling and circularity might benefit from component level resources estimations for potential availability. Most easier circularity pathway could be enabled through reuse of these components in new constructions, such as for public places, social housing or regional low-cost housing. Peri-urban and rural housing demands may become an ideal opportunity for reuse of building components which will help reduce the material cost, enable environmental sustainability and the practice of circular economy. However, the practice of urban mining should be investigated for ease of salvage, costs involved and potential trade-offs.

To address these challenges, further studies should explore the role of MS studies in enabling secondary resources utilization, the ease of representation of stock results for policy makers as well as achieving cleaner production through in-stock resources for sustainability. There is a need for collaborative efforts between industrial ecologists involved in MS studies, Urban developers, planners and policy makers to fill the gap between estimations of stock and application of these stocks for meeting the virgin material demand in inputs to new stock. Realisation of existing stock contribution to lower new material demand would ideally define the success of stock estimation exercises. Component level circularity in that direction would be both desirable and effective if supportive conditions could be enabled.

# Chapter 5

# Urban mining in buildings: Planning, process and prospects

## 5.1 Synopsis

This chapter takes an empirical research approach for urban mining of building components from residential building stock in Singapore. It provides the detailed timelines of various planning stages for urban mining exercise, challenges of securing secondary resources supply based on several practical aspects and opportunities for efficiency gains in salvaging building components. Results highlight that the regulatory requirements for demolition permits can provide sufficiently long-time for urban mining exercise. Though the salvage skills of workers may seem important, this chapter highlights significant improvement in efficiency based on learning while doing approach for salvage of building components. In addition, the quality of urban mined secondary resources in typical deconstruction mode remains reusable. Overall, urban mining of buildings requires multi-stakeholder involvement and can be a limitation in its implementation across geographies and/or stakeholders.

## 5.2 Introduction

Previous chapters have highlighted that there is an increasing momentum towards urban mining across geographical boundaries and sectors. Sectors such as electronic waste have seen significant efforts in developing advanced methods for recovery of metals to a limit where it seems to compete with virgin mining (Zeng et al., 2018). Remanufacturing and the reverse logistics efforts have long been practiced with a reuse perspective for material and environmental benefits in sectors such as automobiles, electrical and electronic products and equipment (Casper and Sundin, 2018, Gutowski et al., 2011, Hertwich et al., 2019, Kwak and Kim, 2016, Saavedra et al., 2013). However in buildings sector, urban mining has been focussed on recycling efforts for the concrete and metals (Brunner, 2011, Cossu and Williams, 2015, Koutamanis et al., 2018, Stephan and Athanassiadis, 2018). Urban mining efforts for recovery of metal scrap and concrete undermine the components proposition for reuse. Reuse of building components require careful salvage which have to be carried out at site with skilled labour (Addis, 2006, Gorgolewski, 2008). In comparison, traditional demolition practices rely on heavily mechanised process with quick site clearance attitude. This contrasts with informal urban mining practices in the developing world where semi-skilled workforce is involved in recycling industry for daily wages and livelihood (Arora et al., 2017, Grant and Oteng-Ababio, 2016). Unavailability of advanced technologies and highly mechanised process influence the prospects of components recovery without breakage for reuse. However, labour costs in developed economies and strict time schedules for construction projects form a major challenge for deconstruction exercises (Dantata et al., 2005).

From an experimental point of view, Dantata et al. (2005) provided a detailed analysis of deconstruction associated on-site costs and time duration at a project level in Massachusetts, USA with conclusion that deconstruction costs could be 17–25% higher than demolition costs. This was after accounting for prospects of selling salvaged building components, avoided disposal costs and additional labour costs From modelling perspective, there are several studies which have looked at prospective benefits of deconstruction through Design for Disassembly approach (Akbarnezhad et al., 2014, Akinade et al., 2017, Huuhka et al., 2015, Rios et al., 2015).

Even though modelling exercise for assuming deconstruction and building components salvage is an important academic exercise, practical realities differ from assumption. There are established opinions in demolition sector that building components salvage would take longer time, extensive efforts, additional costs with uncertainty on finding market for salvaged components. the answer to these opinions can only be imparted through primary data.

This chapter, hence, undertakes an experimental approach for urban mining of building components to look at the planning and process. It also provides man-hours involved in recovering various building components and thus assigns labour costs. This can be further extended to look at the economic costs associated with salvage and transport. Economic benefits of salvage can also be estimated based on the price of a new building component that a salvaged building component can replace. Alternatively, price difference based on recycling and reuse of each building component can also highlights trade-offs of building component salvage. This study further discusses the challenges associated with urban mining of building components based on connection types, behavioural practices in construction sector and service life associated factors such as rusting. Overall, this chapter contributes in assessing the feasibility of urban mining in buildings for non-structural building components.

## 5.3 Methodology

Process of urban mining was investigated through hands-on experimental approach. Two sets of experiments were performed at residential building demolition sites in Singapore. To ascertain the typical demolition process, a case study was carried out at 371 Beach Road, Singapore, as discussed in chapter 3. Subsequently, planning for the urban mining was carried out with a local building demolition company in Singapore. Through collaboration with a demolition company, a demolition project was accessed for initial site visit. Six blocks of public residential buildings were planned for demolition, namely block 167-172 Boon Lay Drive, Singapore (Figure 5.1).


FIGURE 5.1: Residential buildings used for urban mining in Singapore

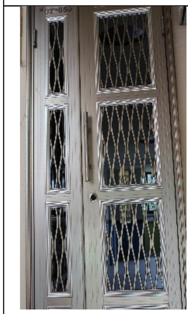
Subsequent site visits were performed for surveying and inventory development. Various building components were measured for their dimensions and marked for recovery. Subsequently, two semi-skilled demolition workers were hired to perform the building components recovery, transfer and storage in a temporary warehouse. In process, several hundred building component recovery experiments were carried out to estimate man-hours needed to salvage building components. The salvage exercise was planned based on typical work routine of workers. Observations regarding ease of recovery, damage and construction practices were documented. 2 hours towards end of workday were kept aside for transfer of building components from different housing units to a common warehouse. Overall urban mining was carried out with a goal for reuse of building components in subsequent construction projects.

## 5.4 Results and discussion

This study attempted to initiate an awareness around urban mining and building components recovery within the existing ecosystem of building demolition in a city. First step in the direction of planning an experimental exercise was to build collaboration. Previous attempts for assessing the status of demolition waste management in the city helped in finding regulatory bodies. However, demolition activities are typically performed by medium and small-scale industries, as highlighted in chapter 3. First, several companies involved in the demolition activities were contacted for potential collaboration. Two companies eventually agreed with one involved in small scale renovation and demolition activities while other with a large-scale demolition focus. Availability of demolition site is another challenge. Even though several demolition activities may be going on around the city, it is not necessarily possible that site can be accessed to perform experimental studies. Once the demolition company received a tender for demolition project, it has to wait for the handover activities where building is formally given in custody of demolition company. Once handover is complete, demolition company prepares documents for regulatory clearance from Building and Construction Authority in Singapore. This time is ideal for planning the surveying and inventory development for urban mining. Typically, a demolition site, after handover, has to disconnected with water and electricity supply. All the sewer lining and open holes need to be sealed so that site can be saved from becoming a breeding ground for mosquitoes, rats etc. This is predominantly a part of public health and safety plan. In addition, entire demolition site needs to cordon off with noise barriers. This is important due to noisy nature of building demolition activities. In addition, building is tested for the presence of asbestos which can have health hazard for workers on site. Singapore has mandated asbestos survey on any building demolition or renovation activity for buildings built before 1st January 1991 (MoM, 2019). The reports for identifying asbestos presence in building can take few weeks to arrange and be processed. All of these activities are crucial from regulatory clearance point of view and hence provide an ideal time frame for urban mining activities to be performed. Even though variations in demolition timelines and completion may differ based on the urgency in site clearance and construction type, regulatory requirements for demolition permits allow sufficient time in Singapore city. There exist a significant perception in existing literature and construction community that urban mining in buildings may affect the timelines of demolition and subsequent construction (Densley Tingley et al., 2017, Gorgolewski, 2008, Rios et al., 2015, Salama, 2017). On the contrary, regulatory clearance formalities from the point of time when a decision is made to demolish a building may take 1-3 months' time. Some may argue that it is a very short time span for urban mining, but practicality of building component salvage only requires four steps, namely, identification of demolition site, survey of building to identify building components of interest, actual urban mining i.e. salvage of components followed by transfer to a

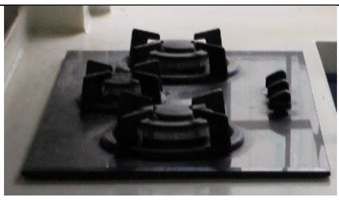
construction site or warehouse where further processing, if required, can be done. Next step in planning requires an understanding of required building components based on the motivation of this exercise. It can be driven a construction project demands or it can be a for selling it through business or charities. Based on the scale of urban mining requirements, manpower and warehouse space needs to be arranged. In this study, urban mining was driven by experimental investigations and potential construction projects. Hence, a warehouse area was secured within the demolition site. Demolition contractor planned for a sequential demolition of buildings which allowed certain buildings to be free from heavy machine activities until very end. Initially three housing units at the ground level were used as warehouse. Additional building components were stored at a carpark which was scheduled for demolition after residential blocks. After initial site visit, a survey was arranged to look at the stock of building components in different housing units. An initial inventory was developed with expected number of building components to be salvaged. This inventory included representative image of each building component and overall quantity to be reclaimed. This was followed by a paste-it note on certain building components to identify the blocks at the time of recovery.

TABLE 5.1: Inventory developed during the survey of end-of-life building

| **Depiction** | **Name** | **Expected Salvage Quantity** |
|---|---|---|
|   | Doors | 20 Units |
|   | Outside Doors | 4 Units |
|  | Kitchen Windows | 8 Sets |
|   | Room Windows | 8 Sets |

Continued on next page

**Table 5.1 – continued from previous page**

| Depiction | Name | Expected Salvage Quantity |
|---|---|---|
|  | Sliding Glass Doors | 8 Sets |
|  | Kitchen Sink | 6 Sets |
|  | Hand Wash Basin | 8 Sets |
|  | Toilet Bowls | 8 units |
|  | Gas Stoves | 5 units |

Continued on next page

**Table 5.1 – continued from previous page**

| Depiction | Name | Expected Salvage Quantity |
|---|---|---|
|  | Wood flooring | $100m^2$ |
|  | Kitchen Cabinet | 5 Sets |
|  | Room Cabinet | 8 Sets |
|  | Marble Flooring | $80m^2$ |
|  | Switch and Plugs | 50 units |
|  | Hanging Lights | 16 units |

Continued on next page

**Table 5.1 – continued from previous page**

| Depiction | Name | Expected Salvage Quantity |
|---|---|---|
|  | CFL Light bulbs | 20 units |
|  | Shower heater | 6 units |
|  | Outdoors Cement Tiles | $80m^2$ |
|  | Wall-mounted Fans | 6 units |
|  | Roof Fans | 8 units |
|  | Air-conditioner | 4 units |
|  | Corrugated Roofing Sheet | 32 Sheets |

Continued on next page

**Table 5.1 – continued from previous page**

| Depiction | Name | Expected Salvage Quantity |
|---|---|---|
|  | Glass Tiles | 40 units |
|  | Hand railings | 4 units |
|  | Expanded Metal Mesh Frame | 16 units |
|  | Steel columns | 8 units |

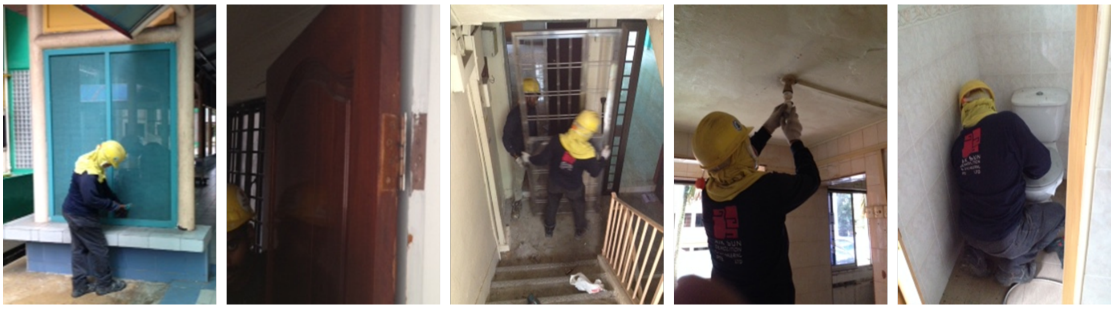


FIGURE 5.2: Urban mining of various building components from residential buildings

Once this inventory was developed, two semi-skilled workers were hired to undertake the urban mining exercise. Even though the workers were previously involved in the demolition activities, salvage of building components was a new assignment for both. This activity hence started focus on each building component with learning while doing approach. The process started with salvage of wooden doors which seemed easy with screw drivers used on door hinge. It was followed by Iron gates, windows, window grills, sliding glass doors, washbasin, toilet bowls, kitchen fixtures etc.

The overall exercise was carried out over different days of the work week. In total two allfull workdays and four half days were spent for salvage of 354 building components with two semi-skilled workers. Timing taken for salvage of each building component was recorded. This was to understand the efficiency gain in recovery process and typical time expected to recover each type of building components. Reclaimed components were transferred to a temporary warehouse in the evening for 90 minutes each day after completing the salvage. In total, 1314 minutes were spent on urban mining exercise of 354 building components by two workers (see SI). This accumulated to be 43.8 man-hours for urban mining, 12 man-hours for warehouse transfer. Once this exercise was completed, salvaged building components were loaded into 15 feet transport vehicle for transfer to a construction site. In total 12 man-hours were spent on loading the vehicle in two trips. In total, this exercise took approximately 68 man-hours to complete.

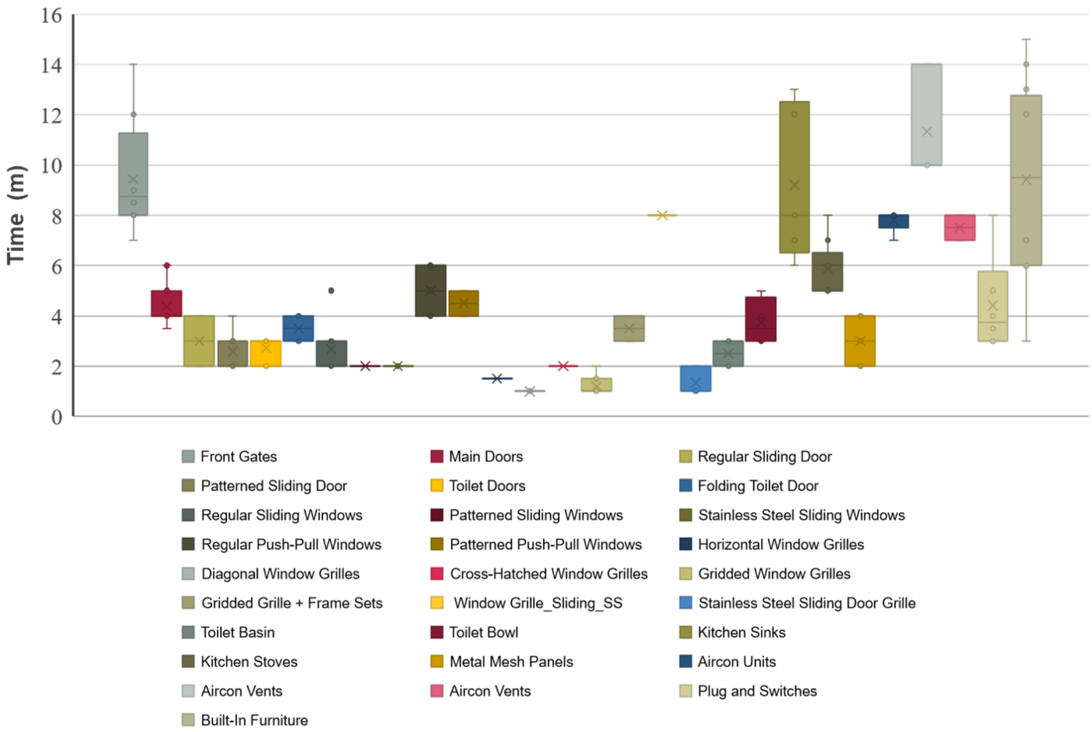



FIGURE 5.3: Time needed for urban mining of building components

Figure 5.3 shows detailed distribution of building component specific urban mining time. It highlights time taken in minutes for two workers on each building components recovery. A total of 28 categories of building components were analysed. The variation in timing was due to two primary reasons. Urban mining time for various building components ranged from 1 min for window grilles to 14 mins for an air-conditioner unit to 15 mins for kitchen counters. One important aspect of salvage time variation was associated with skill learning through practical experience. As previously discussed, it was a first-time experience for both workers in salvaging building components, skills for recovery were developed in repeated attempts. In careful observations on recovery times for same category of building components, it was observed that the time significantly reduced in later attempts with stabilisation after 3-4 recoveries. This can be associated with typical skill gaining process in any sector. Additionally, some recovery attempts didn't go as well as others due to physical differentiation in connection type. This is consistent with previous works on modular products and connection designs with ease for disassembly (de Aguiar et al., 2017, Kroll and Hanft, 1998, Sodhi et al., 2004, Vanegas et al., 2018). It was observed that the fastener design and material play a crucial role in disassembly of building components. Rusting was a major problem for removing screws which led to 4-5 mins additional time in unfastening. Uses of nails instead of screw was another problem which render disassembly process very difficult without physical damage to the components.

An important observation was made regarding the behavioural aspects within construction practices. Several of the building components had nails in addition to typical slots a component had for fasteners. Nails were added for additional safety and/or satisfaction that a component won't disassemble easily. Similar practice was observed for adding cement at the base of toilet bowls even though the bowl has fasteners in place for secured set up. Addition of cement at the base of a component was similarly seen on washbasins, window frames and even electric switches. Undue usage of cement as a practice has been documented in other countries too (Shanks et al., 2019). Usage of cement and/or concrete at the base of building components makes component salvage tedious and time consuming. In most cases of cement adhesives, recovered building components were either completely broken or partially damaged. This prevalent practice in Construction sector can only be avoided with significant efforts on awareness about modularity and disassembly driven mindset. With millions of people involved in this sector across the globe, serious efforts are needed on re-skilling construction workforce on avoiding extra caution efforts such as adding nails or cement in already complete assembly systems in place.

Costs of building components salvaged can be estimated based on the daily wages for a semi-skilled construction worker. In Singapore, it costs 100 SGD for 8 hours workday. In total, 56 man-hours were spent on reclaiming 354 building components. However, this total task was completed in 10 man-workdays. This accounts for timing involved in between walks and/or rest for the workers to initiate salvage of another component. A total cost of 1000 SGD was paid to recover the overall building components. This cost can be distributed for each building components based on the average time of urban mining. Total cost of 1000 SGD was distributed over 1314 mins of actual urban mining time for two workers, leading to 0.76 SGD per mins urban mining cost. Table 2 provides the average urban mining time and costs for each type of building components.

Table 5.2: Average salvage time and labour cost of urban mining

| **Building Component** | **Average Salvage Time (x2)** | **Cost of Urban Mining (SGD)** |
|---|---|---|
| Front Gates | 9.4 | 7.2 |
| Main Doors | 4.4 | 3.3 |
| Regular Sliding Door | 2.6 | 2.0 |
| Toilet Doors | 2.7 | 2.1 |
| Folding Toilet Door | 3.5 | 2.7 |
| Regular Sliding Windows | 2.7 | 2.0 |
| Patterned Sliding Windows | 2.0 | 1.5 |
| Stainless Steel Sliding Windows | 2.0 | 1.5 |
| Regular Push-Pull Windows | 5.0 | 3.8 |
| Patterned Push-Pull Windows | 4.5 | 3.4 |
| Horizontal Window Grilles | 1.5 | 1.1 |
| Diagonal Window Grilles | 1.0 | 0.8 |
| Cross-Hatched Window Grilles | 2.0 | 1.5 |
| Gridded Window Grilles | 1.2 | 0.9 |
| Gridded Grille + Frame Sets | 3.5 | 2.7 |
| Window Frame | 8.0 | 6.1 |
| Window Grille-Sliding-SS | 1.3 | 1.0 |
| Stainless Steel Sliding Door Grille | 2.5 | 1.9 |
| Toilet Basin | 3.8 | 2.9 |
| Toilet Bowl | 9.2 | 7.0 |
| Kitchen Sinks | 5.9 | 4.5 |
| Kitchen Stoves | 3.0 | 2.3 |
| Metal Mesh Panels | 7.8 | 5.9 |
| Aircon Units | 11.3 | 8.6 |
| Aircon Vents | 7.5 | 5.7 |
| Wall Switches (Double) | 4.4 | 3.4 |
| Built-In Furniture | 9.4 | 7.2 |
| Wall Mounted Fans | 3.0 | 2.3 |
| Ceiling Fans | 5.0 | 3.8 |
| Wall Mounted and Ceiling Lights | 4.0 | 3.0 |
| Hanging Lights | 3.0 | 2.3 |
| CFL Bulbs | 1.0 | 0.8 |
| Water Heating Units | 5.0 | 3.8 |

Overall cost for urban mining ranges between 0.8 SGD for bulbs and grilles to 8.6 SGD for Air Conditioners. Cost of sourcing the site and payment to a demolition contractor should also be added to estimate true cost of each building components. The economic incentive of building components recovery can best be estimated based on the market price for a salvaged building component in comparison to metal scrap. The labour costs associated with salvage then needs to be compared with costs of demolition through mechanised process and labour. This study, however, didn't undertake such a comparison. The focus on reuse of building components in this case was driven by costs associated with the disposal of demolition waste. Materials such as wood, glass, plastic, rubber do not have any market as discussed in chapter 3. To process these materials at waste-to-energy plant or landfill, demolition contractor has to pay 77$ per tonne fee. Only metals have value in the scrap form. A window set costs between 100 to 220$ in Singapore while its recovery cost is about 4$. If the same window was to be seen under demolition mode, about 6 Kg of metal scrap with current rates of about 300$ per tonne would mean less than 1$. The intact value of a building component can hence play a crucial role in building components urban mining and eventual reuse.

## 5.5 Summary and outlook

This chapter highlights various aspects associated with the practice of urban mining in buildings. It provides conclusive evidence about feasibility of building components recovery. The estimates of component specific man-hours and costs involved in salvage confirm the practicality of urban mining business case and opens-up opportunities for reuse practice in construction. Even though this chapter investigated building components in a specific project, it would be interesting to estimate urban mining and recovery potential for entire city. Next chapter will develop a methodology and estimates for annual and total urban mining potential of building components in a city.

# Chapter 6

# Buildings and the circular economy: Estimating urban mining, recovery and reuse potential of building components[1]

## 6.1 Synopsis

Continuous accumulation of materials in cities have led to the prospects of urban mining for secondary resources. Several commodities and/or products have been assessed in recent years for urban mining and reuse potential viz. automobiles, electronic waste etc. Urban mining for buildings, the largest material sinks globally, however require considerations which differ from the product-centric urban mining approaches. This chapter proposes a methodological framework for estimating city-wide urban mining, recovery and reuse potential of building materials and components. First, it extends the material stock and flow assessment to urban mining potentials so that recoverable and reusable flows can be highlighted. Secondly, it expands potential applications of recoverable flows to provide an impactful representation to stakeholders such as policy makers, consumers, designers and practitioners. The proposed framework has been applied to the public residential buildings of Singapore, for assessing building components such as windows, doors, tiles, light fixtures, toilet and kitchen fittings. As a case study, construction of low-cost houses in neighbouring Indonesia was explored to receive building component flows. Results highlight that the reuse of building components could have supported construction in the range of 830-1,910 houses in 2016 with more than 30,000 households getting benefit over the six years assessed in this study. Overall, outflows from the Singapore city can partly support the construction of 2,200 to 6,030 houses annually to resource-constrained housing sector in the surrounding developing region. Realization of such a circular economy practice will contribute towards sustainable development goals and climate change mitigation efforts.

[1] Published as Mohit Arora, Felix Raspall, Lynette Cheah, Arlindo Silva (2020) Buildings and the Circular Economy: Estimating Urban Mining, Recovery and Reuse Potential of Building Components, Resources Conservation and Recycling, vol 154, pp 104581

## 6.2 Introduction

Reducing material footprint and achieving sustainable resources consumption remains crucial to climate change mitigation and adaptation strategies as the materials use continue to drive global emissions and unprecedented waste (Hertwich et al., 2019, Kleemann et al., 2017b). Industrial ecology has provided multiple methods and tools to contribute in sustainable resources consumption such as socio-economic stock assessment and material flow accounting yet there is a need to link industrial ecology research with practice for achieving visible outcomes to combat resources scarcity (Haberl et al., 2019). The concept of circular economy has shown promise towards resources sustainability while material flow accounts could help in estimating the scale at which a circularity potential exists (Haas et al., 2015, Krausmann et al., 2018a, Stephan and Athanassiadis, 2018). Though one of the primary motivations of material stock assessment remains resources' sustainability, there is a gap in linking in-stock as well as end-of-life resources (material outflows) with material inflows for consumption and/or new construction. There has been a significant increase in the number of studies analysing material stock and flows for various geographical locations with temporal variations, producing insights on the scale of in-use materials and waste outflows (Krausmann et al., 2017a). These insights are important for predicting annual material demand, import and/or export from an economy perspective, but require a better representation to contribute in resources sustainability.

In the urban context, this study looks at buildings for urban mining because of increasing building density and resource abundance. Evident from material stock and flow studies, the built environment consumes most of the material inflows and leads to significant outflows reaching landfill (Krausmann et al., 2017b, 2018a). Significant understanding on growing consumption patterns and stocks accumulation inspired urban mining efforts (Brunner, 2011, Cossu and Williams, 2015, Koutamanis et al., 2018) and have since been accelerated with circular economy efforts at institutional and geographical scales in an attempt for environmental and/or material efficiencies (Arora et al., 2019, Geissdoerfer et al., 2017, Ghisellini et al., 2016, Haas et al., 2015, Hart et al., 2019, Pomponi and Moncaster, 2017).

## 6.3 Urban mining of buildings

Contribution of socioeconomic metabolism research in general and material stock-flow studies in particular, have helped in developing meso-scale momentum for urban mining and circularity action, however, a fundamental challenge remains in micro-level implementation of such assessments. In addition, Graedel (2011) highlighted that even though the efforts of urban mining would have significant effects, losses associated with each step involved in reaching final processing are huge. In defining the overall system efficiency as the product of the efficiencies of each step, Graedel (2011) argued only about one-quarter of the metal discarded in products actually ends up as recycled metal . Hence, it is crucial to minimise processing steps and/or develop recovery routes which reuse secondary resources instead of recycling.

Most of the material stock and flow studies take a top-down approach which provides a regional or sectoral overview of materials under investigation with typical representation in terms of weight. Though representation in terms of weight remains ideal for highlighting the scale of secondary resources availability and urban mining opportunity, it provides little impetus for practitioners and policymakers which may require detailed information for sector specific applications of secondary resources. Rose and Stegemann (2018) argued that sustainability in the construction industry requires moving beyond the waste management and focus on building components management.

To achieve that, stock and flow representations can best be linked with the potential market expectations to highlight the secondary resource in urban mines. Challenges of urban mining and driving practice of circular economy have indicated the need for additional efforts for its implementation and acceptance (Arora et al., 2018, Kleemann et al., 2017b, Koutamanis et al., 2018, Raspall and Arora, 2016, Su et al., 2013). Although circular economy itself does not distinguish between the mode of circularity, reuse has often been agreed upon as a preferred option over recycling or backfilling (Arora et al., 2019, Cooper and Gutowski, 2017, Hoornweg et al., 2015, Mayer et al., 2019, Raspall and Arora, 2016). Challenges in acceptance of reuse remain under wider scrutiny of the scientific community and often differ based on commodity quality, age and consumer preferences, yet the promotion of reuse over recycling signifies a preferred mode of circularity. This study argues for the need of a reuse potential assessment which links the potential market with outflows of material economies. Urban mining assessments impact need to communicate with communities which can tap on these resources and implement large scale projects. For developing such secondary resources reuse potentials, a resource specific end-use application can help in targeted policy and practice priorities.

The fundamental obstacle in the applicability of results from material stock studies is the way estimations are made and presented to the scientific and practicing community. Most of these stock and outflows are reported as single material-type while a better representation of these results as component-type could help decision and policy makers direct these outflows for upcycling and reuse instead of waste. Buildings are primarily constructed through the assembly of components such as windows, doors, columns, beams, façade, foundations, interior appliances etc. Though individual materials are consumed in construction, the majority of these materials are present in complex assemblies as components in existing stocks. Current material flow accounting methods and material stock studies ignore that the physical presence of materials in existing stock is in the form of finished or partly finished component instead of individual material. Results of these studies are often presented as individual materials such as steel, copper, plastic, wood, glass, concrete etc. To achieve resources reuse and material circularity in the built environment, representation of material stock first needs to be transformed into components stock. This study attempts to tackle this limitation of material stock accounting research through representing building stocks into components stocks and demonstrating the conversion of these building stocks into components reuse potentials to promote a practice-driven functional housing prototype development. Reuse potentials have previously been advocated generically by Park and Chertow (2014) and recently emphasized by Göswein et al. (2018b) specifically for buildings to increase material efficiency. The importance of reuse potential strategy in linking urban built environment outflows in a developed country (Singapore) with inflows for housing construction in a developing country (Indonesia) has been empirically demonstrated in the present study. This approach, hence differs from the prevalent and existing view of urban mining for metals and/or individual materials (Cossu and Williams, 2015, Koutamanis et al., 2018). To quote Graedel (2011), "product designers are crucial, if invisible and unrecognized, actors in the recycling chain". Providing detailed information on stocks and flows of resources hence becomes crucial for designers. Components reuse has been cited as superior to recycling in traditional waste management hierarchy and has been proven to save significant embodied as well as processing energy (Arora et al., 2018, EU, 2008). Despite environmental superiority, the systemic reuse of building components is still far from reality. Examples of building components that can be reused include structural components like beams, columns, steel frames and building interiors like doors, window, frames, kitchen and toilet fixtures, partitions, lighting, furniture etc. However, this study focuses on the latter, the non-structural building components and transforms building stock estimations into annual recoverable building components and reuse potential of urban built environment for meeting regional low-cost housing demand. Adequate and affordable housing is at the centre of multiple United Nations Sustainable Development Goals (SDG), primarily Goal 11 (Sustainable cities and communities), with direct or indirect contributions to Goals 3, 5, 6, 10, 12, 15 and 16 while achieving these SDG remains a key strategy for climate change adaptation and mitigation strategies (Sanchez Rodriguez et al., 2018). Lack of adequate housing has far reaching consequences for climate resilience and yet remains a major challenge for the global community. In South Asia alone, a shortage of 38 million housing units is reported to match the UN standard for decent living (Nenova, 2010). This study argues that premature obsolescence of buildings in cities could drive an affordable supply of components for low-cost housing in developing countries and contribute in solving the housing challenge.

To summarise the main objectives, this chapter develops a methodological framework for estimating city-wide urban mining, recovery and reuse potential of building materials and components as its first objective. It uses the material stock and flow assessment of Singapore city carried out in chapter 4 to estimate the annual urban mining potential from 2010 to 2016. Based on the methodological framework proposed in this study, the second objective of this study is to estimate recoverable and reusable non-structural building components through actual experiments of urban mining and recovery at a residential building demolition site. The third objective of this study focuses on expanding potential applications of reusable building components to low-cost housing in Indonesia through a construction case study for estimating demand factors of a typical house. This would result in assessing urban mining contributions of buildings in a city for construction of low-cost houses in the region. The proposed framework has been applied to the public residential buildings of Singapore, a city state in South East Asia, for assessing building components such as windows, doors, tiles, light fixtures, toilet and kitchen fittings. Such a strategy can potentially contribute to multiple climate change mitigation and adaptation strategies as proposed by Ürge-Vorsatz et al. (2018).

## 6.4 Methodological framework

Material flow and stock analysis is an established methodology within industrial ecology domain (Krausmann et al., 2017a, 2018a). However, defining stocks and flows in terms of availability for urban mining requires an extension of existing doctrine. A typical urban system follows a material cycle with continuous inflow and outflow to support its societal stock. The time scale at which these outflows originate depend on the service life of material usage which often varies from short-lived to decades. Considering service life, the concept of urban mining has found varied interpretations on its potential and scale. Figure 6.1 highlights the general framework used in this study to assess the urban mining potential of a city. This framework has been developed based on the learnings from material stock and flows exercises, extensive field visits to building demolitions to track end-of-life building component flows and housing construction in Indonesia (Arora et al., 2018, 2019, Raspall and Arora, 2016).

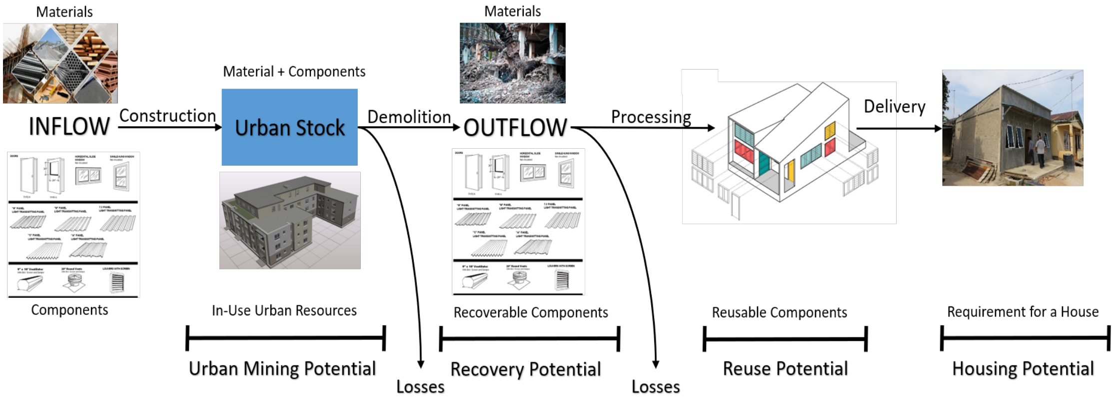



FIGURE 6.1: Conceptual framework for stock and flows to reuse and housing potential estimation

Here, urban mining potential is defined as the total material and/or components stock of a city. Theoretically, everything could be mined and taken out of a city if we were to ignore the practical complexities and hence:

$$\text{Urban Mining Potential}_{Total} = \text{Stock}_{Total} = \text{Inventory of Material} \times \text{Material Intensity Factor} \tag{6.1}$$

Out of the total urban mining potential, only a fraction is released every year due to various obsolescence drivers. This released fraction, often termed as outflow, represents the annual recovery potential.

$$\text{Urban Mining Potential}_{Annual} = \text{Outflows}_{Annual} = \text{Recovery potential}_{Annual} \tag{6.2}$$

Urban mining process typically requires efforts for mining the resources which in simplistic term can be defined as recovery. During this exercise of recovery, various tools might be used which may render a component and/or material irreparable damage. Such damage and/or breakage leads to a reduced recovery of resources compared to previously estimated as Urban mining potentials. Hence, the recovery potential must account for its efficiency and losses:

$$\text{Recovery Potential}_{Total} = \text{Urban Mining Potential}_{Total} = \text{Recovery Efficiency} \tag{6.3}$$

$$\text{where Recovery Efficiency} = 1 - L_{Recovery} \tag{6.4}$$

$L_{Recovery}$ denotes the loss factor associated with the urban mining exercise to recover any item and/or material.

Out of all recovered materials and/or components, not everything can be reused due to losses in the post-recovery processing, transfer, functionality loss associated with age, aesthetics and/or physical damage and hence, the reuse potential is defined based on recovery, functionality and physical conditions.

$$\text{Reuse Potential}_{Total} = \text{Recovery Potential}_{Total} = \text{Reuse Efficiency} \tag{6.5}$$

$$\text{where Reuse Efficiency} = 1 - L_{Reuse} \tag{6.6}$$

$L_{Reuse}$ defines the loss factor associated with the functional, physical and processing damages which diminishes the reusability of an item and/or material. It is important to highlight that the total potentials represent the urban stock while practically, only urban outflows are available for applications. Hence, realistic recovery and reuse potential must be based on the annual outflows from a city- a measure of real secondary resources availability. Eq. 6.2 has been used to estimate the annual potentials and accordingly, Eq. 6.3 and 6.5 have been modified for annual recovery and reuse potentials estimates.

Although reuse potential for an urban mine may be considered an indicator for availability of secondary resources and hence lead to supply quantification, it needs to be further linked with the demand for urban mined resources. In the case of building components, chapter 4 identified self-build affordable housing as a potential market for secondary building components. To provide an impactful representation of reuse potentials, this study analyses design and construction of low-cost houses in Indonesia. A typical low-cost housing model adopted by Habitat for Humanity Indonesia has been used for estimations for average housing units that could be supplied with building components in urban stock as well as outflows. To estimate housing potential of each component:

$$\text{Housing Potential} = \frac{\text{Reuse Potential}}{\text{Demand Factor}} \tag{6.7}$$

Where Demand Factor represents the requirement of the specific building component in one house. Figure 6.2 highlights the process of arriving at the urban outflows in terms of equivalent number of low-cost housing units that could be built annually. The underlying assumption in such an estimate is to link outflows of cities with resource constrained communities which can benefit from urban secondary resources. In this particular case, cleaner production of affordable housing in Indonesia has been considered as a potential circularity route for the outflows from building demolitions in Singapore.

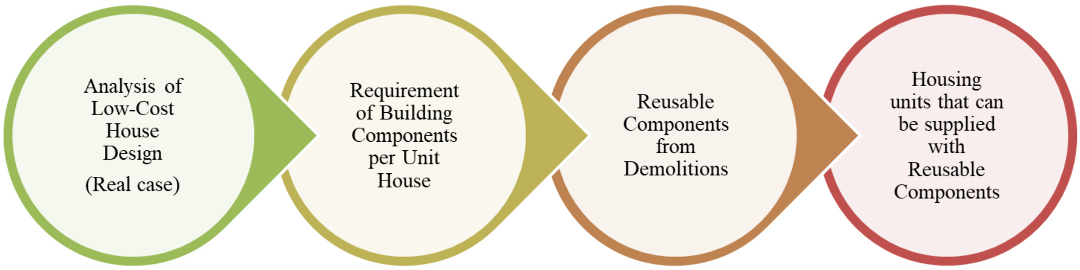



FIGURE 6.2: Estimating housing potential from reuse potential

## 6.5 Data sources

### 6.5.1 Material and components stock data

For estimation of urban mining potential, recovery and reuse potential, this study builds upon the building components stock and flows assessment data developed in chapter 4. To briefly summarise the methodology, a bottom-up material flow analysis approach was used to estimate the material and components inflow, stock and outflows for the residential buildings in Singapore. Using material intensity factors for several public residential buildings in Singapore, estimates of concrete and steel inflow, stock and outflows were made (Eq. 6.1). Similarly, based on floor plans and surveys of various dwelling typologies, an inventory of building components corresponding to each dwelling type was developed and used for estimating building components inflows, in-use stock and outflows. Primary data for overall residential buildings, dwelling type and demolition was obtained from various regulatory agencies in Singapore details of which has been previously discussed in chapter 4. To provide reuse and housing potential, the scope of this study has been limited to six building components type specifically windows, doors, toilet accessories, kitchen accessories lighting fixtures and floor tiles. Lighting fixtures have been combined into a single category due to common functionality. Kitchen accessories includes a cooking stove, sink, tap and kitchen cabinet and have been accounted as a single unit. Toilet accessories combines toilet bowl, sink, tap, flush, shower head, wash basin each as group.

### 6.5.2 Loss factors

In the urban mining exercise, there would be losses associated with the damage of quality and/or functionality. These losses have been grouped in this study in the form of loss factors. Theoretically, most of the building components available for urban mining can be recovered. In practice, the majority of existing buildings were not designed to be disassembled yet the building components can still be recovered with certain damage to physical or aesthetic conditions. So even though components from traditional buildings can be recovered, prospects of their reuse have become low, leading to high losses. In cases where a component can't be recovered without breaking, it's reuse potential becomes zero. It is important to highlight however that the ease of recovering the same building component such as a window varies from site to site within a building itself and hence the combined recovery and reuse potential is based on a large number of onsite experimental exercises of urban mining. Through a series of qualitative inspections and observational experiential exercises on a demolition site in Singapore, average loss factors were developed for building components which have been listed in Table 6.1. An experimental setup was planned with 4 unskilled construction workers assigned to recover each type of building components from over 50 residential apartments in a public residential building managed by Housing Development Board of Singapore. Based on theoretical potential of recovering building components, even though damaged in certain quantity, this study assumes that the loss factor for calculating recovery potential ($L_Recovery$) will be zero. As described in section 6.4, recovery potential needs to be converted into reuse potential which would lead to losses denoted by the loss factor, $L_Reuse$. $L_Reuse$ considers the damage during the recovery and processing of components for making it eligible to be reused.

TABLE 6.1: Building components and respective losses in processing

| Building Components | Loss Factor ( $L_{Reuse}$, %) |
|---|---|
| Floor Tiles ($m^2$) | 30 |
| Windows (items) | 5 |
| Doors (items) | 5 |
| Toilet accessories (items) | 20 |
| Lighting fixtures (items) | 20 |
| Kitchen accessories (items) | 20 |

### 6.5.3 Building components demand factors

A key aspect of this study has been to extend the reuse potential into housing potential. For developing the components demand for a low-cost house, regional housing design and construction methods were studied. Specifically, a construction case of a 39 $m^2$ self-build home was considered at Batam, one of the fastest growing urban islands in Indonesia. With nearest land point 5.8 km far from Singapore, Batam's proximity may play a significant role to promote the reuse potential. An international non-government organisation, Habitat for Humanity through its Batam office identifies economically and/or physically disadvantaged families which are living in poor housing conditions but have land ownership. In such cases, families typically do not have enough income or savings to buy construction materials and financing institutions do not usually approve loans for housing construction due to a variety of reasons including lack of stable income. Habitat for Humanity has a fixed housing layout which spans 6m x 6.5m, with 2 bedrooms, a living room, a toilet and space for a kitchen. Figure 6.3 demonstrates the typical 2-dimensional and 3-dimensional construction layout.

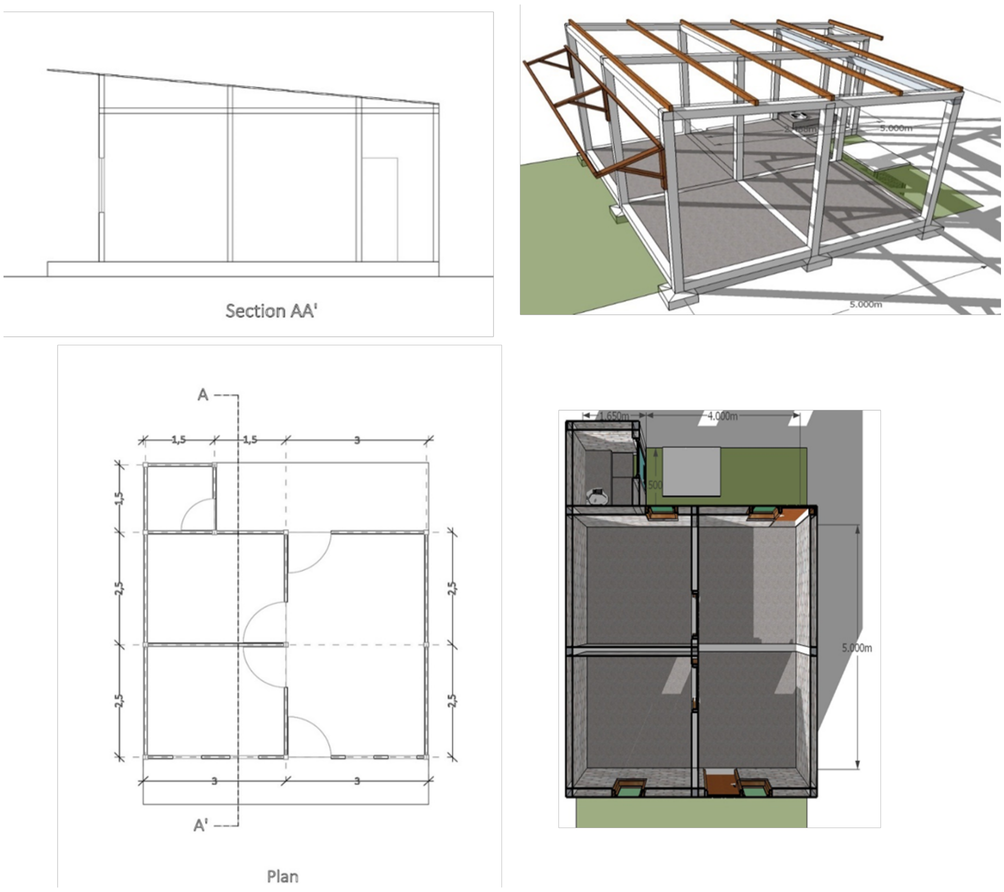



FIGURE 6.3: 2-D and 3-D floor plan (all dimensions in meter) of self-build low-cost house in Batam, Indonesia

Common construction materials for self-build homes include concrete masonry unit, concrete with Portland cement and steel for structural re-enforcement. The construction of 3 low-cost (EU, 2008) houses was examined over an overlapping period of 2 months in 2018. A typical construction cycle takes 21 days with an average of 65 man-days labour intensity per house. The inventory of building components for these houses which can be supplied through urban mining for the final 32.5 $m^2$ built floor area is described in Table 6.2.

TABLE 6.2: Building components demand for construction of a low-cost house

| **Building Components** | **Demand** |
|---|---|
| Floor tiles | 32.5 $m^2$ |
| Lights | 5 items |
| Kitchen accessories | 1 set |
| Doors | 5 items |
| Windows | 4 items |
| Toilet accessories | 1 set |

This demand per house generated by the construction case study are used to convert the reuse potential into a housing potential for each component type. This provides the scale of houses that can be constructed with the supply of a specific building component. Even though the dimensions of building components recovered from urban mining may differ within each category as well as from typical construction model, it does not matter in case of designing with reuse. The informational availability on dimensions and quality of components through components inventory will lead to efficient uncertainty incorporation in construction.

## 6.6 Results and discussion

### 6.6.1 Total potential

The methodological framework presented in section 6.4 expands on the results of a previously conducted material and components flow analysis presented in chapter 4. Considering the theoretical mining potential of everything that a city accumulates, the total urban mining potential would be equivalent to urban material and component stock. Results for total urban mining potential from public housing illustrate that the Singapore city saw a consistent growth from year 2010 to 2016, due to higher inflows and stock accumulation compared to outflows (Figure 6.4A). Over this period, number of windows, doors and toilet accessories grew with a combined annual growth rate of 10%, lighting fixtures and tiles grew at 11% while kitchen accessories grew at 12% (See SI). Total recovery potential, hence, follows a similar trend with availability of 6.45 million windows, 8.6 million doors, 1.97 million toilet accessories, 0.99 million kitchen accessories, 15.33 million lighting fixtures and 52.55 million $m^2$ of floor tiles. This total recovery potential has been used to estimate total reuse potential. Based on the loss factors, as described in section 6.5.2, the total reuse potential was estimated for all years over 2010 to 2016. In 2016, total reuse potential includes 6.13 million windows, 8.19 million doors, 1.58 million toilet accessories, 12.27 million lighting fixtures, 0.79 million kitchen accessories and 36.78 $m^2$ of floor tiles. If these reusable components were to be used in construction of low-cost houses with a design layout described in section 6.5.3, it would help construct 0.79 million houses with full supply of all six building components categories considered in this study. From a component's category perspectives windows, doors, toilet accessories, lighting fixtures, kitchen accessories and tiles could be received by 1.53, 1.64, 1.58, 2.45, 0.79 and 1.13 million houses respectively (Figure 6.4B). Batam, being one of the fastest growing urban regions within Indonesia with 11% annual population increase and 1.3 million population, can hence significantly benefit from these resources.

### 6.6.2 Annual potential

Although total urban mining potential provides important information on the scale of secondary resources, only annual urban outflows, released through various obsolescence pathways, can provide a realistic contribution to circular economy. Hence, this study further estimates annual recovery, reuse and housing potentials based on the residential housing demolition in Singapore over 2010 to 2016. Demolition activity varied significantly over time and dwelling types (Figure 6.4C, see also SI), and hence, the annual recovery potential for building components over six years highlight the uncertainties of scale in developing a reuse-driven supply chain (Table 6.3). This is primarily driven by various obsolescence reasons for buildings which may or may not be based on functional obsolescence (Wuyts et al., 2019).

TABLE 6.3: Annual recovery potential of building components

| Building Component | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|
| Floor Tiles ($m^2$) | 78120 | 175716 | 196305 | 67065 | 37324 | 42668 |
| Windows (items) | 10828 | 23300 | 26662 | 9490 | 4984 | 4176 |
| Doors (items) | 14830 | 32315 | 36212 | 12833 | 6463 | 5573 |
| Toilet accessories (items) | 3560 | 7613 | 8620 | 3092 | 1757 | 1562 |
| Lighting fixtures (items) | 24842 | 54848 | 62735 | 21400 | 11591 | 11952 |
| Kitchen accessories (items) | 1779 | 3807 | 4501 | 1545 | 1022 | 1036 |

As the annual recovery potential changes, reuse and housing potential follows the similar pattern based on loss factor and housing demand factor respectively. For year 2016, we estimate the annual reuse potential of 29,868 $m^2$ floor tiles, 3,967 windows, 5,294 doors, 1,250 toilet accessories and 829 kitchen accessories with 9,562 lighting fixtures. These building components could have supported construction in the range of 829-1912 houses in 2016 with more than 30,000 households getting the benefit over the six years (Figure 6.4D).

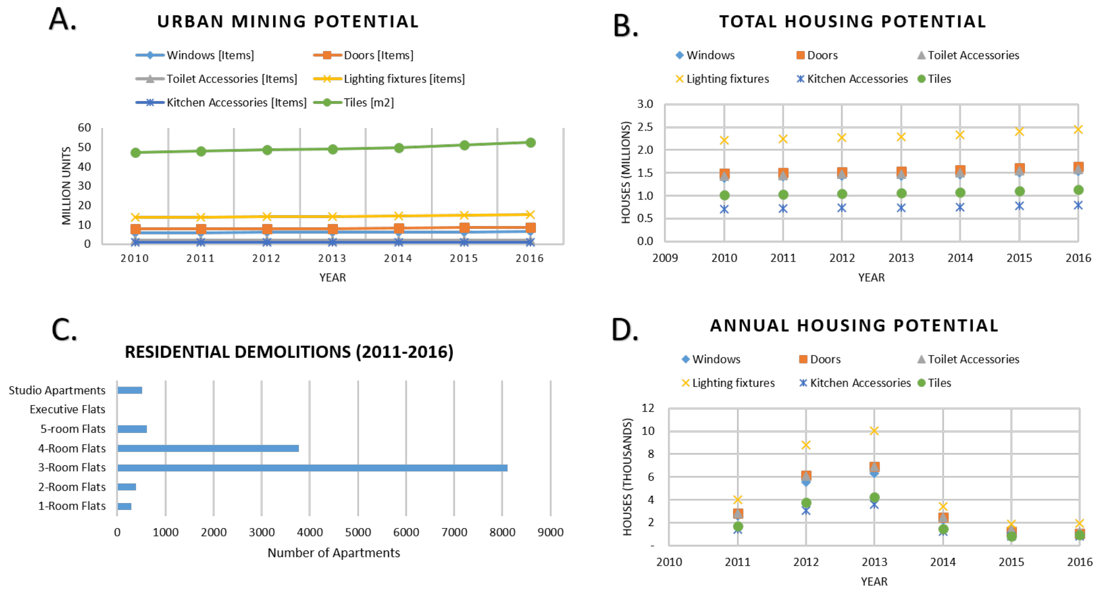



FIGURE 6.4: Total urban mining potential, housing potential and demolitions with annual housing potential in Singapore

### 6.6.3 Average annual housing potential

Looking at the Singaporean's recovery and reuse potential patterns over past 6 years, it is unreasonable to impose a definitive trend and/or distribution function characteristic. Therefore, an indicator of annual urban mining, recovery and reuse potential has been developed based on preceding 6-year average of building demolitions. Such an average annual potential indicator has been recommended as a proxy for near-future resources availability forecast. Based on the residential typologies and archetype demolished during 2010-2016, average demolition factors have been developed for each archetype as:

$$\text{Demolition factor}_{\text{Archetype i}} = \frac{\text{Demolitions}_{\text{Archetype i}}}{\text{Sum of all Demolitions}} \tag{6.8}$$

Table 6.4: Average annual demolitions of public residential houses in Singapore

| **Type** | **Total Unit Demolitions (2011-16)** | **Average Demolition Factor (%)** | **Annual Demolition Forecast** |
|---|---|---|---|
| 1-Room Flats | 288 | 2.1 | 58 |
| 2-Room Flats | 384 | 2.8 | 77 |
| 3-Room Flats | 8113 | 59.26 | 1632 |
| 4-Room Flats | 3773 | 27.56 | 759 |
| 5-room Flats | 618 | 4.51 | 124 |
| Executive Flats | 5 | 0.04 | 1 |
| Studio Apartments | 509 | 3.72 | 102 |

Demolition factors, so developed using Eq. 8, has been used to estimate demolition forecast of dwelling archetypes which adds up to 2753 dwellings (Table 6.4). Based on the components stock assessment method developed by Arora et al. (2019), annual recovery potential has been estimated for all six building components from demolished buildings (Table 6.5). In total, Singapore city can provide 120,094 $m^2$ of floor tiles, 15,976 windows, 21,766 doors, 5,270 toilet accessories, 2,753 kitchen accessories and 37,680 of lighting fixtures annually as recoverable resources.

Table 6.5: Average annual building components recovery potential for Singapore City

| Type | Units | Tiles ($m^2$) | Windows (items) | Doors (items) | Toilet accessories (items) | Lighting fixtures (items) | Kitchen accessories (items) |
|---|---|---|---|---|---|---|---|
| 1-Room Flats | 58 | 1723 | 116 | 116 | 58 | 406 | 58 |
| 2-Room Flats | 77 | 2079 | 308 | 308 | 77 | 847 | 77 |
| 3-Room Flats | 1632 | 63648 | 9792 | 13056 | 3264 | 21216 | 1632 |
| 4-Room Flats | 759 | 40986 | 4554 | 6831 | 1518 | 12144 | 759 |
| 5-room Flats | 124 | 8184 | 992 | 1240 | 248 | 2232 | 124 |
| Executive Flats | 1 | 78 | 10 | 11 | 3 | 19 | 1 |
| Studio Apartments | 102 | 3397 | 204 | 204 | 102 | 816 | 102 |
| Total Recovery Potential | | 120094 | 15976 | 21766 | 5270 | 37680 | 2753 |

Recoverable resources have been further assessed for reuse and housing potential. Accounting for losses associated in processing, annual reuse potential has been minimum for kitchen accessories with 2,202 items while floor tiles of more than 84,000 $m^2$ could be reused (Table 6.6). Overall Singapore city has the potential to support low cost houses in the range of 2,202 to 6,029 every year, a significant contribution to the resource constrained housing sector in the developing region.

TABLE 6.6: Annual reuse and housing potential from Singapore's public residential buildings

| **Building Components** | **Annual Recovery Potential** | **Loss Factor (%)** | **Total Loss** | **Annual Reuse Potential** | **Demand Factor** | **Annual Housing Potential** |
|---|---|---|---|---|---|---|
| Floor Tiles ($m^2$) | 120,094 | 30 | 36,028 | 84,066 | 32.5 | 2,587 |
| Windows (items) | 15,976 | 5 | 799 | 15,177 | 4 | 3,794 |
| Doors (items) | 21,766 | 5 | 1,088 | 20,678 | 5 | 4,136 |
| Toilet accessories (items) | 5,270 | 20 | 1,054 | 4,216 | 1 | 4,216 |
| Lighting fixtures (items) | 37,680 | 20 | 7,536 | 30,144 | 5 | 6,029 |
| Kitchen accessories (items) | 2,753 | 20 | 551 | 2,202 | 1 | 2,202 |

Contextualisation of these secondary resource's potential require understanding of regional requirements and drivers for their potential reuse. In case of reuse driven construction, it is important to consider the location specific construction practices, cultural preferences and a model housing prototype. To create a supply chain of secondary resources, the results highlight that a mixed stream of new and old components would be inevitable. To minimize demolition associated uncertainties, a mixed supply of newer and recovered components would also have beneficial impacts. This also finds merit in consumer acceptance, overall functional performance and aesthetics of the housing construction. Creating such a supply chain and/or developing logistical business plan would have to account for multiple sources of uncertainties, however, this is beyond the scope of the current study.

An important and crucial question for resources efficiency and urban mining in cities emerges from this study: the responsibility for ensuring circular economy. Even though cities have extensive waste management plans which are routinely implemented, circular economy plans need a fresh look at the approach towards material efficiency and reuse. Looking at the construction materials and building components case in Singapore, it is hard to establish stakeholder's responsibilities for overall implementation of a circularity agenda. Regulatory agencies in Singapore have ensured that a landfill fee of 77 Singapore dollars ( 56 USD) per metric tonne of demolition waste is charged for management at designated landfill sites and a deconstruction approach has been recommended for demolition companies. However, individual stakeholders work for their financial profit and in scenarios where incentives for circular economy are financially insignificant, circularity becomes impractical. Punitive measures through policy may work well for waste management but circular economy requires incentives and enabling policies for stakeholders to take up newer pathways of urban mining and reuse.

## 6.7 Summary and outlook

Though there have been significant emphasis and agreement within academic community for upcycling of secondary resources, usage has been limited to predominantly recycling and downcycling. In addition, urban stocks have primarily been looked at in material forms instead of their practical existence in the form of complex assemblies and/or components. Practical implementation of urban mining with upcycling potentials would require several changes to this status quo which includes estimates of recoverable materials, components and streamlined reuse potential visibility. Reuse of secondary resources, hence, would require more granular information on outflows which this study attempts to address through analytical and practical case studies.

An important consideration in this approach has been the acceptance of reuse into newer construction practices. A fundamental influence of such an approach would be on both communities and construction stakeholders. Inclusion of older building components into new houses has been a traditional practice within rural communities, however, putting an organised approach which affects the formal sector would require newer synergies. This approach also remains subject to fluidity based on a typical house layout, cultural preferences and construction practices for a community. And hence, the housing potential estimated based on a specific low-cost house has its regional significance which can be replicated to regions with differentiated construction preferences. This must further be validated with associated embodied carbon savings against the processing and transport emissions which would occur if reuse were to stay environmentally beneficial.

This chapter primarily provides an in-depth case study of Singapore city using the proposed method for estimating Urban Mining, Recovery and Reuse potential. It utilizes data from a material stocks and flow assessment, an urban mining exercise of building components at a residential building demolition site for estimating recovery and reuse potential. It further assesses the low-cost housing construction in Indonesia to estimate housing potential from the reusable building components estimated in previous step. Such an approach is uniquely different previous studies by providing an end-to-end approach for circular economy in construction sector.

With the recent Chinese ban on import of waste (Brooks et al., 2018, Qu et al., 2019), more and more developing countries are becoming vocal about the waste they receive from developed economies, several countries even returning the shipments back (Burlakovs et al., 2017, Lin et al., 2017, Schiller et al., 2017, Yoshida et al., 2017). Social and ethical implications of such a trans-national movement of waste have sparked serious concerns among public and policymakers alike (Liu et al., 2018, Qu et al., 2019). With the advent of circular economy initiatives, nations need to develop an understanding of differentiating waste from reusable products and/or materials. Current trade regulation needs to accommodate the uprising of circular economy business models and defining old, yet reusable products/materials or building components out of the overarching umbrella of “waste”. Incidents of garbage being sent to developing nations in the name of recyclables would lead to angry backlash, potentially harming the spirit of global collaboration to achieve a circular economy. It requires policies of trust and practice of fair play from all stakeholders.

In summary, this chapter first demonstrates that the insights from a material stock and flow assessment could be adapted for urban mining and reuse potential which can be linked with the needs for low-cost housing sector in developing countries. It further extends the results of the traditional material flow analysis to provide the extent at which a city could support adequate housing deficit in neighbouring low-income areas, making these results more impactful for policy makers and stakeholders involved. This research attempts to bring urban mining assessments closure to the demand specific practices through construction of low-cost housing which may help in decarbonisation of cities and provide regional communities with adequate housing to better adapt climate change vulnerabilities. Though challenging, such an attempt to transform research into practice is crucial for realizing UN Sustainable Development Goals and climate change adaptation and mitigation efforts.

# Chapter 7

# Reuse radius: Transport distance and building component specific embodied carbon budget for reuse-driven circular economy

## 7.1 Synopsis

Following the urban mining exercise in previous chapter, it is important to assess if salvaged building components will have any environmental benefits for their potential reuse in building construction at a distant site. To investigate the carbon emissions associated with transport of salvaged building components, this chapter develops a concept of embodied carbon budget for salvaged building components. It further develops estimates of transport distances, coined as reuse radius, within which there would be embodied carbon benefits for the reuse of salvaged building components in a construction project. It further demonstrates that transport of building components from Singapore to Kabil village in Batam, Indonesia would only consume 3-19% of embodied carbon budget, highlighted significant potential for low-carbon construction and emission benefits.

## 7.2 Introduction

Industrial and energy associated emissions have been tightly linked with material consumption. Thus, urgency in achieving material efficiency for reducing production associated global GHG emission have been advocated by several studies as a key climate mitigation strategy (Allwood et al., 2011). These concerns are primarily based on pace of technological advancement and consumer behaviour towards material consumption, leading to sharp decrease in use-phase life of material and products. With decreased product lifetime, reuse remains a favourable abatement strategy for reducing production associated embodied energy and green-house gas emissions as well as potential product demand decrease (Allwood et al., 2010, Geyer and Jackson, 2004, Hertwich et al., 2019). Traditional waste management hierarchy prioritises reuse over recycling, almost always with an assumption that such a practice would be more environmental friendly (Arora et al., 2019, Hering, 2012). In addition, reuse remains the most desirable end-of-life fate for upcycling and meaningful circular economy (Dunant et al., 2017, Reck and Graedel, 2012).

Irrespective of scientific appraisals, reuse has not been able to become a favourable practice. Though there have been studies assuming emissions and climate adaptation benefits associated with a near perfect circularity of materials in human consumption patterns, in rarest cases only a fraction of overall material inputs has been reused (Cooper and Allwood, 2012, Dunant et al., 2017). In a perfectly market driven economy, reuse ecosystem is governed by cost differences and profit margins however there remains social as well as environmental motivations for promoting such an ecosystem. Social arguments of reuse have primarily been based on the access to goods and products for economically poor at a cheaper market price, while the environmental arguments look at the longer service life and avoiding new production resulting lower GHG emissions and associated climate impacts. Various studies have emphasized on reuse to save embodied energy, minimize waste and its environmental impact including circular economy yet the challenges associated with such a practice have not been properly addressed. For GHG emissions reduction and resources efficiency, Allwood and Cullen (2012) argued that the most important steps are to reuse old components before recycling and extend the life of products through next life after first end-of-life. Authors specify that such practices will not only eliminate energy needs for further processing but also enhance materials availability to support its demand. Success for reuse has been met with major challenges such as lack of information on quality and quantity, ambiguity on environmental benefits as well as lack of willing market (Arora et al., 2018, da Rocha and Sattler, 2009, Dunant et al., 2017, Iacovidou and Purnell, 2016). Recycling on the other hand has been promoted vigorously by policy makers and funding agencies despite of being more energy intensive. Recycling of metallic waste has been shown to provide 37-42% embodied energy savings though savings after recycling might be as low as 5% for many construction materials (Allwood et al., 2011, De Wolf et al., 2017, Dixit et al., 2013, Geyer and Jackson, 2004, Göswein et al., 2018a, Reck and Graedel, 2012). Instead, Reuse without energy intensive processing could save as high as 95% of embodied energy (Densley Tingley et al., 2017).

An important aspect of reuse remains the long transportation in search of consumer market. Often in developed world, reuse practices are significantly absent leading to relocation at large distances for a second life of old goods and products. Examples of such practices include electronic waste transport to Asian cities, textile transport to African cities, metal scrap transport to India and China etc (Cooper and Gutowski, 2017, Hoornweg et al., 2015, Qu et al., 2019, Zeng et al., 2018). Existing literature on reuse benefits and/or practices does not include the effects of embodied carbon, used life phase as well as transportation distances in decision making. However, Cooper and Gutowski (2017) emphasised that reuse may not necessarily lead to environmental benefits and thus requires better scientific assessment to change assumptions into understanding. Göswein et al. (2018a) undertook an extensive exercise for concrete and various low-carbon substitutes including recycled concrete aggregates to find out if the transport associated emissions matter in choices for low-carbon concrete. Notably, for recycling driven concrete mix, it turned out that transport emissions can play a role in flipping the overall environmental benefits, highlighting the tight carbon budget in a recycling scenario. Unlike recycling, reuse on the contrary does not involve extensive energy in processing and hence may lead to interesting insights on transportation distances.

There are several challenges for reuse driven circular economy in buildings. Cities themselves have failed to accommodate urban mined building components into newer construction at the pace end-of-life building demolitions occur so there is a potential surplus as previously demonstrated in chapter 3. The other problem is the transport associated emissions for transferring salvaged building components to a location which may well be willing to reuse them. Such locations can be suburban or rural regions of the same country or far from the city across the sea. This chapter, hence, assesses environmental dimensions of reuse associated with building components and defines a reuse radius- distance within which reusing building components would remain within environmental benefits in comparison to a new building component. Based on this approach of embodied carbon in buildings, environmental analysis will consider the embodied carbon associated with components production process and on-site delivery to a construction site, service life within a building, transportation and processing emissions involved in successive reuse. The eventual aim of this study is to estimate the embodied carbon in typical non-structural building components and develop a concept of carbon budget for each component which can then be used for process and transport associated emissions. The motivation behind such an analytical framework is to assign a reuse distance within which a salvaged building component can be transported with net carbon emission savings. Even though reuse has been predominantly acknowledged to be superior environmental strategy, finding out the balancing point of embodied and transport associated emissions can lead to drawing a boundary for reuse. Recent trade bans on recyclable materials across Asia and trade regulatory grey zone for reusable materials may limit future trans-national shipments. However, such a reuse radius, still provides an objective metric for reuse within mainland transportations for large distances within free economic trade zones or charity associated construction initiatives.

After developing a generalised framework for reuse distance of building components, it will be applied and tested for the case of salvaged building components from a demolition site in Singapore for their reuse radius. A real case will assess the reuse boundaries for a variety of non-structural building components such as salvaged windows, doors, wash basins, toilet bowl, etc. Analysis will help in visualising the scope of second-hand market locations and potential of sustainability contribution of otherwise discarded and waste components and products into willing communities. Such a tool will help in ensuring cross-boundary contributions of developed economies in the region and urban support for rural sustainability within national boundaries can have a scientific basis for embodied carbon savings. Based on the recommendations of Korhonen et al. (2018), this chapter will further discuss the social and economic dimensions of reuse for an effective circular economy which could contribute in sustainable development. In summary, this chapter will help visualise the geographical scope and limits of reuse.

## 7.3 Motivation

In a simple framework, this study estimates embodied carbon associated with building components by using cradle to gate emissions. As discussed in Chapter 3, building components typically are an assembly of different materials. For example, a typical window may have a metal frame, glass panel, paint, rubber for better packing, screws or rivets for assembly. Each material type will have its own weight and equivalent embodied carbon associated with it. To account for each constituent of a building component, total embodied carbon is estimated as the sum of embodied carbon in each material constituent multiplied by its respective mass.

$$EC_T = \sum_i EC \times M \tag{7.1}$$

Practically, to estimate the mass of individual material constituent of each building component, a reverse engineering route was followed. After salvaging building components from an end-of-life residential building, they were broken down to separate each material type and weighed to document accordingly. Such a practical exercise has helped in developing primary data for material mass matrix for building components. Several variations of each component have helped in developing a mass per unit area factor (in gm/$cm^2$) which can be used as a proxy in cases where access to a demolition site or salvaged building components is difficult. De Wolf et al. (2017) and Pomponi and Campos (2018) have compiled a list of various databases and methods which can be used for embodied carbon of construction materials. This study uses one such inventory, ICE:v3 (Inventory of Carbon & Energy) database, developed by Hammond and Jones (2008) and updated recently in November, 2019. Choice of this database is primarily driven by its transparency in developing the inventory and complete open access to public. Table 7.1 provides the cradle to gate embodied carbon values used in this study.

TABLE 7.1: Material specific embodied carbon based on ICE database

| **Material** | **Embodied Carbon - $kgCO_2$ eq/kg** |
|---|---|
| Iron | 2.03 |
| Aluminium | 13.06 |
| Wood | 0.49 |
| Porcelain | 1.61 |
| Rubber | 5.55 |
| Glass Double Glazing | 1.63 |
| Steel, Organic coated sheet | 3.06 |
| Stainless Steel | 4.41 |
| Glass Reinforced Plastic - Fibreglass | 8.10 |
| PVC General | 3.10 |
| Plastic General | 3.31 |
| Paint | 2.91 |

An important aspect of looking at the service of building components is their replacement or maintenance as buildings may require from time to time. Some studies assume service life in terms of years while others have developed replacement factors for building components over building lifetime. Such a practice of replacement and maintenance is affected by the component obsolescence which could be driven by functionality, aesthetics or regulatory requirements. Dixit et al. (2013) showed significant variations in assumed replacement factors within various studies for different building components which vary from 1 for structure, 8-10 for paint, 1-2 for windows and 1.3-2 for doors etc. It is notably based on the assumptions that one or the other factor may be considered based on logical reasoning. In this study, all building components have been recovered from an end-of-life building. It can then be assumed that the embodied energy of these components has served one functional life and yet these components are in functional quality to be accepted into a new building. Assigning embodied carbon for the next functional application can then be assumed as a carbon budget (CB) within which these components can be processed and transported to a new site for reuse. Hence, embodied carbon budget of a specific building component is defined as:

$$CB = \alpha \times EC_T \ where \ 0 \leq \alpha \leq 1 \tag{7.2}$$

$\alpha$ represents the efficiency of embodied carbon usage over previous service lives of a building component and $EC_T$ represents the total embodied carbon in a building component. The matrix for determining what level of initial embodied carbon of building component should be assigned for carbon budget is a subject of discussion. Even though a component has finished its service life for an end-of-life building, the component itself may not reach its functional end-of-life. If one were to reuse this building component into a newer construction, it will prevent one new building component purchase and hence will save the embodied energy for an otherwise bought building component. The embodied carbon for a new building component can be assumed to be the same as a salvaged building component from cradle to gate system boundary. It may then be justified to use the cradle to gate embodied carbon as the overall carbon budget available for processing and transport of salvaged building components to a new location for reuse.

Transport associated emissions, hence, are at the centre of the argument in this study for determining a reuse distance for specific building component against its carbon budget. This study assumes $\alpha = 0.5$ with an assumption that a salvaged building component will have at least two service life- one that was just completed and another at the building in which it will be reused. $EC_T$ can be assumed to be half at the time of salvage. This provides a carbon budget at 50% of $EC_T$ for subsequent processing and transport associated with reuse of building component. Process based embodied carbon is predominantly consumed in using electric tools such as screwdriver or laser cutter which may be used for salvaging building components. It may also be the case that these salvaged building components need to be packaged or painted which would cause addition embodied carbon which must be subtracted from a component's specific carbon budget.

$$E_{T,Max} = \alpha \times EC_T - E_p \tag{7.3}$$

Where $E_{T,Max}$ represents maximum limit of transport associated emissions for which reuse of a building component will have environmental benefits while $E_P$ represents the process associated emissions involved in salvage and post-salvage processing of building components to make it reuse-ready.

Reuse radius ($RR_{Max}$) can hence be defined based on total transport emission budget ($E_{T,Max}$) divided by transport associated emissions ($E_{T,i}$) for a specific building component i.

$$RR_{Max} = \frac{E_{T,Max}}{E_{T,i}} \tag{7.4}$$

To estimate transport associated emissions for a building component ($E_{T,i}$), to transfer it to a construction site, emission factors in the form of equivalent $kgCO_2$/tonne-km have been used. De Wolf et al. (2017) suggested transport associated emissions provided by Department for Environment, Food & Rural Affairs, UK (DEFRA, 2019) for embodied carbon transport methods. Such emission factors are available from a variety of sources and hence the choice of DEFRA is predominantly because of its match with ICE database in United Kingdom and open access availability. Table 7.2 provides the emission factors used for sea and land-based transport emission factors in this study.

TABLE 7.2: Fright transport emission factors (DEFRA, 2019)

| **Transportation Mode** | **Factor** | **Unit** |
|---|---|---|
| Road Freight Rigid- > 3.5–7.5t | 0.585 | $kgCO_2$ eq/t-km |
| Ship Freight: General cargo | 0.016 | $kgCO_2$ eq/t-km |

## 7.4 Results and discussion

As discussed in Chapter 5, various building components were salvaged from a demolition site to ascertain their reusability in building construction. Several of the building components so salvaged were broken down to individual material level to ascertain their composition by weight. A total of 19 different categories of building components have been analysed in this study for their constituent material specific weight (Fig. 7.1). Of over 350 building components recovered in the urban mining exercise, 90 windows, 78 Grills, 31 doors and several wash basins and toilet bowls have been analysed for their embodied energy and reuse radius. Figure 7.2 provides the estimated embodied carbon of each building component. As the aluminium remains one of highest embodied carbon material, its usage in windows, doors and grills have caused a significant increase in embodied energy for respective building components. On the contrary, wood components, stainless steel and iron components have lesser embodied carbon (Fig. 7.2). As discussed in methodology, this embodied energy can be used as carbon budget for specific components to be processed and transported. In this assessment, processing was assumed to be minimal and embodied energy at the first end-of-life was halved. Based on these parameters, transport associated emissions were estimated for building components from demolition site in Singapore to Kabil village in Batam, Indonesia. The transport to Kabil involves 80 Km of land transport and 50 Km of sea transport. This was accordingly used for total land and sea-based transport emissions. Results highlight that transport associated emission ($E_{T,i}$) ranged between 0.8% to 19.3% of available component specific carbon budget (CB). In absolute terms, it ranged from 0.1 kg-$CO_2$ eq. for small window to 2.15 kg-$CO_2$ eq. for toilet bowl. This is primarily governed by the weight of building component being transported. Aluminium based components had lower carbon budget used in comparison to materials such as wood where over 19% of available carbon budget was used for mere 130 km of transport. This highlights an important aspect for reuse. Not all building components can be transported to equal distances. After estimating maximum available transport emission budget ( $E_{T,Max}$), component specific reuse radius ($RR_{Max}$) was estimated. Figure 7.3 provides component specific reuse radius for land transport. Land transportation has been used as an indicative distance because of its carbon emissions being just below air freight transport options.

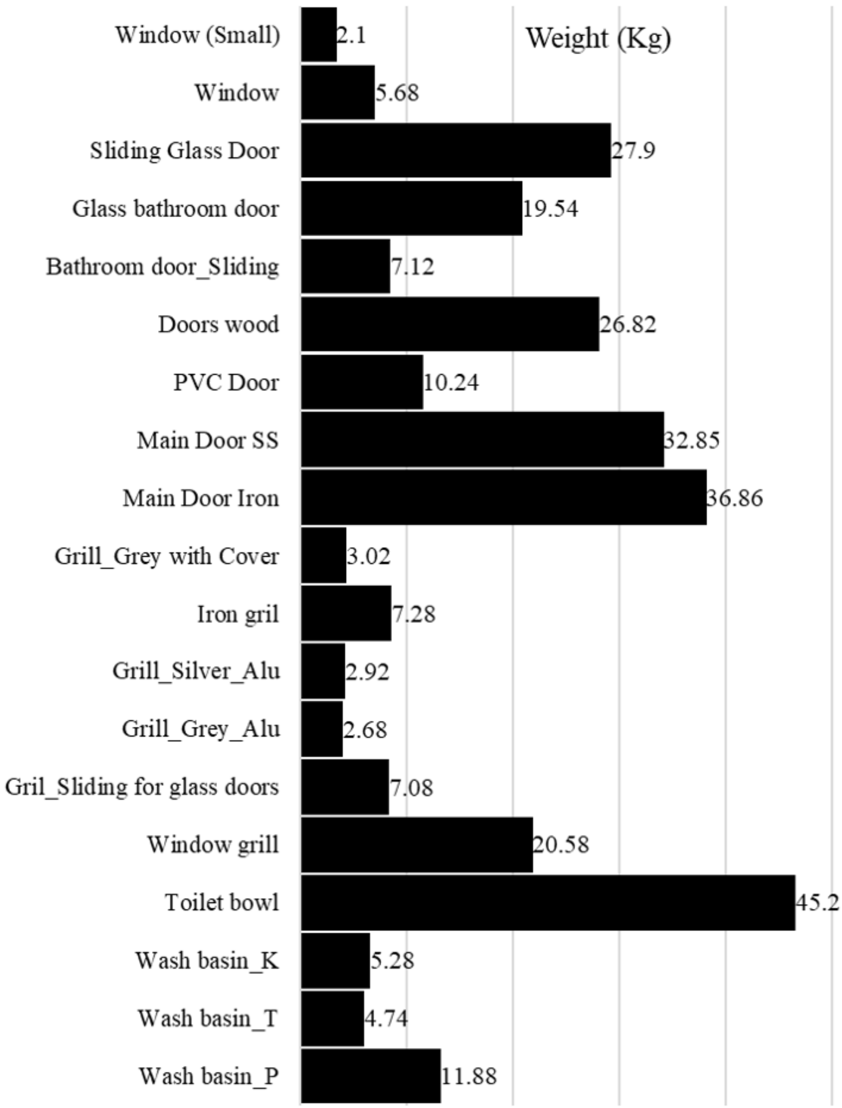



FIGURE 7.1: Weight of different building components analysed in this study

Minimal reuse radius was observed for wood doors, followed by porcelain-based wash basin and toilet bowl. However, the distances for reuse are not small such as 339 Km for wood doors and 1300 Km for porcelain-based building components. This was followed by Iron based building components in the range of 1600 Km and PVC based doors up to 2500 Km, stainless steel and glass-metal components in 3600 Km range. Aluminium based grills turned out to be highest in their reuse radius with environmental benefits expected to reach up to 11000 Km (see A.1 SI).

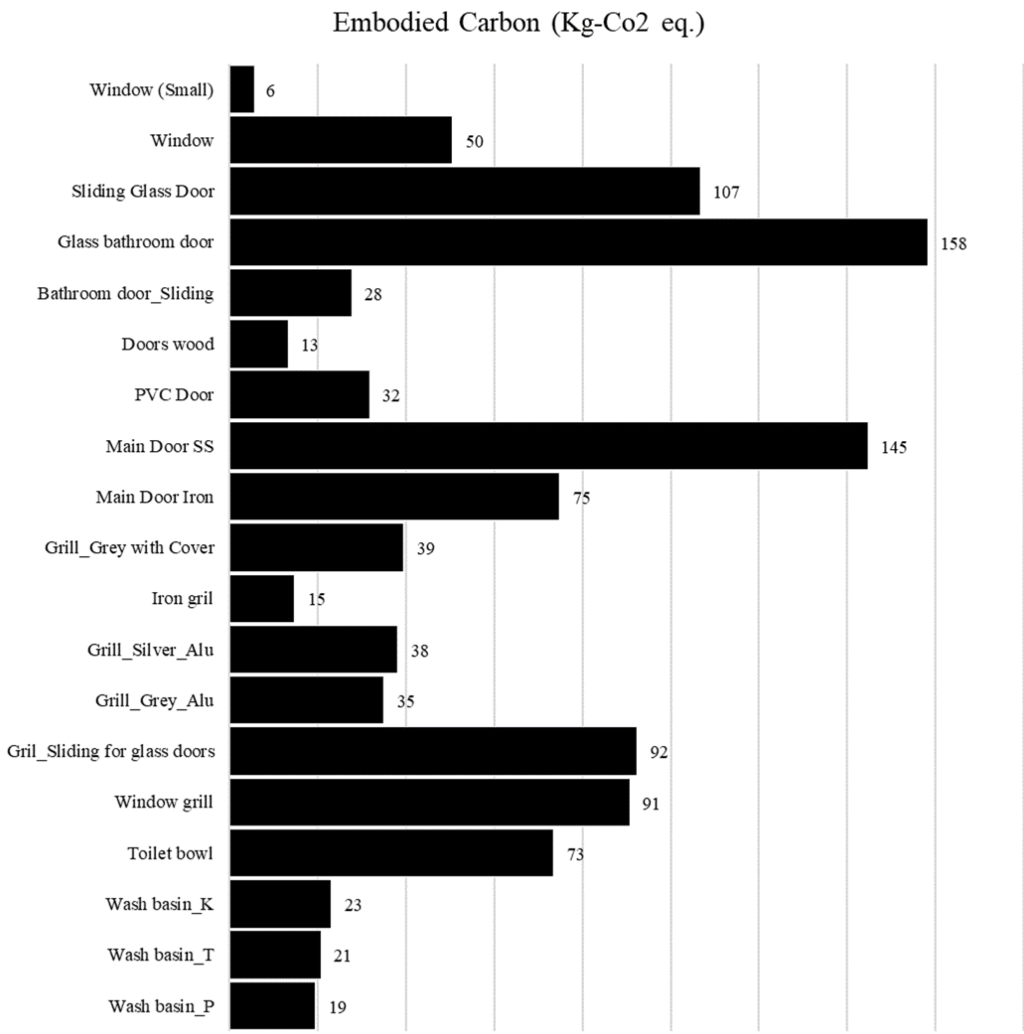



FIGURE 7.2: Embodied carbon of building components assessed in this study

This analysis leads to several discussion points in reuse associated environmental benefits. From a methodological point-of-view, it becomes crucial to see how the initial embodied carbon of a building component can be assigned for reuse associated emissions. In typical embodied energy assessment methodologies, the concept of incremental embodied energy exists predominantly for maintenance and repair (Dixit, 2019, Rauf and Crawford, 2015). However embodied energy transfer into subsequent lives of a building component require more attention in detail to promote reuse-driven circular economy. For metal recycling and subsequent metal production with scrap feed, embodied carbon values consider aspects of raw material processing and reduced energy requirements (Allwood et al., 2011). Similarly, the approach used in this study for $\alpha$=0.5 such that embodied energy is equally distributed over complete number of life cycles can be established further with more field-based studies.

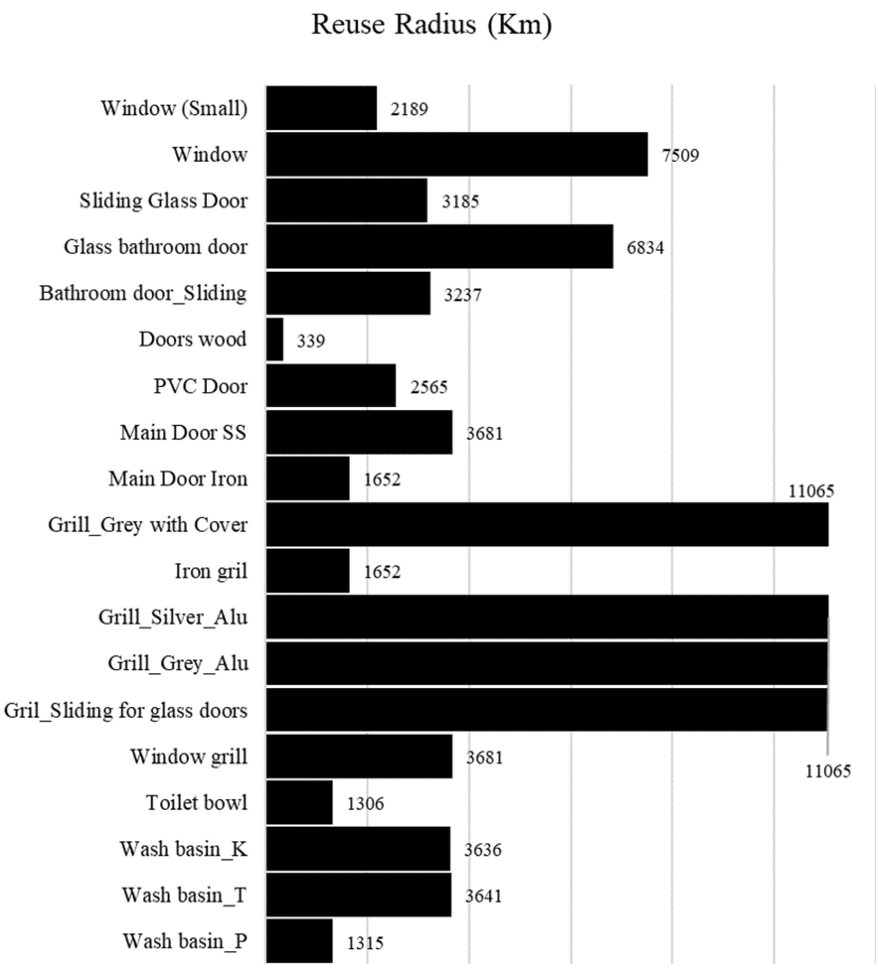



FIGURE 7.3: Maximum land transport distance for building components reuse to be environmentally beneficial

Another important aspect of this analysis hints towards payload specific disparities in transport associated emission factors. Emissions per tonne-Km assume 50% or 100% payload for vehicle or shipping container. This may not really be the case for construction project associated trips for vehicles. Sourcing of salvaged building components may not always be from same site. This may lead to few building components being transported by a single vehicle trip. Looking the size of building components, it may not be feasible to use a vehicle lesser than 15 feet in size for transporting many of the building components. On the contrary, the weight of most building components remains less than 100 Kg. In converting emission factors from per tonne-Km to per kg-km, reuse radius is significantly affected by the same factors. This suggests that the reuse radius estimated in Fig. 7.3 may serve as an upper bound transport distance which can be used as a guide for building components reuse.

Liu et al. (2015) suggested a systemic integration approach should consider all aspect of sustainability. In going beyond carbon benefits associated with reuse, it will also be important to acknowledge the economic and social drivers of reuse. Goods and products of developed economies are well accepted in global south for recycling and reuse such as textile reuse in Africa, electronics reuse in Asia (Cooper and Allwood, 2012, Cooper and Gutowski, 2017, Hoornweg et al., 2015). Financial benefits have predominantly allowed such a practice to blossom. This is predominantly because of high labour costs in developed economies and low trade tariffs in growing countries. The economic limit of reuse may often surpass the environmental limit. However, in a holistic approach for sustainability, economic costs and emission benefit needs to estimated based on the target location of reuse.

Social transport limit for reusable goods, products or building components goes beyond environmental and economic limits. This is predominantly due to over 20% global population living in underprivileged conditions. There remains a demand which has be to met at lowest costs by delivering dignified quality of reusable commodities. The overall balance between all three reuse distances remains subjective to specific building components and/or products. Although the economic and social limits were not calculated in this study, they are expected to be broader than the reuse radius (which takes only into account the environmental penalty).

An additional consideration in this work is uncertainty associated with the use of an embodied carbon dataset. The choice of the ICE database will have uncertainty in this assessment due to various factors such as production associated technology for material and building components as well as the source of energy for manufacturing to name a few. Pomponi and Campos (2018) highlighted that embodied carbon will vary based on the source of energy in a specific country and compared embodied carbon of glass in UK, based on ICE database, with that for Colombia, Peru and Chile to conclude its value is higher for UK. This however remains difficult to estimate for salvaged building components. For an end-of-life building, finding out origins of a specific building component which were probably purchased decades ago remains very challenging. The approaches such Building Information Models and use of technology to feed source information can be a realistic yet costly way forward to deal with these uncertainties.

## 7.5 Summary

This analysis affirms that reuse associated environmental benefits can be reaped even after transportation to long distances. Even though reuse has been proposed as a consistent priority to avoid production associated emissions, it is not explicitly demonstrated in previous studies. This study establishes that not all building components have equal environmental benefits when it comes to their reuse. Transport emissions play a key role in defining how far can a target market be searched for specific building components. It also opens up the boundary of reuse into countries where communities struggle to find cheaper and high-quality building components just because of its cost. On methodological aspects, a concept of component specific carbon budget for reuse can have significant implications on reuse practice. However, using generic emission factors for transport associated emissions provide an upper bound of reuse radius. This is because of the payload variation in the transport vehicle. A project specific emissions approach would provide more reliable results because this would allow the estimates based on specific vehicle-trips for exact building components instead of per tonne payload. Nonetheless, this assessment can help businesses and policy makers to consider transport distances in promoting building components reuse. With feasibility study for urban mining of building components and significant embodied carbon benefits in reuse of building components, challenges of uncertainty in design and construction process needs to be investigated. Next chapter would provide experimental proof-of-concept and prototypes of design with reuse.

# Chapter 8

# Design with reuse: Process and prototypes

## 8.1 Synopsis

This chapter attempts to critically assess the opportunity for combining design with reuse and design for reuse at the early design phase of construction, instead end-of-life of existing building. Through development of functional prototypes, this chapter highlights the possibility of reuse incorporation in modular construction with a combination of primary and secondary resources. Design with reuse have been demonstrated within two different contexts in this chapter. First, salvaged building components, from previous urban mining exercises have been used for reuse-driven low-cost self-built housing designs. Prototypes of these designs were printed using addition manufacturing methods for customer feedback. In another case, a reuse driven multi-functional pavilion was designed and constructed based on Design for Disassembly principles. These design experiments and functional prototypes demonstrate technical feasibility and market acceptance of reuse in construction. This chapter further provides steps involved in Design with Reuse for construction sector based on these experiential experiences.

## 8.2 Introduction

Previous chapters in this thesis have attempted to investigate various aspects of building components reuse in construction sector. Chapter 4 estimated the overall availability of building components in a city and annual availability. Chapter 5 assessed the feasibility of building components recovery through costs, timelines and skills. Chapter 6 estimated the overall housing potential, assuming building components can be reused in construction. Chapter 7 showcased that the reuse building components would lead to significant benefits of embodied carbon. Overall, it has been settled that both economic and environmental benefits exist for reuse. However, the practical aspect of design and construction with reuse of salvage building components, needs to be investigated. This chapter primarily focuses on developing the process and prototypes for designing with reuse of building components. This is evidently one of the crucial aspects in demolition to design approach (Fig. 8.1).

Typically, a building is designed based on architects and real estate developer's preference and then relevant materials are sourced in the desired quality and dimensions. Traditional construction and building design process differ in the planning phase from a reuse driven process. Building component reuse fundamentally reverses the practice of

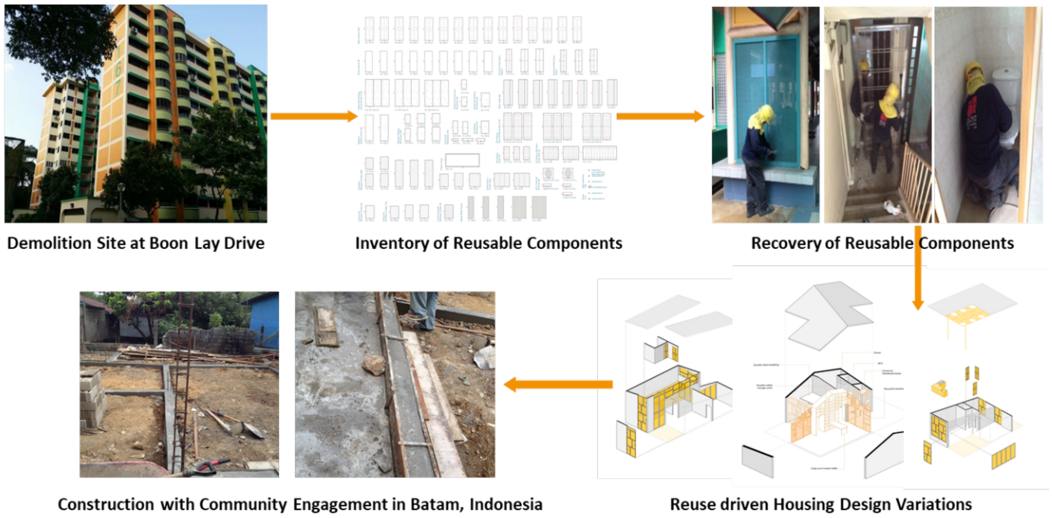



FIGURE 8.1: Implementation of demolitions to design framework for low-cost housing construction

material sourcing in construction business. In a reuse driven design, material inventory drives the designer's choices. Lack of standardized sizes of building components, such as windows and doors in existing built environments, creates an unwarranted diversity and subsequent uncertainty which is a major design challenge for their acceptance in the next phase of construction. Nonetheless, it also provides an opportunity for unique architectural innovation due to size, variability and limited components options. Limitation of design with material availability could also be a great challenge in cases where the components inventory isn't rich enough for project size. Hence, flexible designs are crucial to accommodate the size variation into unit designs and reuse-driven construction.

From design perspectives, it is important to highlight to seemingly similar yet different approach of 'Design with Reuse' and 'Design for Reuse'. Design with Reuse focuses on designing with salvaged building components, incorporating the uncertainties surrounding the size, quality, quantity and availability. Design for Reuse is an early design consideration which aims to build new product and/or buildings with an intention that part of it can be disassembled and reused at the end-of-life. This chapter primarily focuses on Designing with Reuse but will also combine the aspects of Design for Reuse in one of the prototypes developed in this study.

### 8.2.1 Existing design concepts

With increasing environmental consciousness and market pressures for product performance, traditional design processes have been transformed broadly to Design for X (DfX) approach. Design for X represents an integrated approach for designing products and processes with cost effective, high quality life cycle management (Kuo et al., 2001, Rose, 2000). At the core of these processes remains customer satisfaction and profitability while ensuring cost, reliability and environmental sustainability. Early design stage decisions on these aspects remain a key feature and advantage of DfX strategies (Kuo et al., 2001). Several product development methodologies have been developed in recent past to contribute within DfX to cater to sector and product category specific demands:

- Design for Assembly and/or disassembly
- Design for Process
- Design for Serviceability
- Design for Product Variety
- Design for Supply Chain
- Design for Environment
- Design for Product Retirement
- Design for Recyclability
- Design for End-of-Life

Design for Environment focuses on some of the key issue associated with environmental impact of productions (Telenko et al., 2016). It brings in recycling, remanufacturing, reuse and life cycle impacts into the early design phases of the product (Ramani et al., 2010a, Rose, 2000). Some of the main considerations in DfE include:

- Use of low environmental impact (clean) technologies
- Reduce product chemical emissions
- Reduce product energy consumption
- Use non-hazardous recyclable materials
- Use recyclable material and reuse components
- Design for ease of disassembly and/or assembly
- Prospects of product reuse or recycle at end-of-life

The concept of modular components has gained momentum in previous decades with applications in diverse sectors including space, automobiles, appliances, and buildings (Boothroyd, 1994, Chung et al., 2013, Kimura et al., 2001). The advantages of modularity have been described in several studies which include efficient assembly, disassembly, advantageous replacement, process efficiency, durability, time savings and most importantly reusability at the end-of-life (Bonvoisin et al., 2016, Jovane et al., 1993, Sodhi et al., 2004). This is part of a bigger shift within engineering design community towards Design for disassembly in general.

### 8.2.2 Design with Reuse in construction sector

Even though Design for Reuse is not very prevalent, Design for disassembly has been a fairly adopted approach in construction sector for process efficiency, modular off-site construction and on-site assembly (Akbarnezhad et al., 2014, Crowther, 2005, Ness et al., 2015, Rios et al., 2015, Salama, 2017). Modular construction, a DfD process of combining prefabricated modules for construction efficiency and possible end-of-life reuse, has gained acceptance in real estate sector in recent years (Addis, 2006, Rios et al., 2015, Salama, 2017). Although the end-of-life reuse of modules has been a contested argument, the off-site construction advantages for project timeline and management have typically been favored by construction industry. A major motivation, that the modularity would promote end-of-life reusability in building sector, has been hampered due to low salvage rates and/or interest. In addition, several challenges leave little to no prospects for end-of-life reuse. Tough demolition timelines, lack of stakeholder's interest and/or lack of market for re-usability all play role in making design for disassembly less successful in end-of-life reuse.

The end-of-life uncertainties for reusability are high due to several influencing factors but these can be controlled through reuse driven construction. This approach may help create a win-win scenario of waste management, resources efficiency and low carbon construction.Several challenges have previously been with identified for reuse driven construction such as information on quality, quantity, availability and sizes. Swift et al. (2015) suggested that information about quality of materials can be linked with building information systems like BIM (Building Information Model) through Radio Frequency Identification (RFID) tags as a possible strategy. McGinley (2015) specified that there is a lack of information system to support the procurement of used materials at a scale suitable for construction projects. It was also noted that current systems do not provide any surety on risk to safety, quality and delivery of material. However, Gorgolewski (2008) argued that reuse of components from old buildings can significantly reduce the life cycle environmental impact of new buildings but warned about greater uncertainty in costs, design and timely construction completion.

These challenges have been solved within this thesis by a. developing an inventory, b. urban mining and salvage of building components, c. ensuring environmental benefits, and d. finding clients and willing market. Hence, this chapter would primarily focus on developing designs and functional prototypes of reuse-driven spaces.

### 8.2.3 Low and high-end Design with Reuse

For different market segments of construction sector, this study aims to developed design alternatives and prototypes for low-cost housing and high-end multi-functional spaces. For low-cost housing, the Riau Islands region of Indonesia was chosen, both based on its proximity to Singapore and need for adequate housing. Batam island has been the fastest growing urban region in Indonesia, with consistent global attention for its urbanization pace. With more than 1.3 million population, Batam faces the challenge of meeting decent housing for all. A housing design from Batam was previously used in chapter 6 to estimate housing potential of building component outflows. This chapter presents design alternatives based on the design with reuse principle. For high-end Design with Reuse, a multi-functional space has been developed based on the requirements from a client in

Singapore. Overall, this chapter focuses on designing aesthetically superior functional spaces with reuse of salvaged building components.

## 8.3 Methodology

In this chapter, Design with Reuse principle has been used to showcase the reuse of salvaged building components in the design and construction process. Even though the prototypes cater to two different segments of market and/or client requirements, the fundamental design and construction process for a generic building or product has been used with series of iterations. However, the designs were based on context and analogy driven by local preferences. For low-cost housing, design and construction process in Batam, Indonesia was thoroughly assessed. The field research on current practices helped in developing an improved ideation for design alternatives to accommodate salvaged building components.

Similarly, requirements for a multi-functional space for students in Singapore University of Technology and Design, initiated the ideation process for high-end reuse pavilion which eventually became Casa Azul. An additional opportunity for multi-functional space became available through a client who was looking for reusable tent system for organising events in the city. Based on the requirements from client, reuse pavilion design was upgraded to include both the principles of Design with Reuse and Design for Disassembly for ease of intermittent transfer, assembly and disassembly.

Overall, a typical design and construction methodology has been used in this study which involves ideation, iteration and prototyping. Based on generic process of building design, steps included interviews with clients, development of first sketch with concept design, adjustments based on available material inventory, technical and structural assessment, initial mockup, prototypes and final construction. Initial designs were 3-D printed for prototyping and used in discussion with Habitat for Humanity, house owners and other clients for customer feedback. Digital database for material inventory helped in identifying requirements for additional material sourcing. After a consensus on final design with end-users, construction process was carried out.

## 8.4 Results and discussion

### 8.4.1 Low cost housing design alternatives

An international non-profit organization, Habitat for Humanity, was contacted for collaboration in low-cost housing designs. The organization, with offices in Singapore and Jakarta, facilitated the community conversation for exploring housing expectations of residents, local construction methods and existing bottlenecks in finding adequate low-cost building resources. Construction process, for three low-cost houses, was thoroughly documented. In addition, thee cost of building materials and their prospects for replacement by salvaged building components were assessed. Table 8.1 provides the overall cost distribution of the construction materials and reuse possibilities of urban mined components. The overall construction process in Batam was manual with one masonry supported by to semi-skilled workers. Figure 8.2 provides typical construction process and a constructed low-cost house.

TABLE 8.1: Building material costs and prospects of replacement by salvaged components

| **Material** | **Cost (IDR)** | **Cost in (SGD)** | **Reuse Prospects** |
|---|---|---|---|
| Toilet Accessories | 127000 | 12.86 | Yes |
| Ventilation | 135000 | 13.67 | Yes |
| Door Locks | 220000 | 22.28 | Yes |
| PVC Pipes | 361000 | 36.56 | Yes |
| Wire and Spikes | 454000 | 45.98 | No |
| Wood | 932000 | 94.4 | Yes |
| Window | 1000000 | 101.29 | Yes |
| Wood for Frames | 1323000 | 134 | Yes |
| Roof Spandex Sheet | 1565800 | 158.6 | Yes |
| Doors | 1885000 | 190.93 | Yes |
| Cement | 2200000 | 222.83 | No |
| Sand and Gravel | 2350000 | 238.03 | No |
| Bricks | 3120000 | 316.02 | No |
| Steel Bars | 5308000 | 537.63 | Partial |
| Total cost | 20980800 | 2125.09 | |

FIGURE 8.2: Status of housing and existing prototypes of low-cost house in Batam

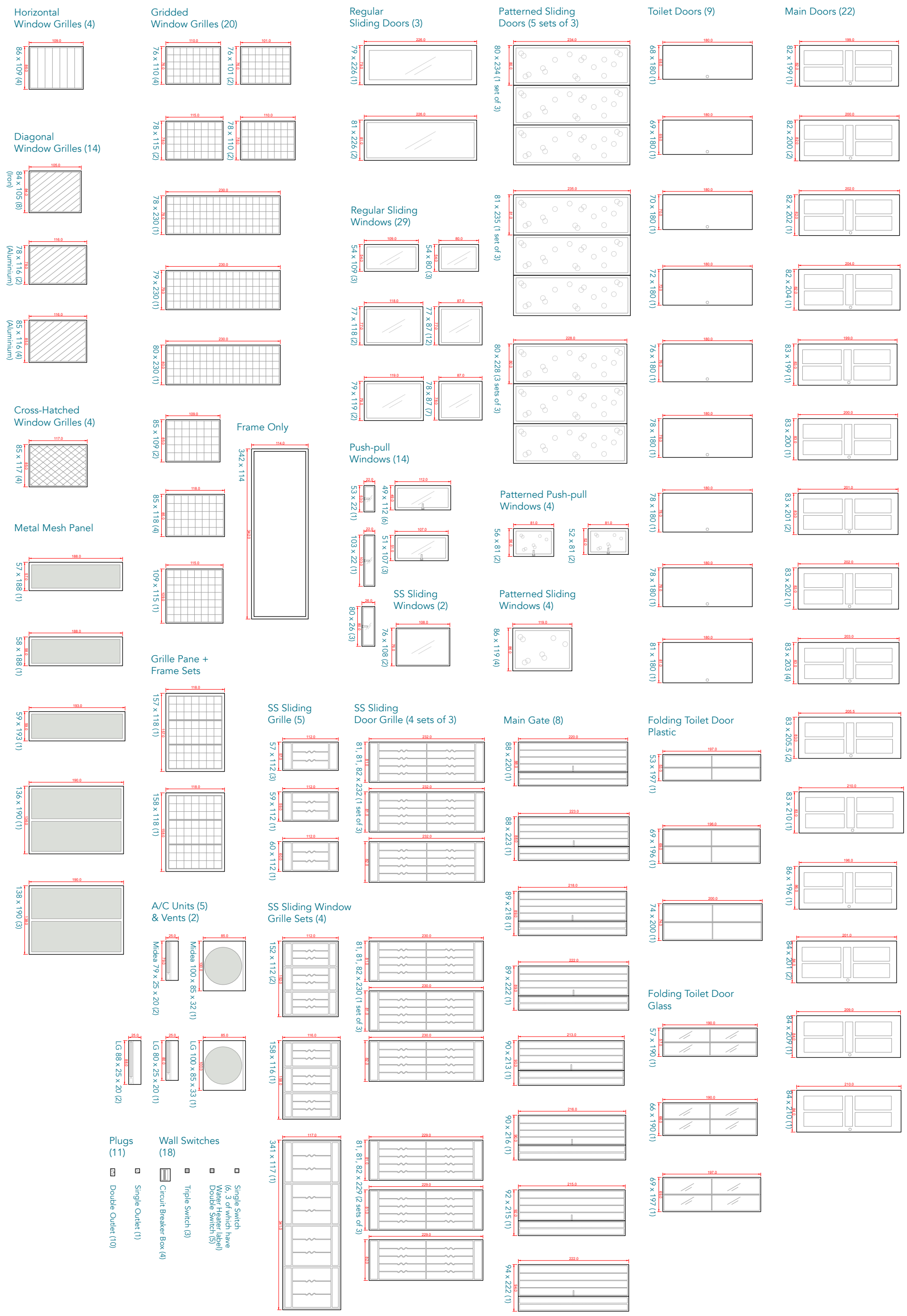



FIGURE 8.3: Digital inventory of salvaged building components

Typical cost of construction of one house is about 36 million Indonesian rupiah (IDR). This includes 20-24 million cost of building materials. Most of this cost is raised by Habitat for Humanity through donations. Starting in year 2004, approximately 1300 houses have been constructed in Batam. From construction timeline point of view, each house takes 21 days in completion. It can be sometime delayed, but the workers are paid for 21 days in total. These houses are constructed only for people who have land but can't afford the construction costs. The construction includes 2 rooms, 1 living space and a bathroom. Typical plot size in village is around 6m X 10m and hence a house is constructed with 6m X 6m built up area. With a sloping roof, maximum height at front is 3.8m and minimum height towards back is about 3.2m.

The design layouts of existing house were then used as analogy in design for reuse. A digital database was first prepared for salvaged building components for an inventory. It was further linked with component specific QR codes. This inventory contains detailed size information and hence can facilitate the design process (Fig. 8.3).

Using the digital inventory, three different design layouts were developed (Fig. 8.4). For discussions with Habitat for Humanity and house partners, 1:100 and 1:50 prototypes were constructed using poly-lactic acid based 3-D printing. Based on detailed feedback from end users, iterations were made for improvement. Finally, one of the design was shortlisted for construction in Batam (Fig. 8.5). Appendix A.2 provides detailed architectural drawings for the final low-cost house. The site for construction was selected in Batam. However, export of the salvaged building components was denied by the Batam Port Customs department over several attempts. Official request to allow reusable building material transport was made through several meetings with Indonesia's Finance and Commerce Attaché and Counsellor Minister. However, it failed. The trans-boundary movement of mid-age functional components remains in a grey zone of international export-import policies. A potential option was to establish a spin-off company which states each component's cost in an official invoice for near-new packaged shipments. An official import license holder in Indonesia would then be required, who is either an official buyer or a partner in venturing the building components' supply chain. Due to academic nature of this exercise and regulatory requirements, the actual construction in Indonesia couldn't happen. Nonetheless, these efforts confirm the feasibility of design and open avenues for its implementation in use cases.

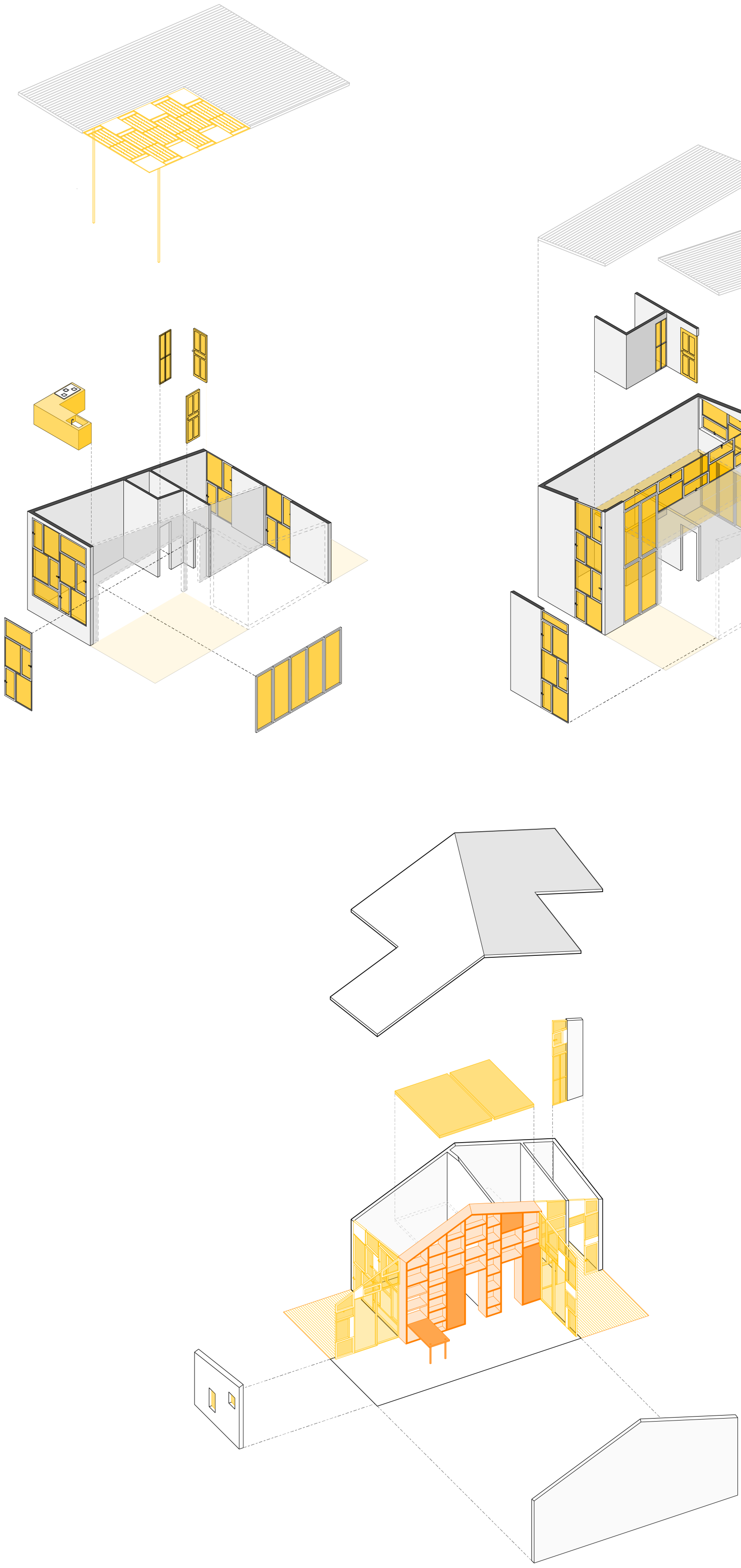


FIGURE 8.4: Design alternatives for low-cost housing

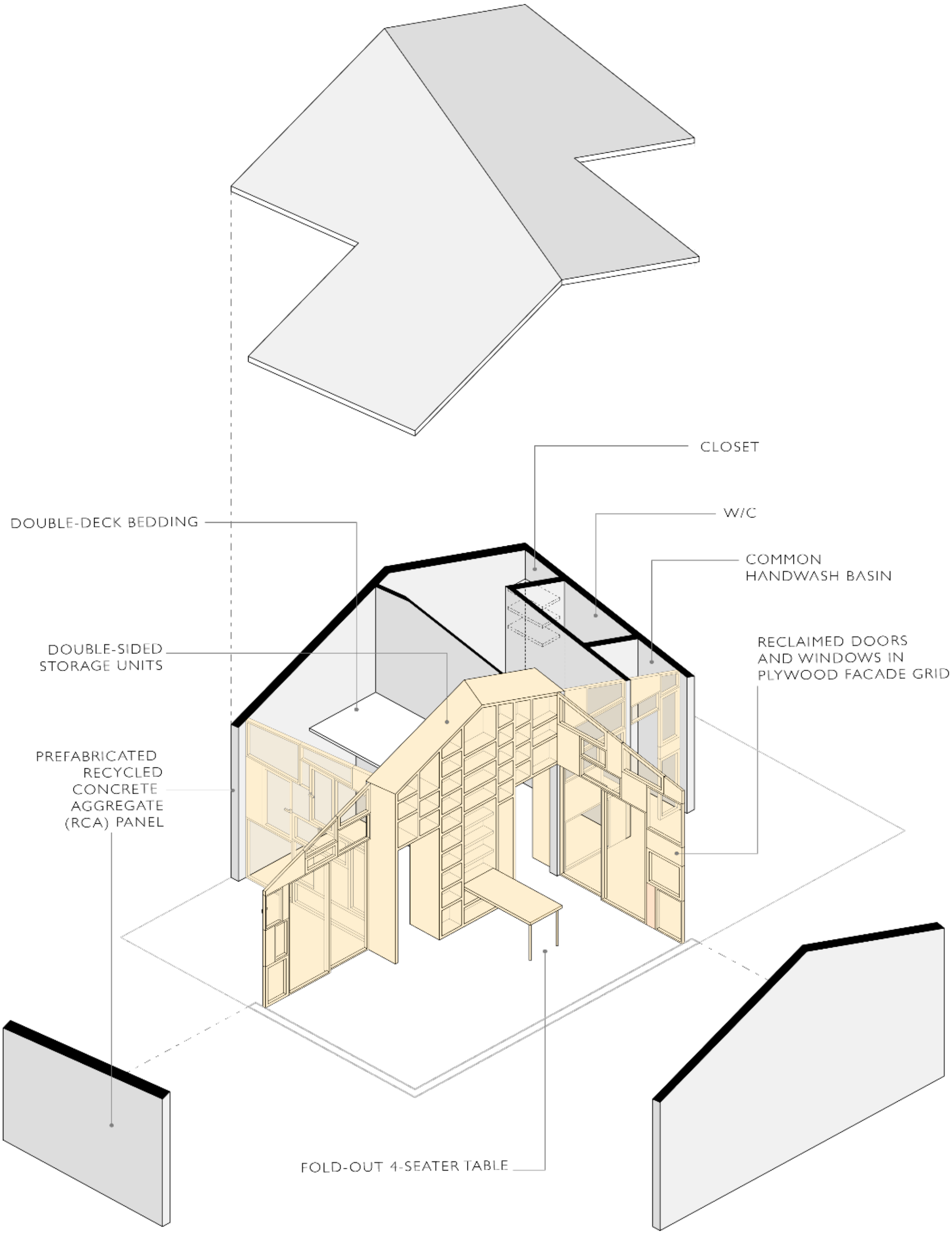



FIGURE 8.5: Selected house design for construction in Batam

### 8.4.2 Multifunctional club house design

Based on the opportunity and requirements from clients for a high-end multi-functional spaces, Design with Reuse principle was used to create urban spaces. Previously developed designs were presented to prospective clients and were further transformed from a concrete masonry type construction to an aluminum frame structural construction.

Utilizing the same salvaged materials, a new design was developed for an SUTD clubhouse, named Casa Azul (see SI A.3 for detailed design). Casa Azul is a multi-functional pavilion designed for sustainable redeployment at short-term events. The pavilion was designed with reuse and for disassembly to ensure its circularity (Fig. 8.6). Casa Azul is a testbed for quality, aesthetics and methods of utilizing salvaged building components in Singapore for high-end spaces. Stability of these designs were first tested for load wearing, shear stress and wind pressures using Karamba3D – parametric engineering software. A professional engineer was hired to attest the safety aspects of design and eventual construction. Firstly, over 100 salvaged components from demolition sites in Singapore were inventoried in a digital database and physically tagged with a unique QR code label. From a study of the database, two predominant width categories were identified: 0 to 790mm and 790 to 1095mm. Subsequently, these two fixed widths determined the sizes of the skeletal frames. Various windows were fitted within either of these widths, and leftover space was infilled with 18mm boards made from agricultural waste. Keeping two constant widths to accommodate the wide variety of window sizes allows the structure to remain modular. Its replicability ensures quick assembly carried out by semi-skilled labor. This strategy also allows the pavilion to be pre-designed and controlled, rather than requiring in-situ fitting and cutting, which may be needed for reclaimed items.

Casa Azul's main structure is composed of 30mm x 30mm aluminum T-slot extrusions, which are lightweight and highly versatile in orthogonal connections. These versatile profiles are easy to reuse, as they are assembled and disassembled with mechanical fasteners. Casa Azul's basic form resembles an archetypical house. Keeping the angles at 90 and 45 degrees enables off-the-shelf connectors to be used rather than requiring custom joints. The front elevation comprises 5 modules of planar trusses: the base is a Vierendeel truss, while the sides and pitches are parallel chord trusses. The truss webs constituted 5mm turnbuckles holding 1mm steel cables in tension.

A first mockup of the structure was assembled with involvement of undergraduate students in a workshop. Mockup with salvaged façade elements was initially developed to check the feasibility. Fully assembly was eventually carried out by students, volunteers and hired workers. The pavilion was constructed into two modules, each made of 5 flat panels (floor, two walls and two sloped roofs). Wheels were secured on the bottom face to allow easy maneuvering. With the modules on their sides, windows and opaque panels were mounted and held in place by aluminum tabs, keeping the salvaged windows and infill panels intact. Erection was a simple but exciting process: each module, assembled horizontally, was manually rotated 90 degrees about its base. Wheels that had been pre-secured onto the base allowed the whole lightweight structure to be mobile. Two such erected sandwiches were then pushed together to form the Casa Azul. An interior roof of 10mm polycarbonate is then suspended at the tip and corners of the structure's pitch. Along each of the 5 planes a 9m long LED-strip is fitted within the cavity of the extrusions, lighting up the structure with a prominent blue in the evenings.

The priorities informing Casa Azul's design are thus ordered as (1) versatility of the structure to accommodate variable sizes of salvaged windows, (2) installation without damaging salvaged material or new material, (3) modularity for simplified assembly and transport, and (4) design for final disassembly and reuse. First construction exercise took place at the Singapore University of Technology and Deign for a university open

FIGURE 8.6: Prospective designs for Casa Azul

FIGURE 8.7: Casa Azul at Singapore Design Festival and SUTD

house event. It was then disassembled and transported to city area for use during Singapore Design festival (Fig. 8.7). After several rounds of assembly and disassembly at various events, Casa Azul would be located at the Singapore University of Technology and Design.

The prototypes developed in this study were aimed to represent the theme of this thesis to link demolitions with design as represented by Figure 8.1. Even though actual construction in Batam couldn't be carried out, this chapter highlights that it is technically feasible.

Some key lessons can be summarised based on the design, prototype and construction exercises carried out in this chapter. Digital inventory of salvaged and/or available building components plays a significant role in helping the design process. It helps in identifying key size ranges and/or categories for a design to accommodate the size uncertainties. In a design layout, a designer can identify specific location or create assemblies of components to localise the size driven uncertainties in a building and/or functional space. It allows creative and aesthetic opportunities of innovation. The choice and selection still remains in the control of a designer. Consolidation and/or clustering of size and concentration of diverse colors can also be done which have great impact in dealing with these uncertainties common in salvaged components. This chapter demonstrate that it is feasible to achieve aesthetic and acceptable results. Further, making panels of building components help in ease of assembly and designing with reuse. Panels also facilitate efficient design for disassembly as has been the case of multiple assembly exercises of Casa Azul.

Consumer behaviour is at the centre of reuse and circularity. Though developing countries and often marginalised subsection readily accept reuse driven material systems, developed economies with high-end life style tend to distance themselves from old until its antique (Cooper and Gutowski, 2017, Huang et al., 2018, Huuhka et al., 2015, Jin et al., 2017, Ng and Chau, 2015). Acceptance of old building components in a newly constructed, high cost apartment remains a skeptical proposition within real estate developer's perspective. Though sustainability has taken a major leap in terms of green product acceptance within commodities, it will still need a greater motivation for reuse acceptance within the formal, high cost urban construction. In contrast, marginalized families living in poor housing conditions, prefer a better quality over a new tag. As the building components salvaged within this study remain far superior in quality due to strict building codes as well as high cost real estate origin, their acceptance hasn't faced any challenge. This showcases the importance of superior quality urban demolition products compared to low-cost new products used for self-built low-quality houses. The low-cost housing sector however remains financially dependent on public funds or non-profit organisations which require close stakeholder participation and institutional support. Overall this chapter ensures the feasibility of overall concept.

## 8.5 Summary and outlook

This chapter evaluates the feasibility of building low-cost housing using salvaged building components by investigating the complete process. The research culminates in the designs for low-cost housing prototypes and high-end multi-functional spaces. By delivering empirical information and hands-on experiences across the process of material recovery, transportation, reuse driven design and construction, this chapter provides a demonstration and lessons in Demolition to Design approach. The building materials bear a significant cost in construction. The proposed reuse approach in this chapter may provide evidence for salvaged building components to disrupt the current model of affordable housing for construction cost reduction and environmental savings.

# Chapter 9

# Conclusion and future work

This thesis focused on developing a system-wide understanding of circular economy in cities, starting with measurement methods, assessing ongoing practices and developing design interventions to improve circularity. Even though the circular economy has found a greater momentum in recent years, disruption in current practices require thorough understanding of existing context and key enablers for reform. A top-down perspective, hence, has been complimented with the bottom up perspective of data and practices. Based on monitoring the status of circular economy in a city using top-down data driven approach, it can be concluded that waste management narrative for cities do not necessarily results in higher level of circularity. Various point-of-views on circularity rates and system boundary within which policymakers find higher circular economy may not, in the end, result in lower emissions or consumption. This brings in the importance of intended outcomes and goals within circular economy narrative. If the objective of the circular economy is to reduce global carbon emissions, then reduced consumption and fossil free society can be the only absolute answers. Absolute measurements instead of comparative metrics can hence provide a better monitoring and policy priorities.

This thesis further investigated prospects of building components reuse in existing construction practices. First, it established lack of building components reuse and challenges associated with it through field research and case studies. A hybrid approach for building material and components stock and flows estimation in cities remains vital to find out the scale at which secondary resources are available. It extends the traditional material stock estimation approach to provide scale at which a city could support adequate housing deficit in a neighbouring peri-urban region. Results of this research may serve as initiating points for advanced academic research questions pertaining to reuse in general. Realisation of such a practice will not only reduce demolition waste stream but also create a market for sustainability contribution of otherwise discarded and waste building components. It may help in ensuring cross-boundary contributions within a region or urban support for rural sustainability within national boundaries. Such an attempt to transform research into practice is crucial for climate change mitigation efforts and contribution of cities towards neighbouring regions in realizing UN Sustainable Development Goals.

One of the important aspects of DRM framework used in this thesis is also to evaluate the success of support and/or solutions developed in research. The success of Prescriptive Studies have been discussed in each chapter which contributed towards solving various research objectives. Further a detailed Descriptive study II (DS-II) can be undertaken based on the results in this thesis. First assessment tool developed in this thesis relates to the status and progress of circular economy. The comparative positioning of Singapore with global and European context confirms validity of results. In terms of urban mining costs and embodied carbon benefits, results highlight that the building components salvage, and reuse has both environmental and economic savings in Singapore as well as Kabil village of Batam, Indonesia. Further, design with reuse approach for low-cost housing design and Casa Azul functional prototypes were both went through with positive customer feedback. Both designs were appreciated and accepted to be used by prospective clients and/or users. From end-user acceptance point of view, process and prototypes can be considered successful in intended objectives. However, at a city scale, this thesis attempted to bring out possibilities of reuse practice. Creating a practice in cities would require industrial disruption and/or creation of entrepreneurial ventures.

## 9.1 Upscaling and replicability of the approach

The culture and practice of reuse needs revival for dematerialization, emission reduction and resources efficiency. In the revival attempts, upscaling strategies needs to be focused within and across the cities. Sectoral specificity of reuse in housing contributes a solution which caters to multiple objectives of sustainable development and climate change mitigation efforts. Looking at the systematic approach discussed in this thesis, it is possible to replicate it across geographical boundaries as the demolition outflows and housing challenges have become as common as the rich-poor societal divide. With rapid innovation, the prospects of material passports and material bank may become a reality. Progress with building information modelling would play a crucial role in digitising the inventories and automating the building salvage process. However, this may take longer than decades, based on average building service life and adoption of digital initiatives in construction. Until then, urban mining and material efficiency efforts at the end-of-life of products and materials need local and practical approaches. This may ensure the benefits at the end-of-life of buildings and infrastructure across countries.

There has been a significant increase in the number of studies analysing material stock and flows for various geographical locations, generating insights on the scale of in-use materials and demolition waste outflows, which could provide valuable information on the scale of annual secondary resources availability. This information, along with region specific construction practices and cultural expectations, can be used to provide estimates of potential houses which can be constructed from demolition outflows. A push from real-estate developers towards prioritising reuse of building components in design and construction as well as development of building components inventories for planned demolition estates can bring greater climate benefits. Involvement of organised real estate sector remains crucial for the supply side which can be complemented with material demand within informal sector construction, creating a mutual win-win. Such an institutional arrangement can create a new model of sustenance for sustainable development. It requires multiple stakeholders and partnerships to systematically upscale a functional prototype into an acceptable urban practice of reuse in construction.

With a business case for building components reuse and the circular economy, needs for an innovative business model are imperative. An unconventional sustainability approach necessitates an innovative business model adoption (Geissdoerfer et al., 2018), which often requires consumer, market and supply factors to be clearly taken into account

(Bocken et al., 2014, 2016). It is important to highlight that several possibilities exist for an ideal financial strategy for reuse driven construction which should be specific to target consumer and geographical preferences. The focus on low-cost housing sector for reuse would benefit through public-private partnership and/or social entrepreneurial ventures in which local governments can play catalytic role. Demolitions to design approach developed in this thesis can be advanced and adapted to study other cities and potential markets. To replicate exact methodology for quantitative assessments, Supporting Information in this thesis provides spreadsheet models which can be updated with city-specific data for results. Here are some step-by-step recommendations for replicating the urban systems-level approach:

1. Develop a context specific understanding of circularity in built environment through field research.
2. Identify key stakeholders and arrange meetings to discuss potential challenges associated with circular economy.
3. Develop a hybrid material flow assessment for intended sector using a methodology developed in chapter 4. The data sources for material and component intensity can best be locally sourced to maintain robustness of estimates.
4. Collaborate with medium and small-scale companies to access site for urban mining and/or process investigation.
5. Search for a potential market which can accommodate circular flows. Design a business model. It can be a business, charity, community centre or non-government organisation.
6. Develop design alternatives to accommodate urban mining resources into identified market.
7. Identify legal and regulatory provisions and ensure that the design alternatives comply with safety standards.
8. Develop functional prototypes and start upscaling process.

## 9.2 Future work

Even though several aspects of circular economy have been evaluated in this thesis, many more questions have emerged. Some of these questions are methodological while others are specific to a city under investigation:

- This thesis started with overall material consumption and circularity with eventual focus on buildings sector. It did not specifically estimate sector specific input and output circularity rates. An important extension of this work can attempt at exploring circular economy from a sectoral point of view such as food, services, construction, energy or manufacturing etc.
- Quantitative circular economy model, developed in Chapter 2, could not estimate the scale of societal stocks. This is due to limited number of years for which the

assessment has been carried out. To estimate overall societal stock, net addition to stocks over the years can be cumulatively assessed either through top-down material flow analysis approach (Haberl et al., 2019) or with dynamic stock flow modelling approach (Wiedenhofer et al., 2019).

- Building material and components stock and flow analysis in this thesis was limited to public residential buildings. This assessment can be further advanced to include industrial, commercial and residential public-private buildings and infrastructure such as roads, railway network, airports.

- Even though reuse of building components in this study was driven by customer acceptance, there remains cultural, geographical and personal differences on what can be accepted for reuse within families or communities. A window may be easily accepted by a community for reuse in comparison to a washbasin or toilet bowl. However, this must be thoroughly investigated through ethnographic studies and conversations within potential markets for reuse.

- Building components inventory in this thesis was limited to a project level urban mining effort. In an ideal context, the supply chain development requires a comprehensive city-scale inventories with web interface. A web-based tool can thus be developed for regional sourcing of salvaged building components. This may require setting up entrepreneurial initiatives.

- Trade regulations are key in supporting the cross-boundary nature of circular economy. The efforts to construct houses in Indonesia from urban mined building components couldn't materialise in this thesis due to grey zone in regulations surrounding import-export. There is a need for comprehensive study on positioning of salvaged material and products in trade regulations. Scope of recognising reusable goods/products from typical waste driven legal frameworks may include potential markets for reuse in the global south.

- Component specific embodied carbon budget can be further extended to all possible combinations of building components. This can then be transformed into an open access web portal for estimating transport distances and embodied carbon benefits in component specific reuse.

- Within carbon tax regimes, it would be wise to estimate the abatement cost of carbon emissions within building components reuse ecosystem. Avoided emissions through reuse can be considered against landfill scenario with associated carbon price which can highlight construction industries willingness to pay under polluters pay principle.

- Reuse-driven prototypes needs to be formalised as accepted construction practice for low-cost housing and high-end spaces. This would highlight additional opportunities and long-term trade offs associated with this practice.

- An ambitious goal, however, could be to look at the overall construction demand in developing countries over next decades and compare it with projected demolition rate s in the developed economies or cities. Material consumption and GHG emission benefits of reuse can then be estimated at a country and global scale.

Comprehensively, embodied carbons savings for reuse of building components can then be linked with global carbon budget to see how reuse may contribute in curbing climate risks.

# Appendix A

# Supporting Information (SI)

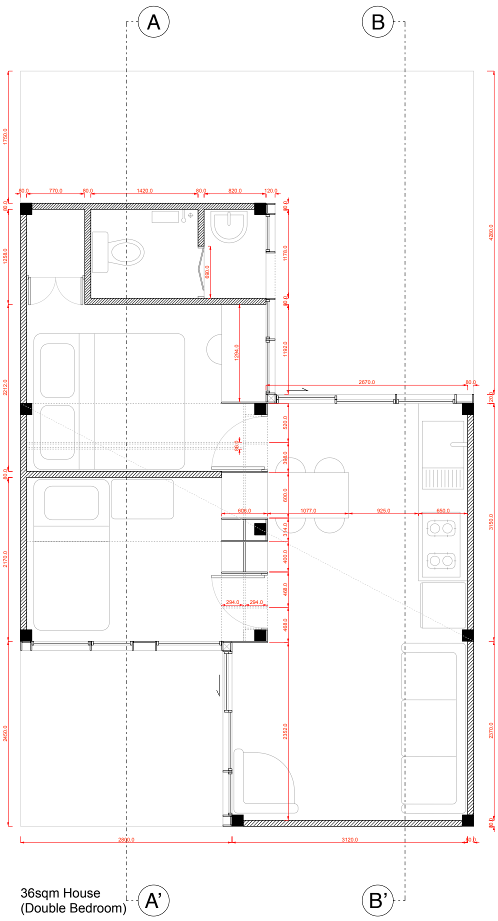
## A.1 SI

- Chapter 2- available at https://bit.ly/2P5RSyV
- Chapter 4- available at https://bit.ly/2s6UTWv
- Chapter 5- available at https://bit.ly/36mcZmp
- Chapter 6- available at https://bit.ly/350ktv2
- Chapter 7- available at https://bit.ly/2P4bao0

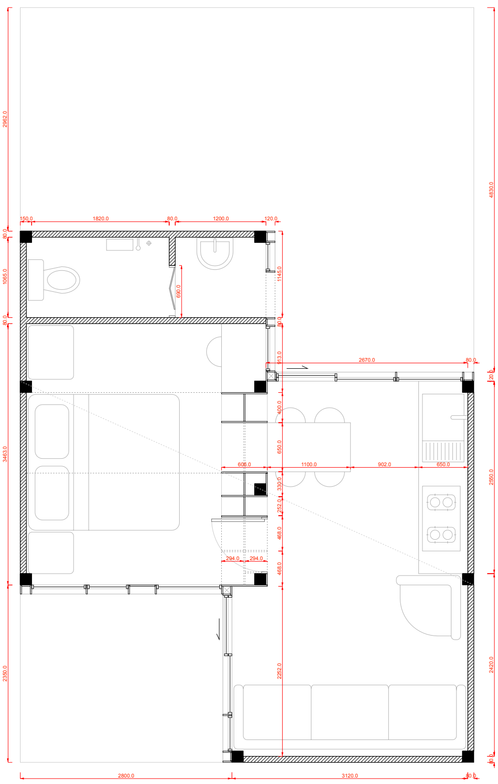
## A.2 Design drawings for low-cost house

RE-HOPE HOUSING
ARCHITECTURAL DRAWINGS LIST

| DRAWING NO. | DRAWING TITLE | SCALE | SIZE |
|---|---|---|---|
| REHOPE_001 | ARCHITECTURE FLOOR PLAN | 1:50 | A3 |
| REHOPE_002 | COLUMN & RING BEAM PLAN | 1:50 | A3 |
| REHOPE_003 | GROUND BEAM PLAN | 1:50 | A3 |
| REHOPE_004 | ROOF PLAN | 1:50 | A3 |
| REHOPE_005 | 36SQM STREET ELEVATION | 1:25 | A3 |
| REHOPE_006 | 36SQM BACK ELEVATION | 1:25 | A3 |
| REHOPE_007 | 36SQM RIGHT ELEVATION | 1:25 | A3 |
| REHOPE_008 | 36SQM LEFT ELEVATION | 1:25 | A3 |
| REHOPE_009 | SECTION AA' | 1:25 | A3 |
| REHOPE_010 | SECTION BB' | 1:25 | A3 |
| REHOPE_011 | SECTION CC' | 1:25 | A3 |
| REHOPE_012 | SECTION DD' | 1:25 | A3 |
| REHOPE_013 | 36SQM RECLAIMED FACADE ELEVATION FRONT | 1:25 | A3 |
| REHOPE_014 | 36SQM RECLAIMED FACADE ELEVATION BACK | 1:25 | A3 |
| REHOPE_015 | 30SQM RECLAIMED FACADE ELEVATION FRONT | 1:25 | A3 |
| REHOPE_016 | 30SQM RECLAIMED FACADE ELEVATION BACK | 1:25 | A3 |
| REHOPE_017 | INTERIOR SHELVES ELEVATION PERSPECTIVE | NTS | A3 |
| REHOPE_018 | INTERIOR SHELVES ELEVATION PARALLEL | 1:25 | A3 |
| REHOPE_019 | INTERIOR SHELVES ELEVATION AXO BEDROOM | NTS | A3 |
| REHOPE_020 | INTERIOR SHELVES ELEVATION AXO LIVING | NTS | A3 |
| REHOPE_021 | DETAIL SECTIONS | 1:10 | A3 |
| REHOPE_022 | RECLAIMED WINDOW INVENTORY | 1:50 | A3 |
| REHOPE_023 | 36SQM OVERALL EXPLODED AXO | NTS | A3 |
| REHOPE_024 | 30SQM OVERALL EXPLODED AXO | NTS | A3 |
| REHOPE_025 | FACADE GRID DETAIL | 1:2 | A3 |




36sqm House
(Double Bedroom)



30sqm House
(Single Bedroom)

ARCHI FLOOR PLANS
SCALE 1:50

25 75 200
10 50 100

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PROJECT

RE-HOPE PROJECT

DRAWING TITLE

ARCHITECTURE FLOORPLAN

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| Job No | |

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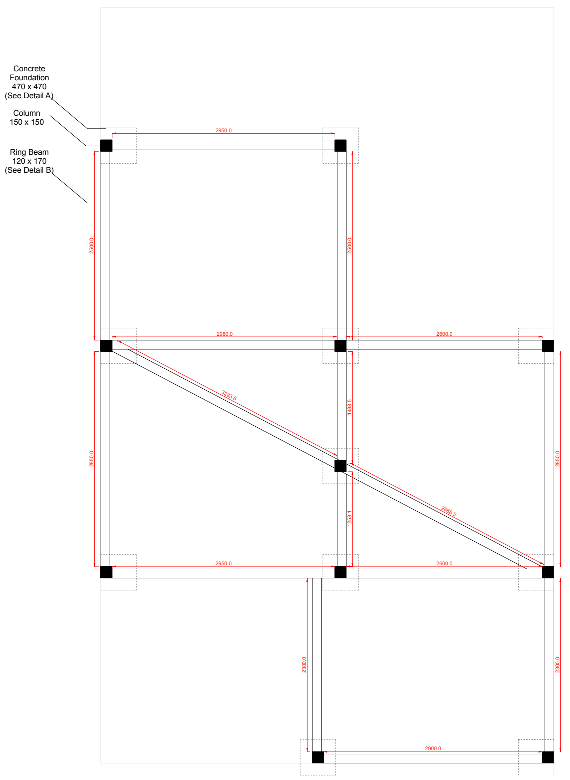
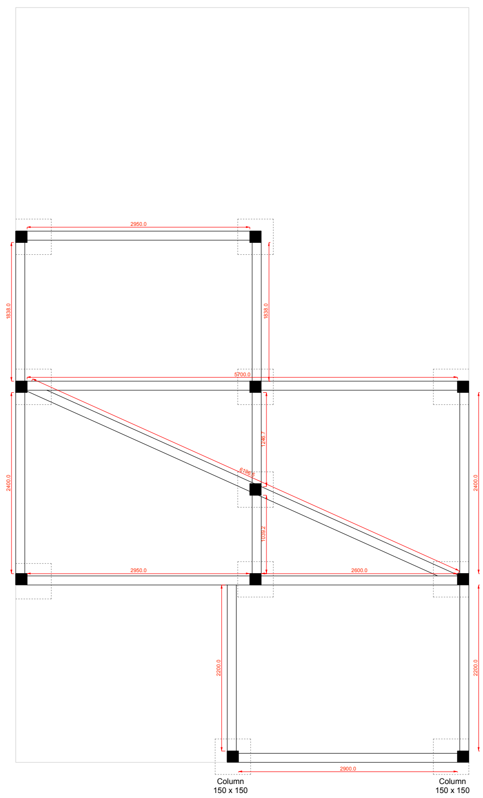



36sqm House
(Double Bedroom)




30sqm House
(Single Bedroom)

COLUMN &
RING BEAM PLAN
SCALE 1:50

25 75 200
10 50 100

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DRAWING TITLE

COLUMN &
RING BEAM PLAN

| Date | Drawing No |
|---|---|
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| Scale | |
| 1:50 @ A3 | |
| Job No | |

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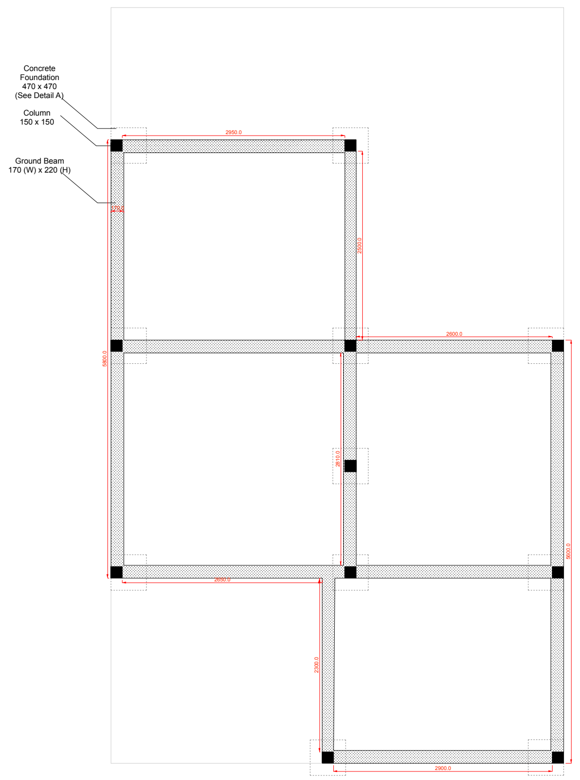
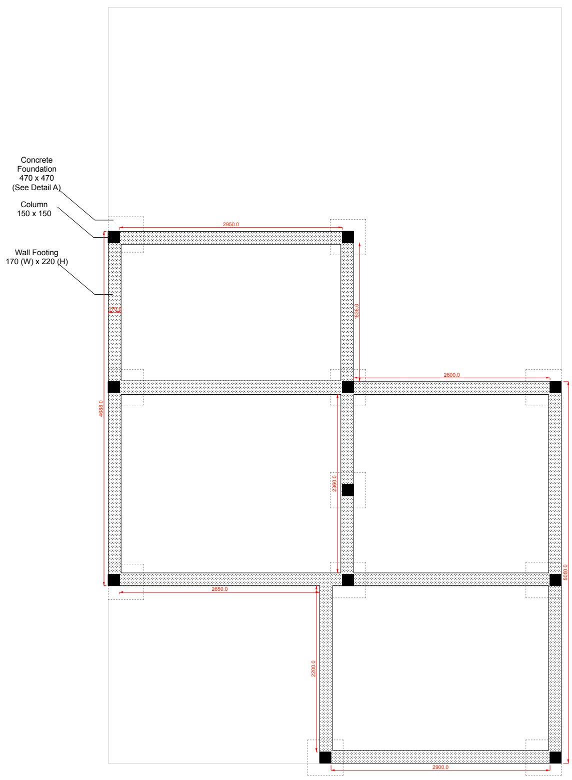
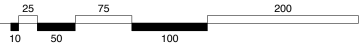



36sqm House
(Double Bedroom)




30sqm House
(Single Bedroom)

GROUND PLAN &
WALL FOOTING
SCALE 1:50





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RE-HOPE PROJECT

DRAWING TITLE

GROUND BEAM PLAN

| | |
|---|---|
| Date<br>20180424 | Drawing No |
| Scale<br>1:50 @ A3 | REHOPE-003 |
| Job No | |

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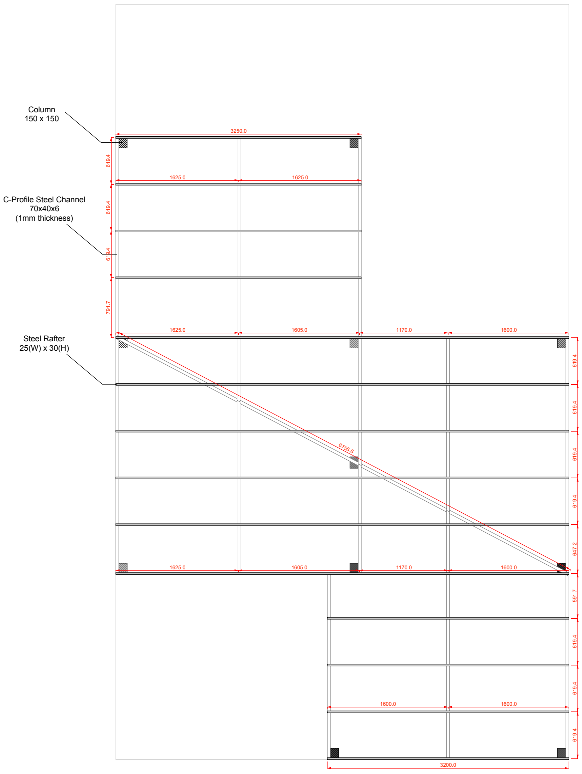
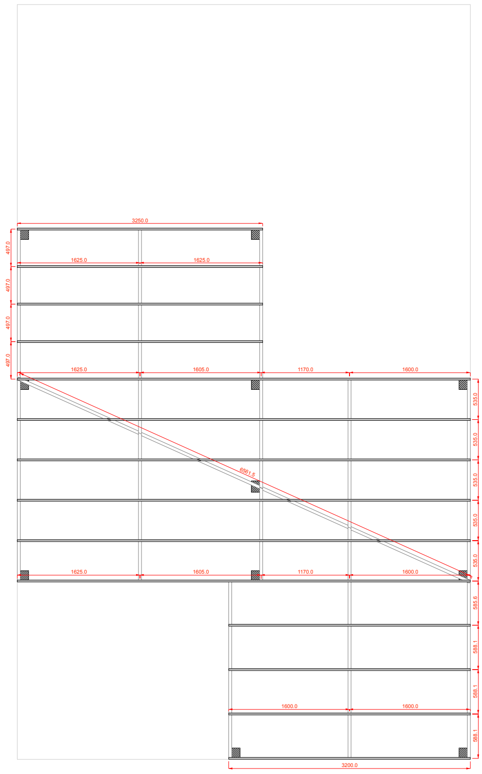
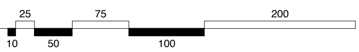



ROOF PLAN
SCALE 1:50





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DRAWING TITLE

ROOF PLAN

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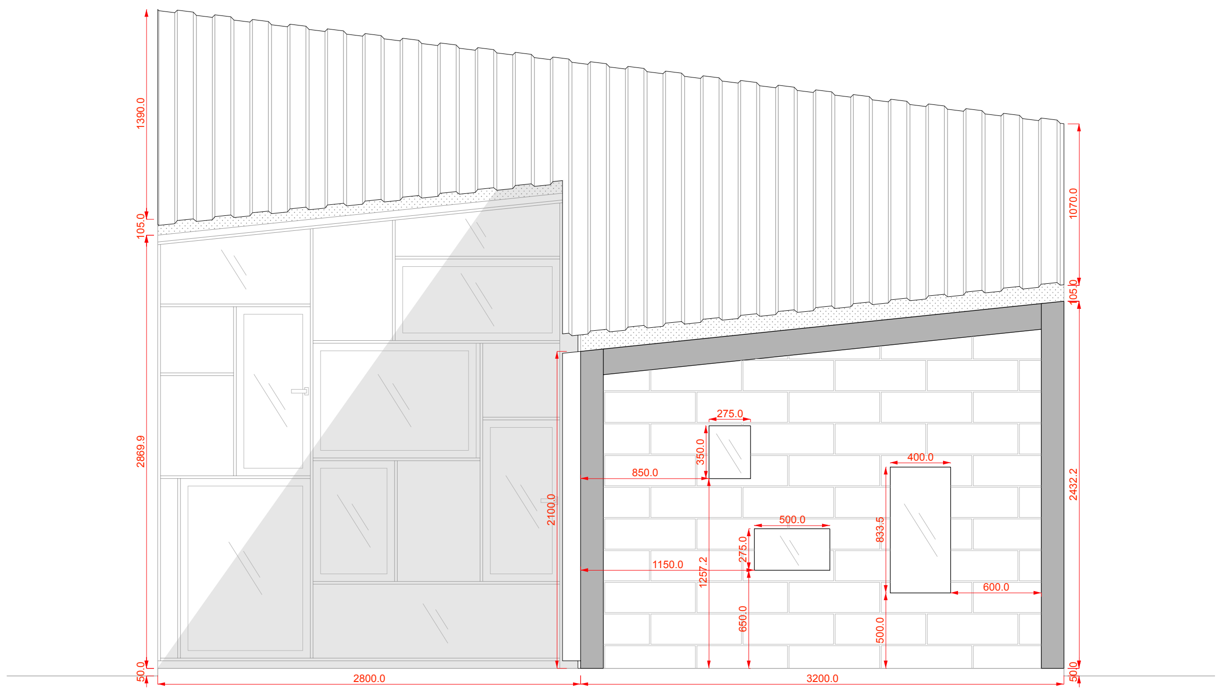


36SQM STREET ELEVATION
SCALE 1:25

250 750
100 500 1000

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DRAWING TITLE

36SQM
STREET ELEVATION

Date
20180424

Scale
1:25 @ A3

Job No

Drawing No
REHOPE-005

CAD File Name
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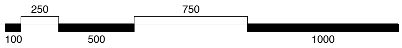
36SQM BACK ELEVATION
SCALE 1:25





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36SQM
BACK ELEVATION

| | |
|---|---|
| Date 20180424 | Drawing No REHOPE-006 |
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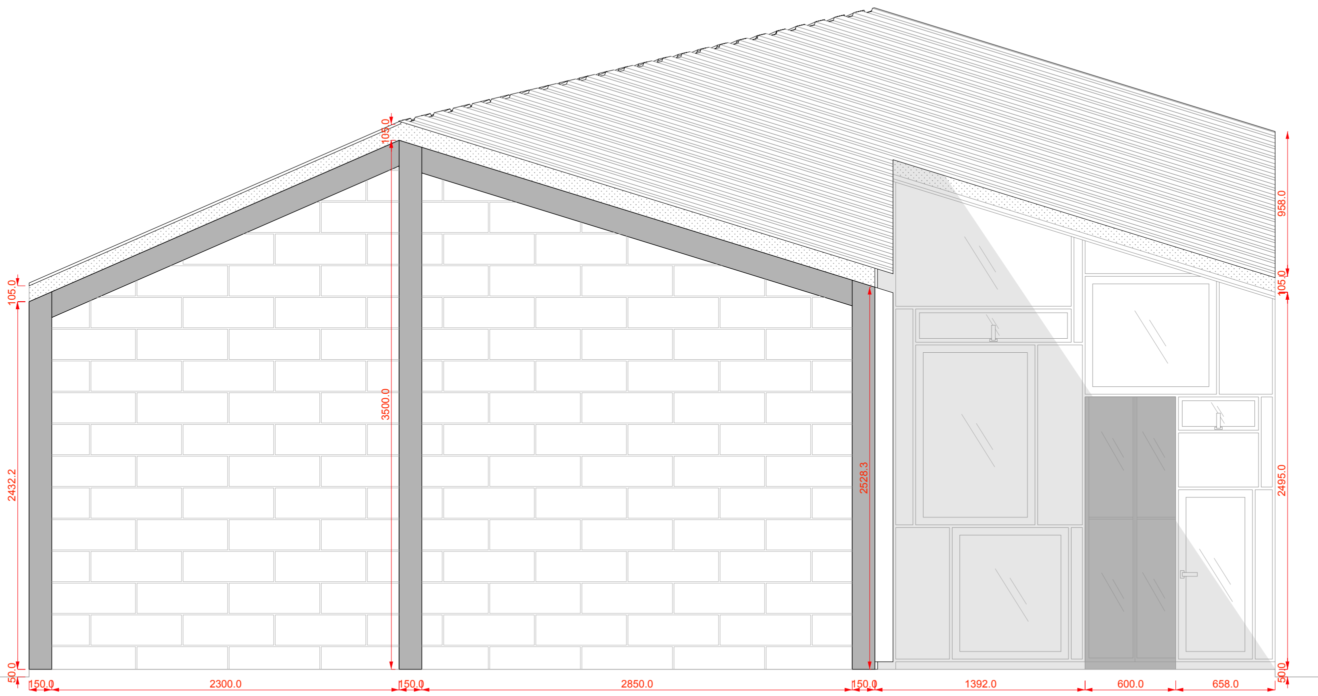


36SQM RIGHT ELEVATION
SCALE 1:25

250 750
100 500 1000

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36SQM
RIGHT ELEVATION

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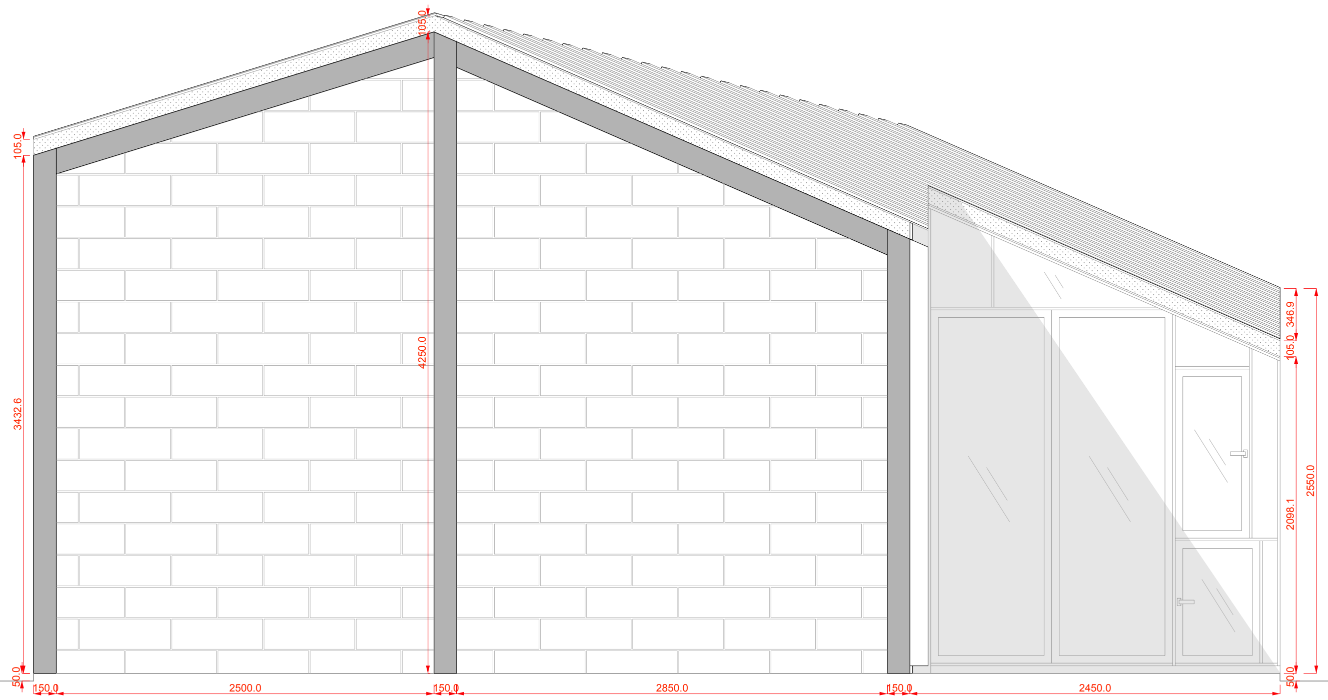
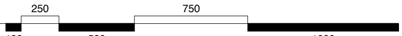



36SQM LEFT ELEVATION
SCALE 1:25





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DRAWING TITLE

36SQM
LEFT ELEVATION

| | |
|---|---|
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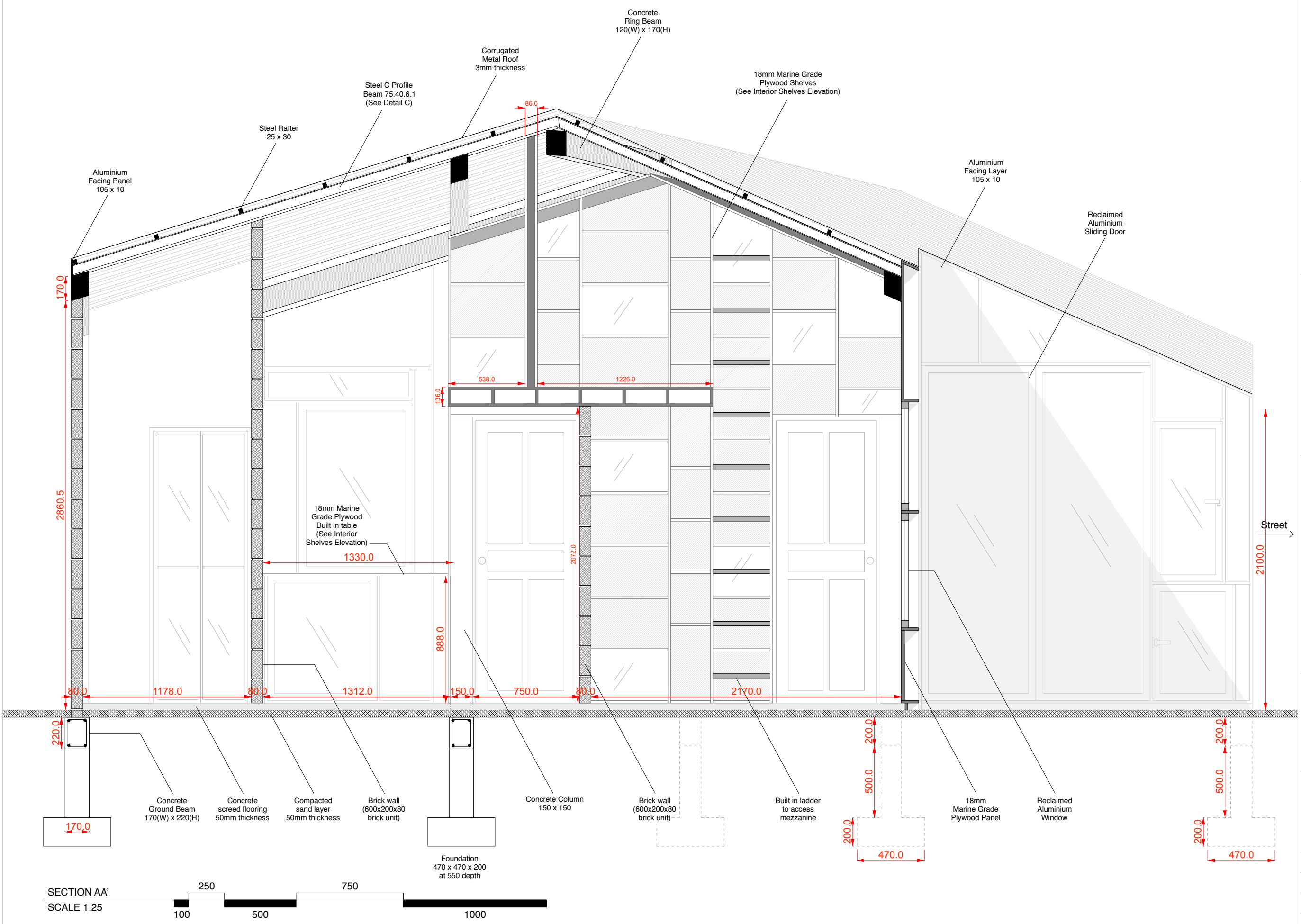



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RE-HOPE PROJECT

DRAWING TITLE

36SQM
SECTION AA'

Date: 20180424
Scale: 1:25 @ A3
Job No
Drawing No: REHOPE-009

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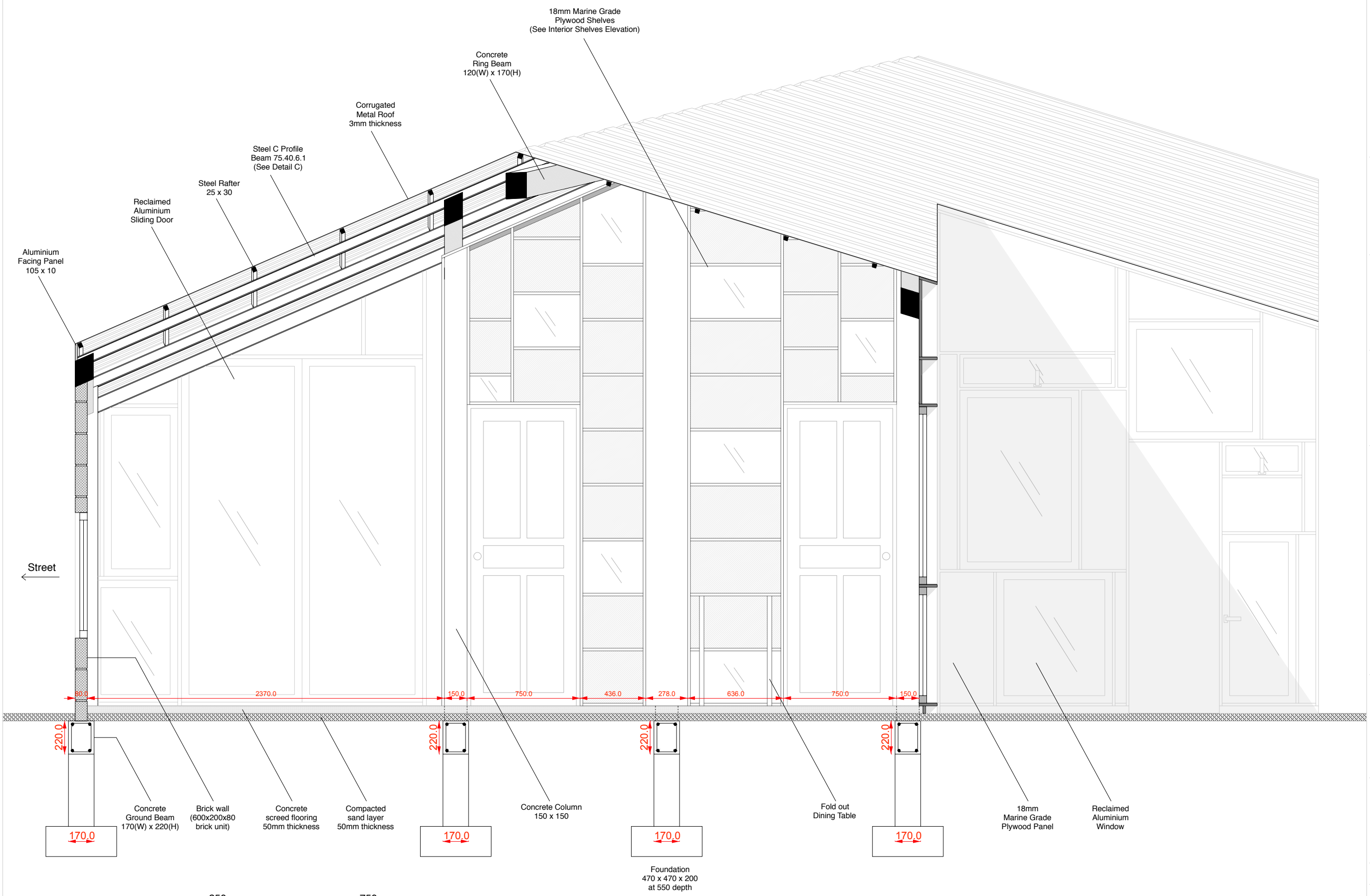
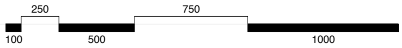



SECTION AA'
SCALE 1:25





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DRAWING TITLE

36SQM
SECTION BB'

| | |
|---|---|
| Date<br>20180424 | Drawing No<br>REHOPE-010 |
| Scale<br>1:25 @ A3 | |
| Job No | |

CAD File Name
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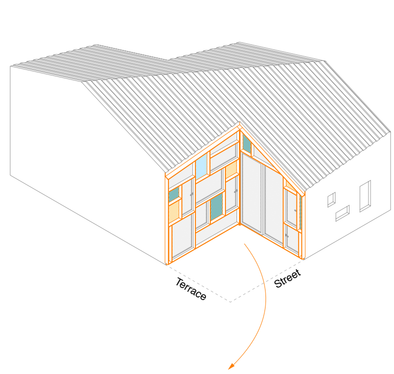
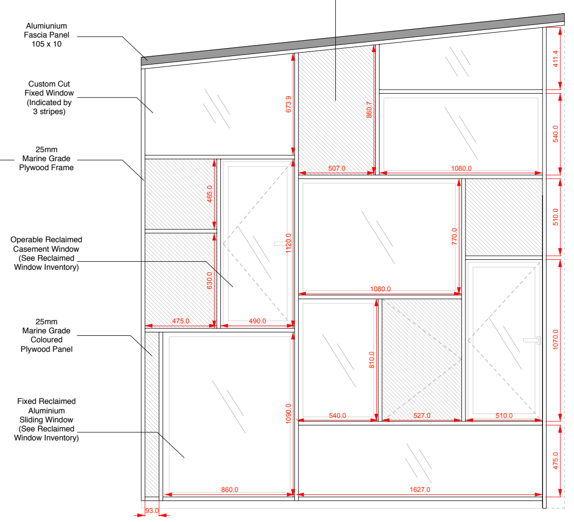
Front Facade Grid
25mm Depth x 120mm Width Marine Grade Plywood
Total Length Required = 45,521.8 mm

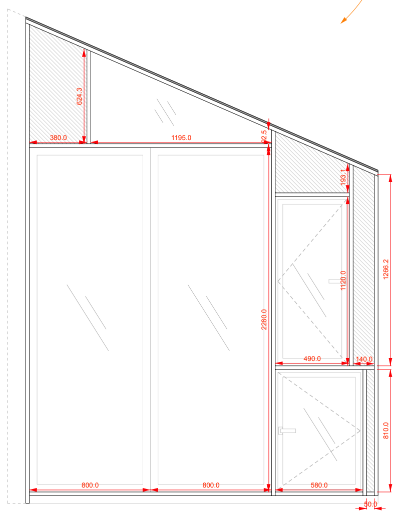
Front Plywood Panels
25mm Depth Marine Grade Plywood
Total Area Required = 2,400,295 mm2




Facing Street

Perpendicular




Facing Terrace

36SQM RECLAIMED
ELEVATION FRONT
SCALE 1:25

250 750
100 500 1000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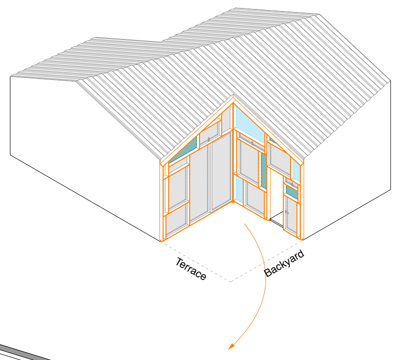
RE-HOPE PROJECT

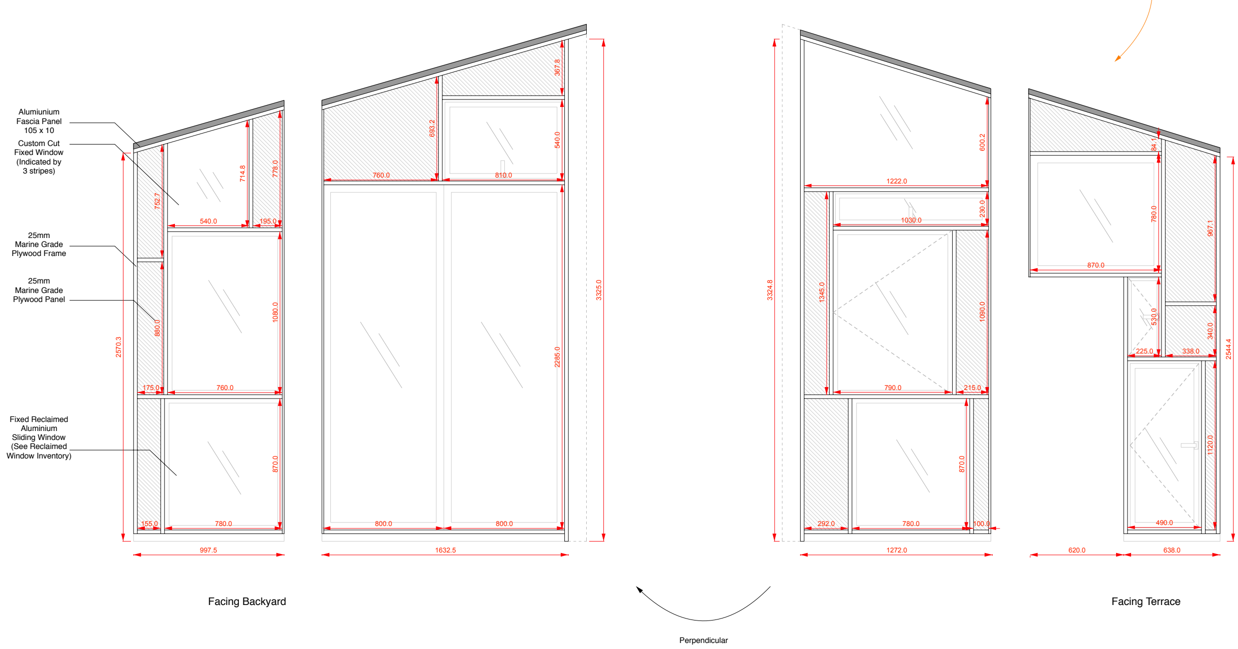
DRAWING TITLE

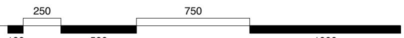
36SQM RECLAIMED FACADE ELEVATION FRONT

| Date | Drawing No |
| --- | --- |
| 20180427 | REHOPE-012 |
| Scale 1:25 @ A3 | |
| Job No | |

CAD File Name
REHOPE_180427_36sqm_RcFacadeElv_Front.dwg



36SQM RECLAIMED ELEVATION BACK
SCALE 1:25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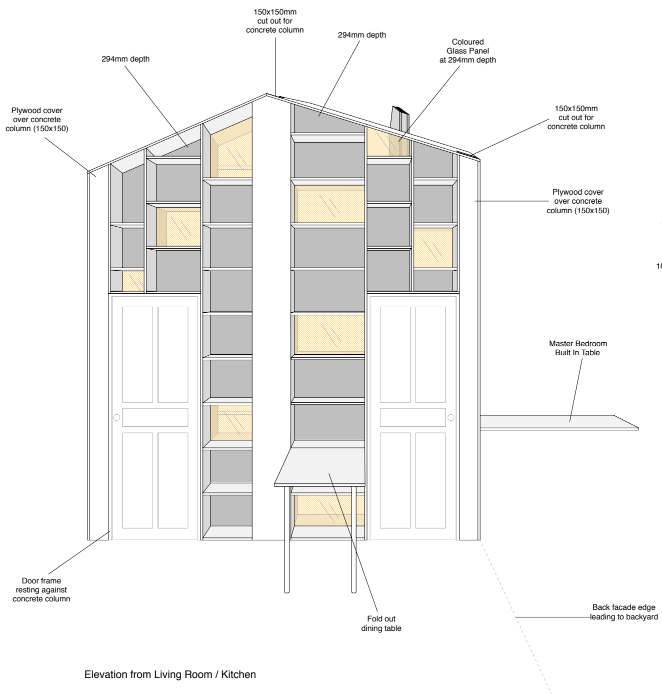
RE-HOPE PROJECT

DRAWING TITLE

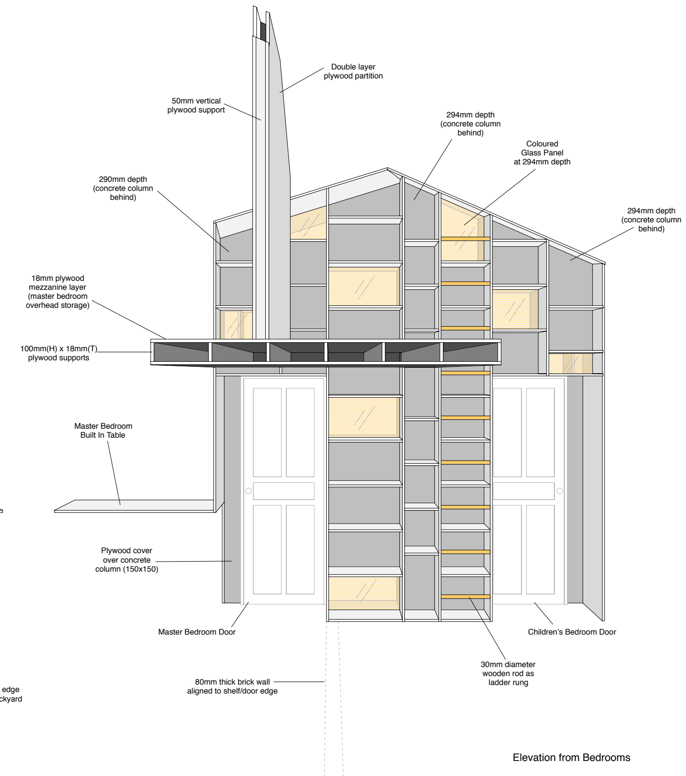
36SQM RECLAIMED FACADE ELEVATION BACK

| | |
|---|---|
| Date 20180427 | Drawing No |
| Scale 1:25 @ A3 | REHOPE-013 |
| Job No | |

CAD File Name
REHOPE_180427_36sqm_RcFacadeElv_Back.dwg




Elevation from Living Room / Kitchen




Elevation from Bedrooms

INT SHELVES ELEV PERSPECTIVE
Not to Scale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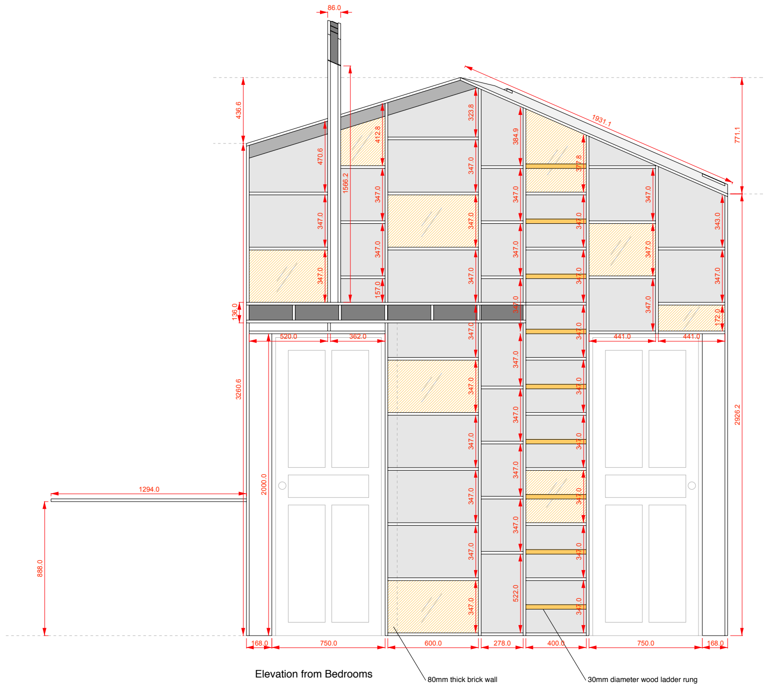
RE-HOPE PROJECT

DRAWING TITLE

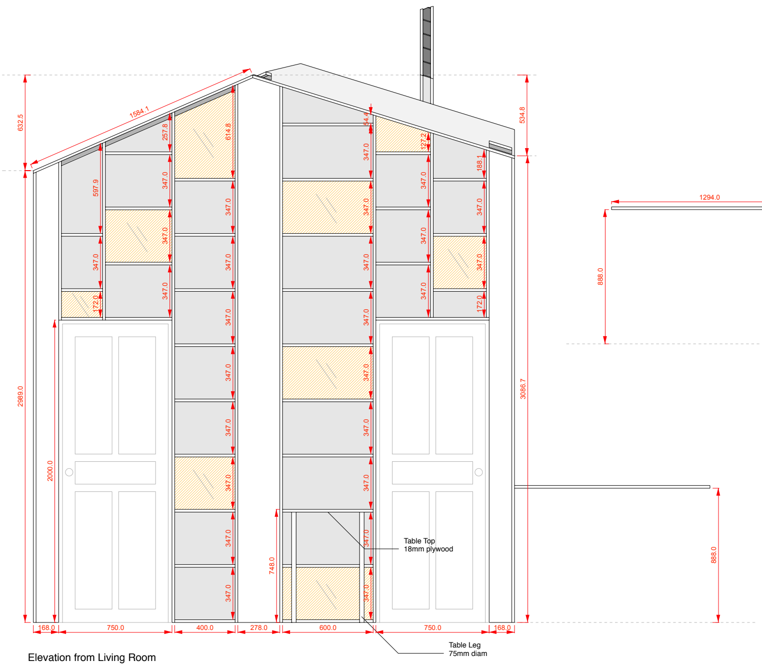
INTERIOR SHELVES ELEVATION PERSPECTIVE

| | |
|---|---|
| Date 20180424 | Drawing No REHOPE-017 |
| Scale Not to Scale | |
| Job No | |

CAD File Name
REHOPE_180424_36sqm_Int Shelves Elev Pers.dwg




Elevation from Bedrooms




Elevation from Living Room

INT SHELVES ELEV PARA
SCALE 1:25

250 750
100 500 1000

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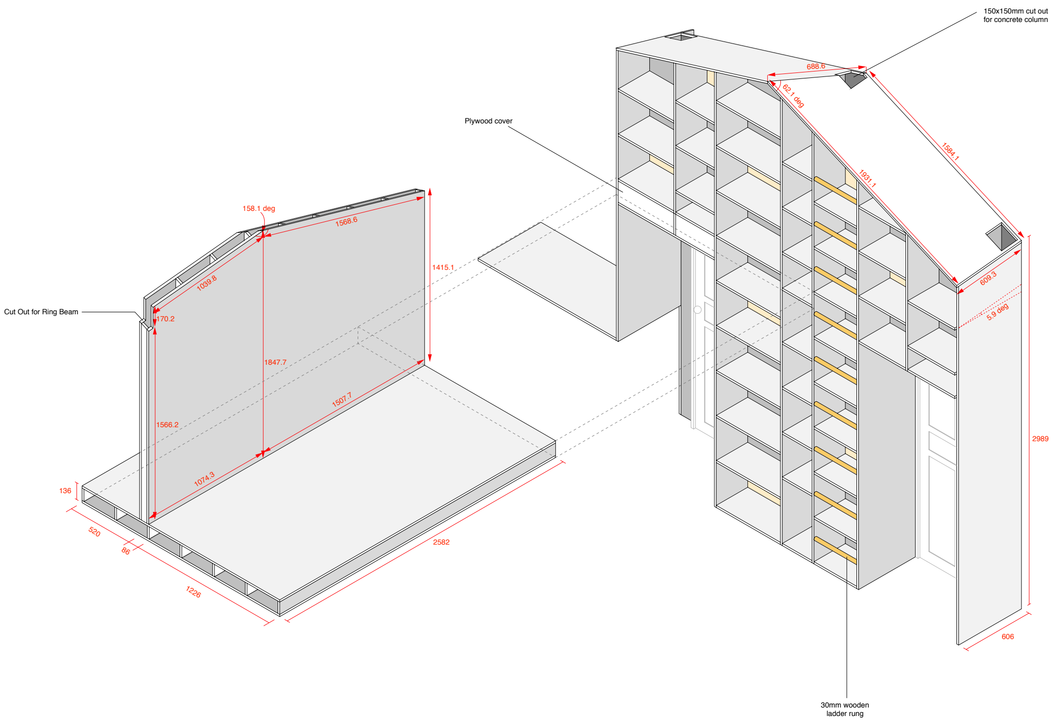
RE-HOPE PROJECT

DRAWING TITLE

INTERIOR SHELVES
ELEVATION
PARALLEL

| Date | Drawing No |
|---|---|
| 20180424 | REHOPE-018 |
| Scale 1:25 @ A3 | |
| Job No | |

CAD File Name
REHOPE_180424_36sqm_Int Shelves Elev Para.dwg




INT SHELVES
AXO FROM BEDROOMS
SCALE 1:25

250 750
100 500 1000

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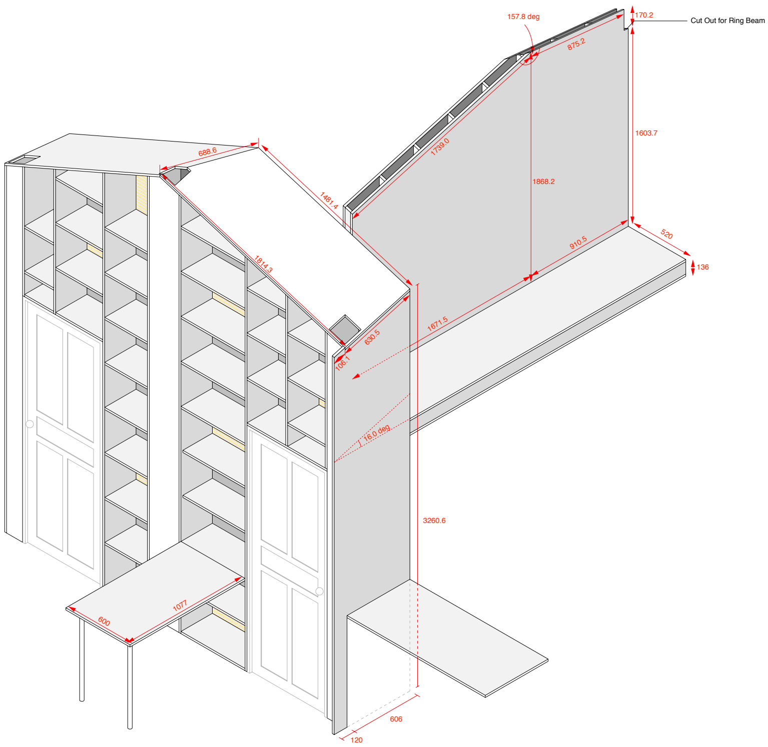
RE-HOPE PROJECT

DRAWING TITLE

INTERIOR SHELVES
AXO BEDROOMS

| Date | Drawing No |
|---|---|
| 20180424 | REHOPE-019 |
| Scale | |
| 1:25 @ A3 | |
| Job No | |

CAD File Name
REHOPE_180424_36sqm_Int Shelves Axo Bdrm.dwg




INT SHELVES
AXO FROM LIVING ROOM
SCALE 1:25

250 750
100 500 1000

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RE-HOPE PROJECT

DRAWING TITLE

INTERIOR SHELVES
AXO LIVING ROOM

Date
20180424
Scale
1:25 @ A3
Job No

Drawing No
REHOPE-020

CAD File Name
REHOPE_180424_36sqm_Int Shelves Axo Living.dwg



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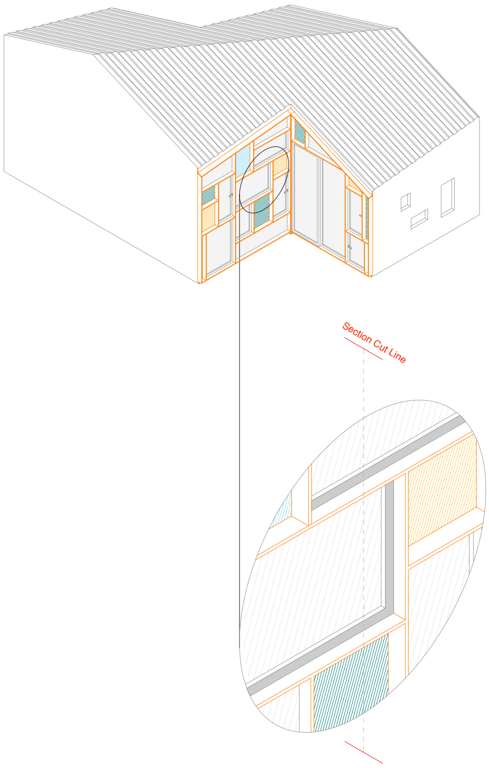
RE-HOPE PROJECT

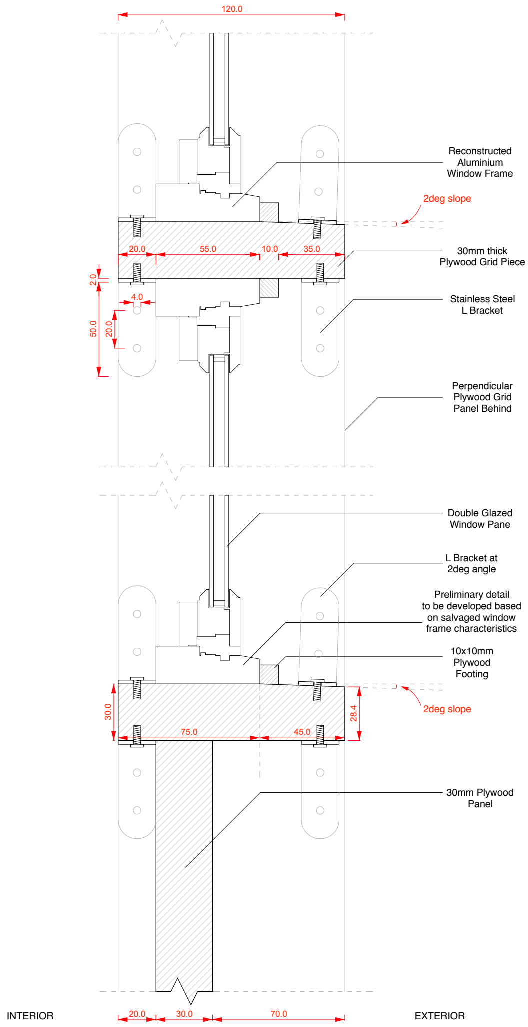
DRAWING TITLE

RECLAIMED
WINDOW INVENTORY

Date: 20180424
Scale: 1:50 @ A3
Job No
Drawing No: REHOPE-021

CAD File Name: REHOPE_20180424_Reclaimed Windows.dwg




FACADE GRID DETAIL
SCALE 1:2

12.5 37.5
10 25 50

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RE-HOPE PROJECT

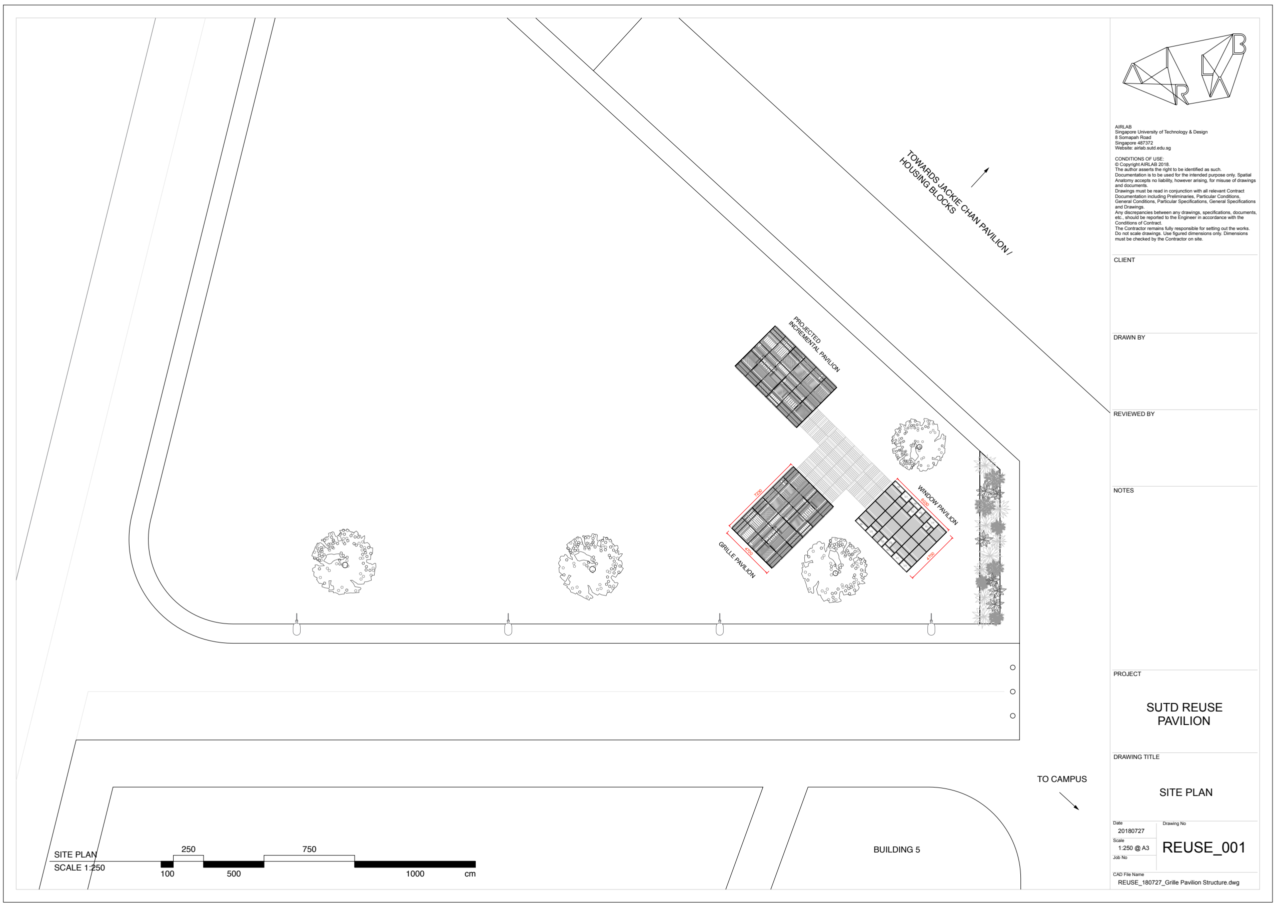
DRAWING TITLE

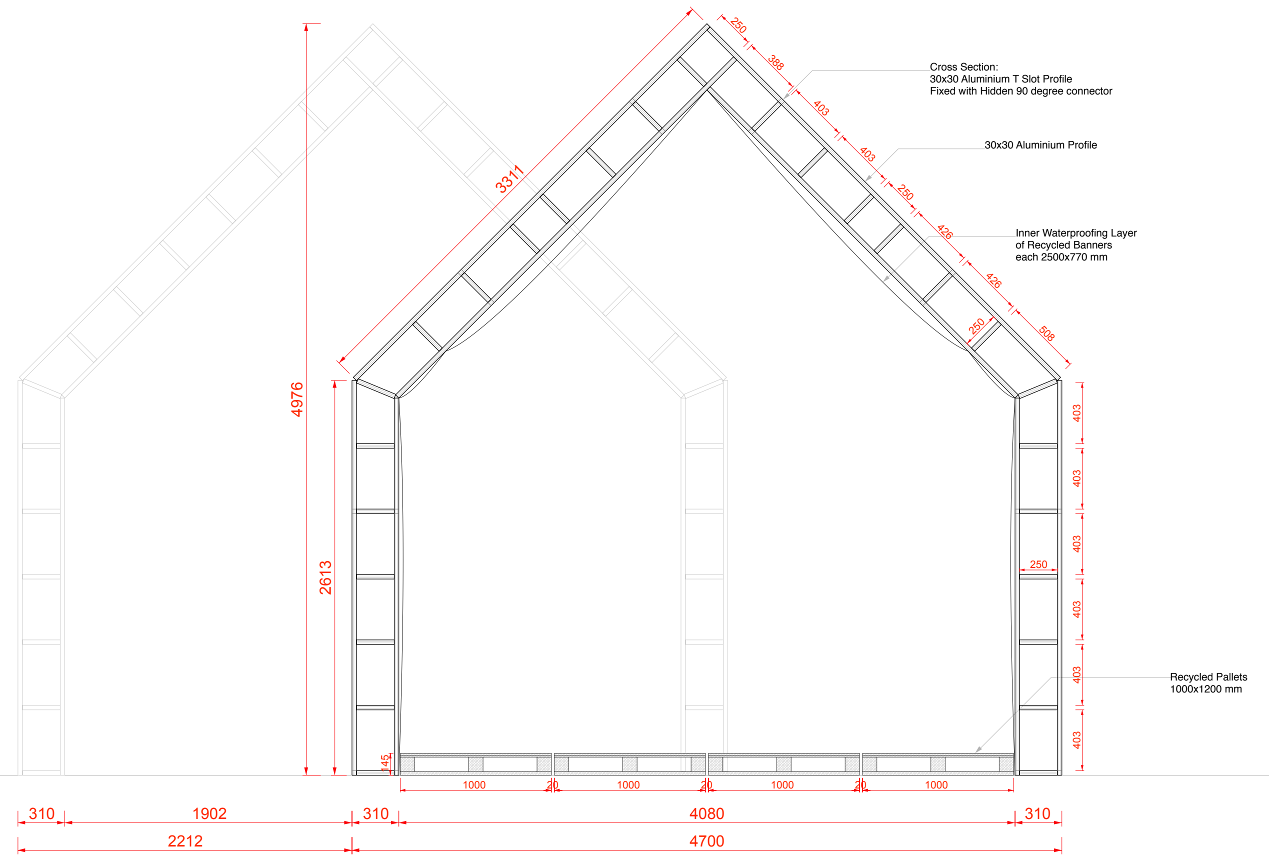
FACADE GRID DETAIL

| | |
|---|---|
| Date 20180424 | Drawing No |
| Scale 1:2 @ A3 | REHOPE-024 |
| Job No | |

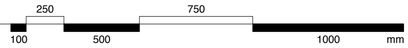
CAD File Name
REHOPE_180424_Facade Grid Detail.dwg

## A.3 Design drawings for Casa Azul






T SLOT STRUCTURE
FRONT ELEVATION
SCALE 1:25





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SUTD REUSE PAVILION

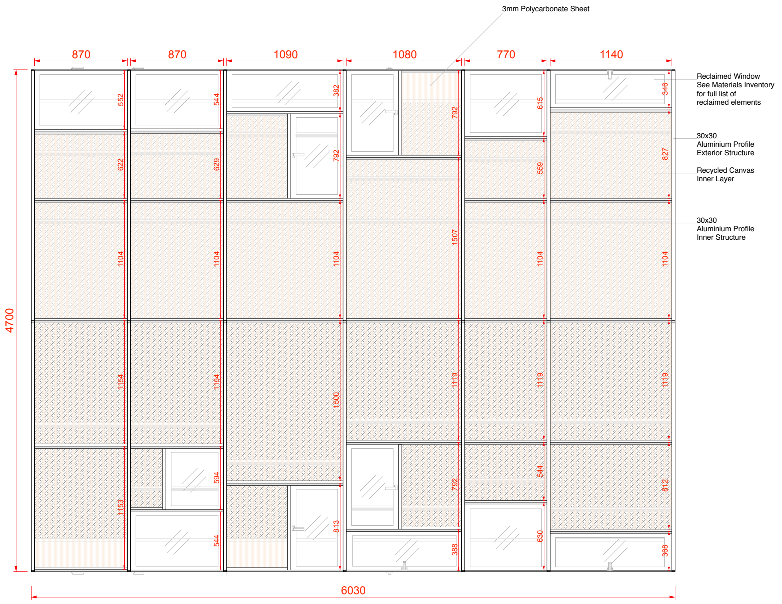
DRAWING TITLE

T-SLOT STRUCTURE
FRONT ELEVATION

Date
20180726
Scale
1:25 @ A3
Job No

Drawing No
REUSE_001

CAD File Name
REUSE_180726_Structure Front Elevation.dwg




WINDOW
PAVILION PLAN
SCALE 1:25

250 750
100 500 1000 mm

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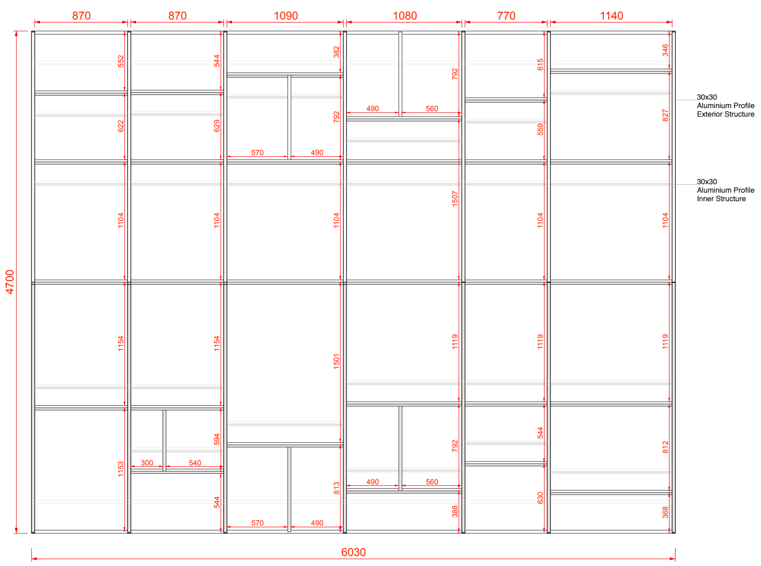
SUTD REUSE
PAVILION

DRAWING TITLE

WINDOW
PAVILION PLAN

| | |
|---|---|
| Date: 20180727 | Drawing No: REUSE_002 |
| Scale: 1:25 @ A3 | |
| Job No | |

CAD File Name
REUSE_180727_Window Pavilion Structure.dwg




WINDOW PAVILION
STRUCTURE PLAN
SCALE 1:25

250 750
100 500 1000 mm

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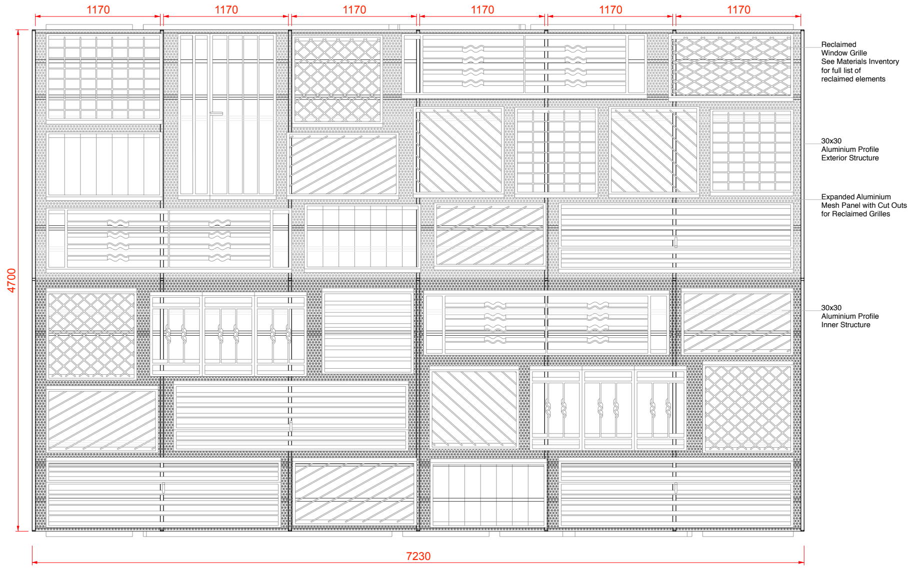
PAVILION

DRAWING TITLE

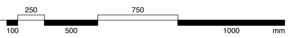
WINDOW PAVILION
STRUCTURE PLAN

| Date | Drawing No |
|---|---|
| 20180727 | REUSE_003 |
| Scale: 1:25 @ A3 | |
| Job No | |

CAD File Name
REUSE_180727_Window Pavilion Structure.dwg




GRILLE
PAVILION PLAN
SCALE 1:25

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SUTD REUSE
PAVILION

DRAWING TITLE

GRILLE
PAVILION PLAN

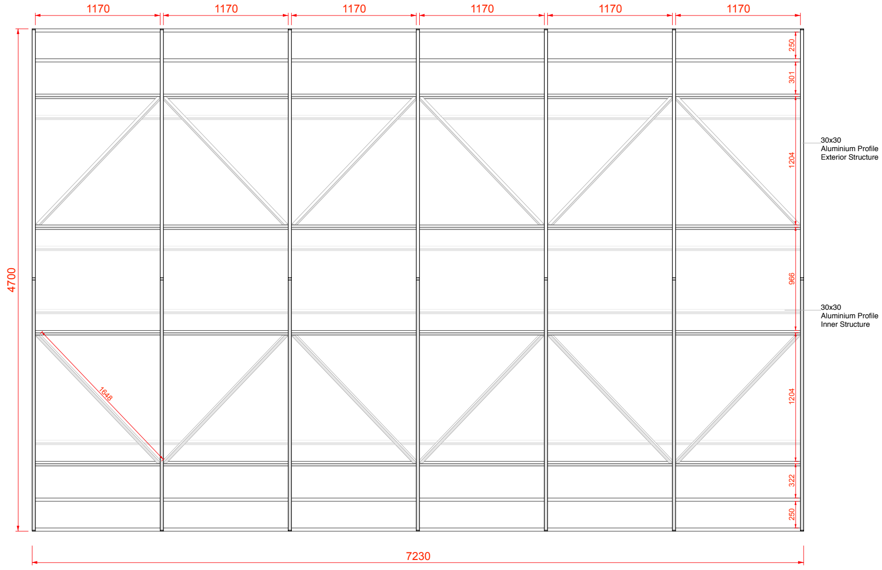
Date
20180727

Scale
1:25 @ A3

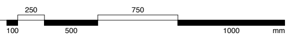
Job No

Drawing No
REUSE_004

CAD File Name
REUSE_180727_Grille Pavilion Structure.dwg




GRILLE PAVILION
STRUCTURE PLAN
SCALE 1:25

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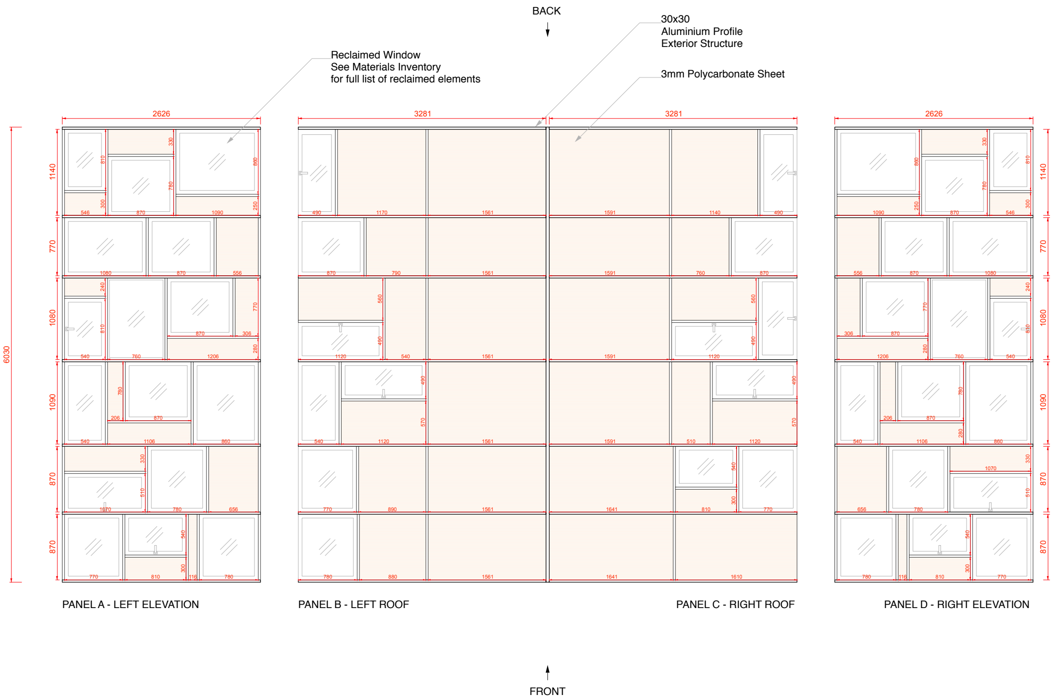
PAVILION

DRAWING TITLE

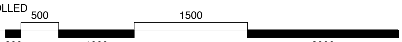
GRILLE PAVILION
STRUCTURE PLAN

| Date | Drawing No |
| --- | --- |
| 20180727 | REUSE_005 |
| Scale: 1:25 @ A3 | |
| Job No | |

CAD File Name
REUSE_180727_Grille Pavilion Structure.dwg




WINDOW PAVILION UNROLLED
MATERIAL LAYOUT
SCALE 1:50





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SUTD REUSE PAVILION

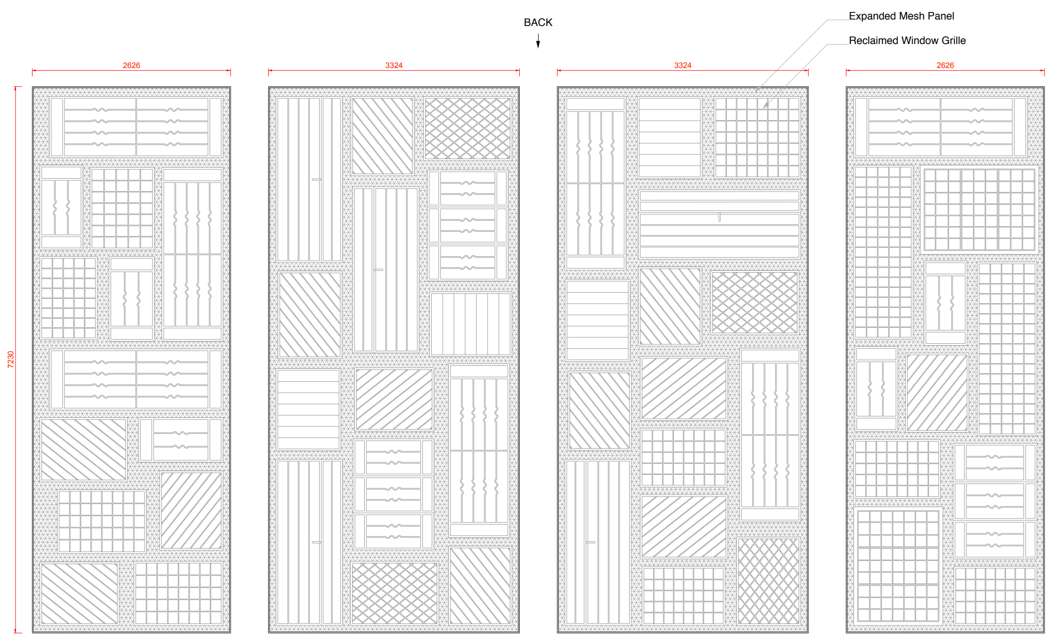
DRAWING TITLE

WINDOW PAVILION UNROLLED MATERIAL LAYOUT

| Date | Drawing No |
| --- | --- |
| 20180727 | REUSE_006 |
| Scale | |
| 1:25 @ A3 | |
| Job No | |

CAD File Name
REUSE_180727_Window Pavilion Structure.dwg

BACK




PANEL A - LEFT ELEVATION

PANEL B - LEFT ROOF

PANEL C - RIGHT ROOF

PANEL D - RIGHT ELEVATION

FRONT

GRILLE PAVILION UNROLLED
MATERIAL LAYOUT
SCALE 1:50

500 1500
200 1000 2000 mm

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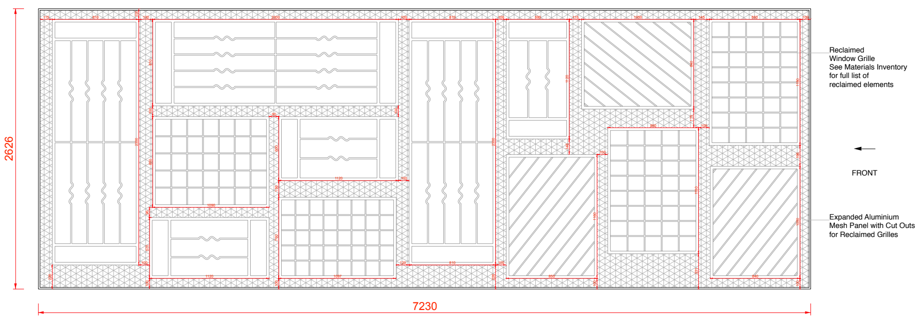
SUTD REUSE
PAVILION

DRAWING TITLE

GRILLE PAVILION
UNROLLED
MATERIAL LAYOUT

| Date | Drawing No |
|---|---|
| 20180727 | REUSE_007 |
| Scale | |
| 1:25 @ A3 | |
| Job No | |

CAD File Name
REUSE_180727_Grille Pavilion Structure.dwg




PANEL A - LEFT ELEVATION

GRILLE PAVILION
PANEL A ELEVATION
SCALE 1:25

250 750
100 500 1000 mm

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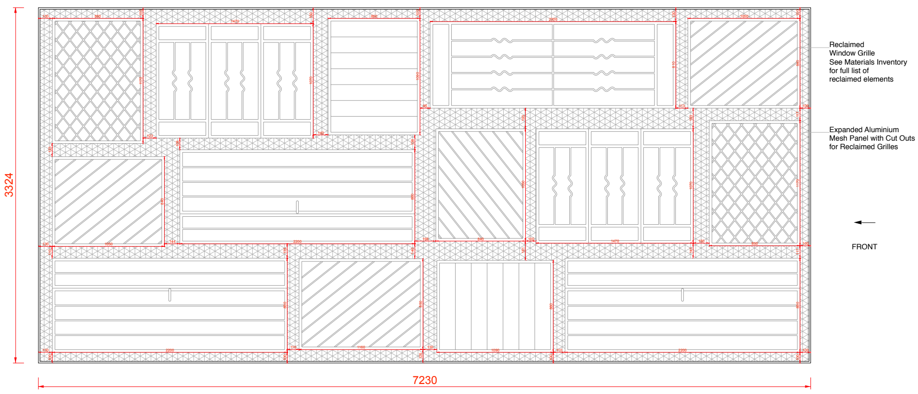
SUTD REUSE
PAVILION

DRAWING TITLE

GRILLE PAVILION
PANEL A ELEVATION

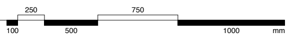
| Date | Drawing No |
| --- | --- |
| 20180727 | REUSE_008 |
| Scale: 1:25 @ A3 | |
| Job No | |

CAD File Name
REUSE_180727_Grille Pavilion Structure.dwg




PANEL B - LEFT ROOF

GRILLE PAVILION
PANEL B ELEVATION
SCALE 1:25

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PAVILION

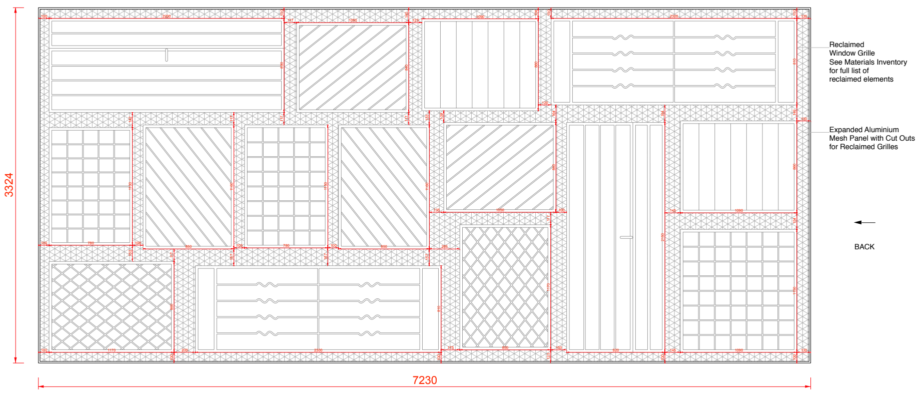
DRAWING TITLE

GRILLE PAVILION
PANEL B ELEVATION

Date
20180727
Scale
1:25 @ A3
Job No

Drawing No
REUSE_009

CAD File Name
REUSE_180727_Grille Pavilion Structure.dwg




PANEL C - RIGHT ROOF

GRILLE PAVILION
PANEL C ELEVATION
SCALE 1:25

250 750
100 500 1000 mm

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PAVILION

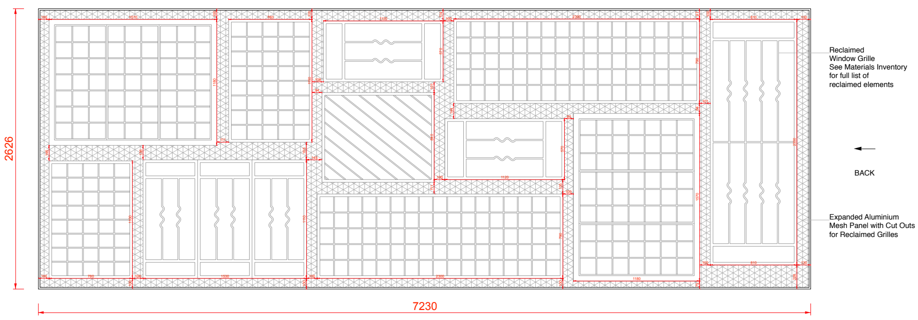
DRAWING TITLE

GRILLE PAVILION
PANEL C ELEVATION

Date
20180727
Scale
1:25 @ A3
Job No

Drawing No
REUSE_010

CAD File Name
REUSE_180727_Grille Pavilion Structure.dwg




PANEL D - RIGHT ELEVATION

GRILLE PAVILION
PANEL D ELEVATION
SCALE 1:25

250 750
100 500 1000 mm

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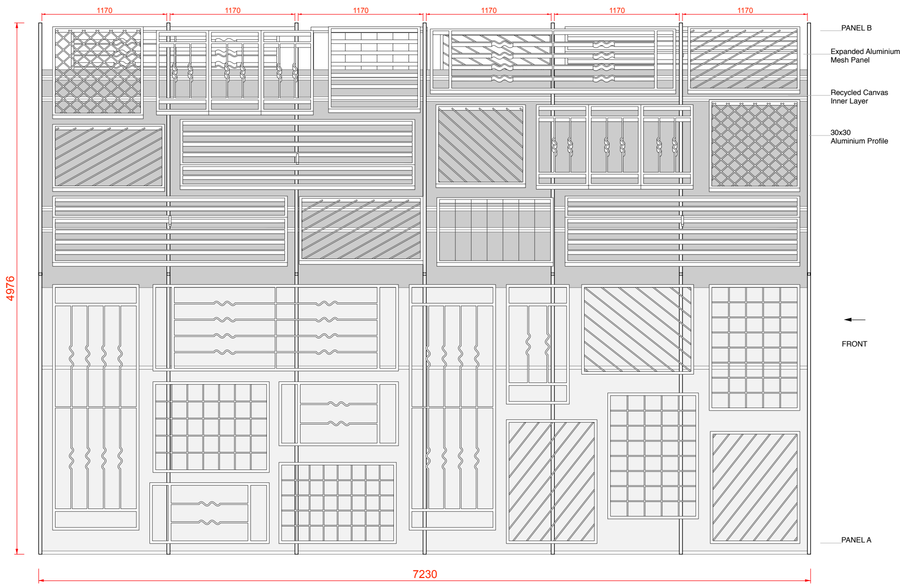
PAVILION

DRAWING TITLE

GRILLE PAVILION
PANEL D ELEVATION

| | |
|---|---|
| Date 20180727 | Drawing No REUSE_011 |
| Scale 1:25 @ A3 | |
| Job No | |

CAD File Name
REUSE_180727_Grille Pavilion Structure.dwg




GRILLE PAVILION
LEFT ELEVATION
SCALE 1:25

250 750
100 500 1000 mm

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PAVILION

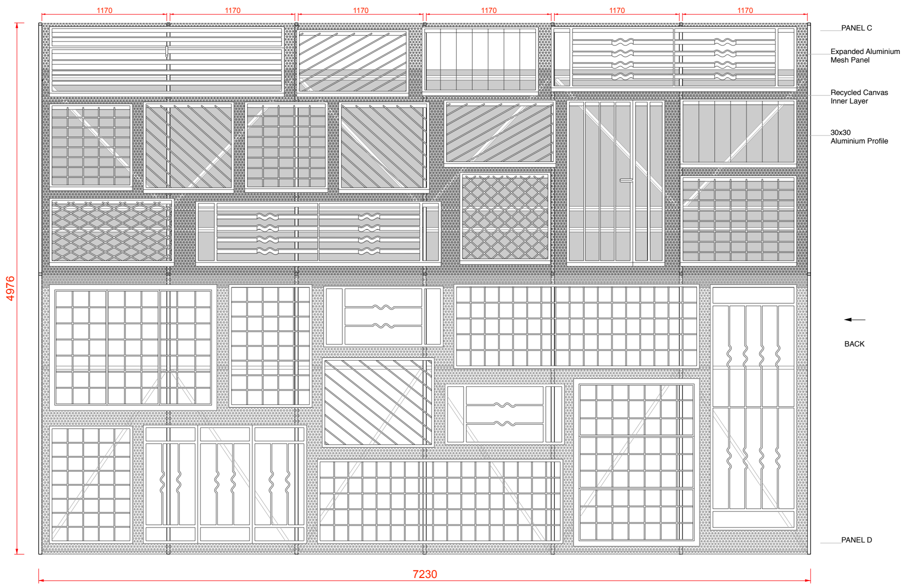
DRAWING TITLE

WINDOW PAVILION
LEFT ELEVATION

Date
20180727
Scale
1:25 @ A3
Job No

Drawing No
REUSE_012

CAD File Name
REUSE_180727_Grille Pavilion Structure.dwg




GRILLE PAVILION
RIGHT ELEVATION
SCALE 1:25

250 750
100 500 1000 mm

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SUTD REUSE PAVILION

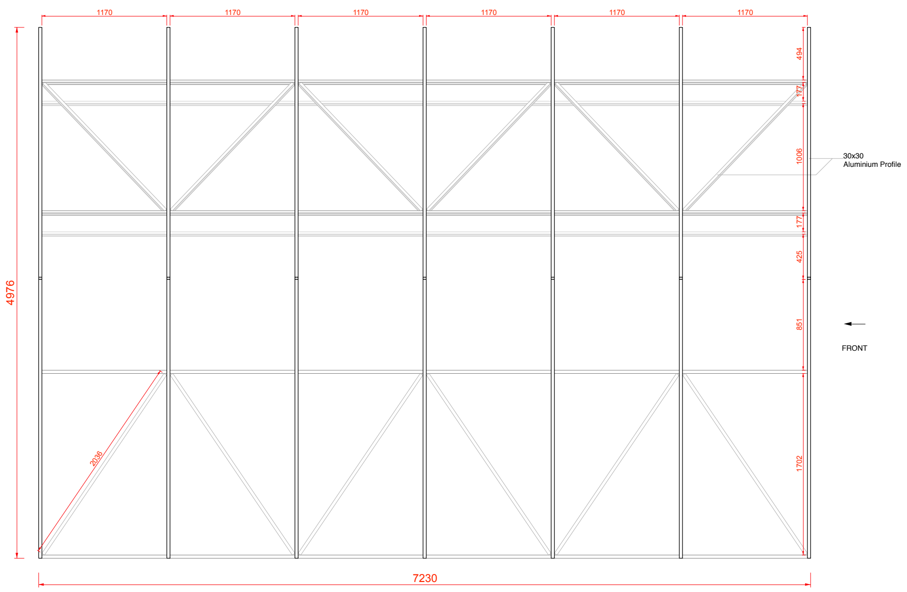
DRAWING TITLE

GRILLE PAVILION RIGHT ELEVATION

Date
20180727
Scale
1:25 @ A3
Job No

Drawing No
REUSE_013

CAD File Name
REUSE_180727_Grille Pavilion Structure.dwg




GRILLE PAVILION
STRUCTURE ELEVATION
SCALE 1:25

250 750
100 500 1000 mm

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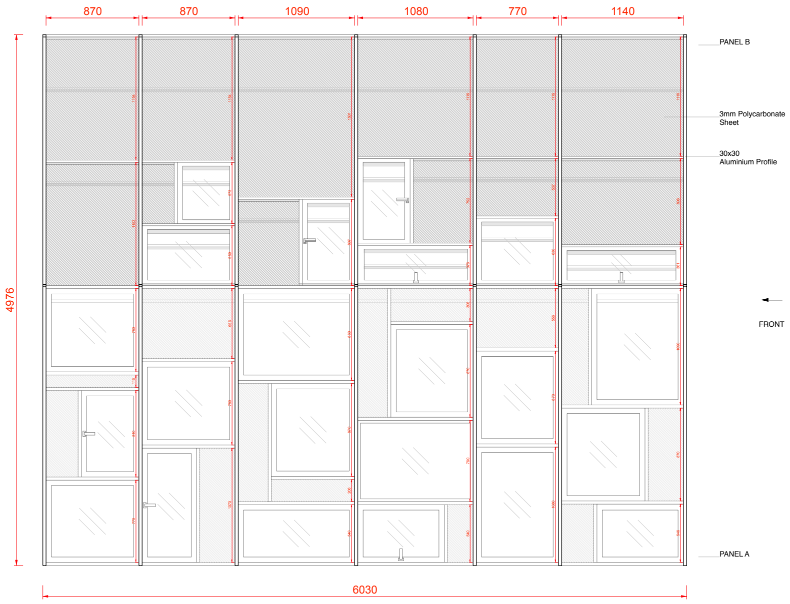
SUTD REUSE
PAVILION

DRAWING TITLE

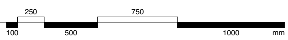
GRILLE PAVILION
STRUCTURE
LEFT AND RIGHT
ELEVATION

| Date | Drawing No |
|---|---|
| 20180727 | REUSE_014 |
| Scale | |
| 1:25 @ A3 | |
| Job No | |

CAD File Name
REUSE_180727_Window Pavilion Structure Elev.dwg




WINDOW PAVILION
LEFT ELEVATION
SCALE 1:25

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PAVILION

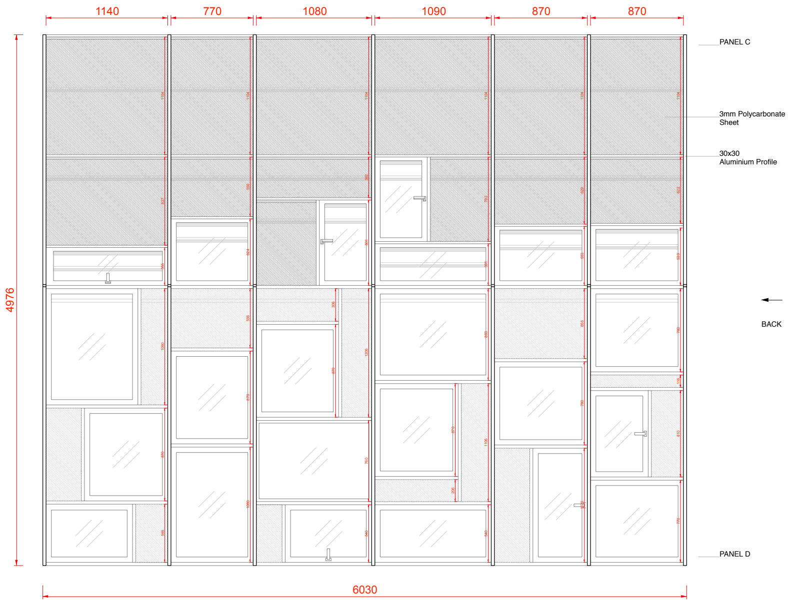
DRAWING TITLE

WINDOW PAVILION
LEFT ELEVATION

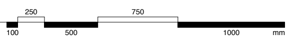
Date
20180727
Scale
1:25 @ A3
Job No

Drawing No
REUSE_015

CAD File Name
REUSE_180727_Window Pavilion Structure.dwg




WINDOW PAVILION
RIGHT ELEVATION
SCALE 1:25





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PROJECT

SUTD REUSE PAVILION

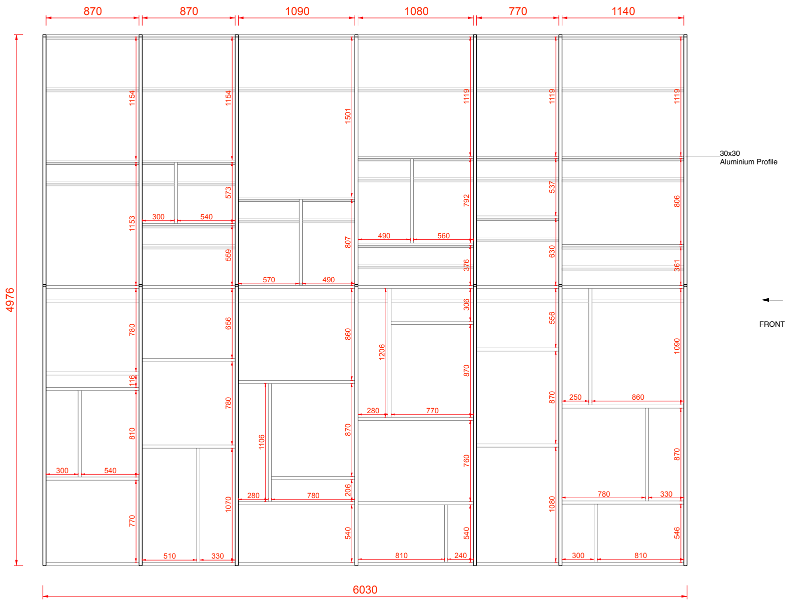
DRAWING TITLE

GRILLE PAVILION RIGHT ELEVATION

Date
20180727
Scale
1:25 @ A3
Job No

Drawing No
REUSE_016

CAD File Name
REUSE_180727_Window Pavilion Structure.dwg




GRILLE PAVILION
LEFT ELEVATION
SCALE 1:25

250
750
100
500
1000
mm

AIRLAB
Singapore University of Technology & Design
8 Somapah Road
Singapore 487372
Website: airlab.sutd.edu.sg



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NOTES

PROJECT

SUTD REUSE
PAVILION

DRAWING TITLE

WINDOW PAVILION
STRUCTURE
LEFT ELEVATION

| Date | Drawing No |
|---|---|
| 20180727 | REUSE_017 |
| Scale | |
| 1:25 @ A3 | |
| Job No | |

CAD File Name
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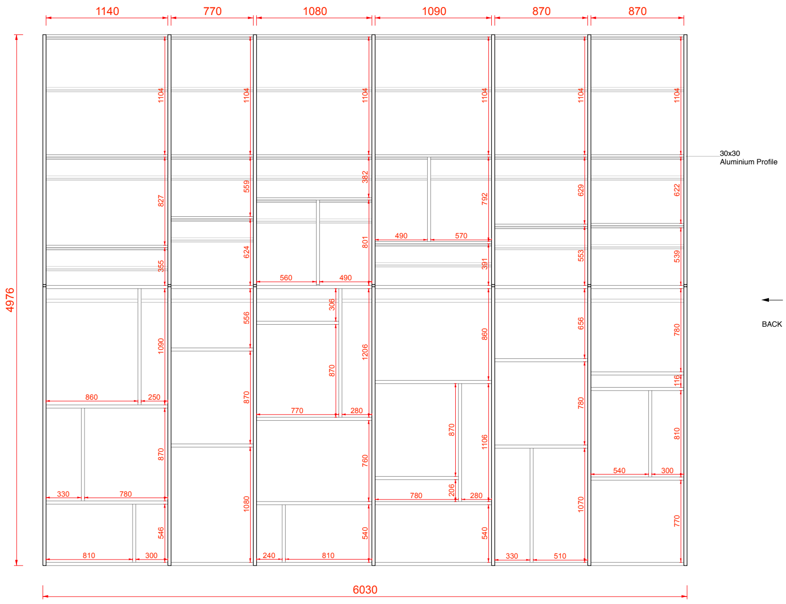


GRILLE PAVILION
RIGHT ELEVATION
SCALE 1:25

250 750
100 500 1000 mm

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PROJECT

SUTD REUSE
PAVILION

DRAWING TITLE

GRILLE PAVILION
STRUCTURE
RIGHT ELEVATION

Date
20180727
Scale
1:25 @ A3
Job No

Drawing No
REUSE_018

CAD File Name
REUSE_180727_Window Pavilion Structure.dwg

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