Revival

A study of regeneration for
unitised curtain walls in healthcare sector

by

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A thesis

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Author’s Declaration

I hereby declare that I am the sole author of this thesis.
This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Keywords: Aluminium Curtain Walls; Embodied Carbon; Circular Economy; Reuse- Reduce- Renew; D-f-D.
This study examines the circular potential and limitations of current aluminium unitised curtain wall facades, primarily through strategies such as reuse, refurbishment, and remanufacture. Despite being widely used in commercial buildings, including healthcare facilities, curtain walls present significant challenges in performance, adaptability, and sustainability. The research aims the critical issue of embodied carbon and resource depletion associated with these facades, particularly in the context of Toronto's healthcare infrastructure, which is undergoing extensive renovations. Buildings contribute immensely to environmental disruption, accounting for a significant portion of energy consumption, waste generation, and carbon emissions. The construction industry is working to reduce operational carbon emissions and enhance occupant safety. However, there is little focus on embodied carbon and the act of valuable materials in the early design phase, particularly in complex facade systems where high-carbon-intensity materials are found in curtain walls, such as aluminium and glass.

To address global issues, the development of Toronto's healthcare infrastructure from the 1970s onwards, with ongoing renovations focusing on its building envelope systems, has become a potential model for studying, analysing, and applying sustainable practices. Hospitals like SickKids, Mount Sinai Hospital, and Toronto General Hospital are in the process of sustainably upgrading their building exteriors. This process includes updating their curtain wall and window-wall systems with material substitution and modular designs. It's crucial to incorporate end-of-life plans for new products and strategies for older ones to combat the "take-make-dispose" culture", especially in Toronto's healthcare sector. A forensic analysis, including a Life Cycle Analysis (LCA), is being carried out to measure the quantity and quality of curtain walls and window wall systems and to assess the potential carbon emissions produced by facilities like the Patient Support Centre (Research site) at SickKids. Also, a mixed-method approach, combining interviews with international facade and material experts and case studies, is being used to investigate the possibility of implementing circular practices.

The Design for Disassembly practice is customised and adapted to the research site (Patient Support Centre building), reflecting the opportunity and limitations of the curtain walls and offering guidance for handling such complex facade systems. The study found that while downcycling unitised curtain wall components is possible, achieving true circularity through reuse and remanufacturing is hindered by factors such as poor thermal performance, complex disassembly, and limited compatibility with new building designs. While the research demonstrates the potential for upcycling certain components, it highlights the need for a paradigm shift toward building better envelope systems that prioritise disassembly, adaptability, and material recovery. The findings emphasize the importance of developing alternative facade systems that better align with circular economy principles and exploring policy incentives to encourage their adoption. By uncovering the current unitised curtain wall systems, this research contributes to a broader understanding of the challenges and opportunities for achieving circularity in the building industry. The findings provide valuable insights for policymakers, designers, and building owners seeking to reduce the environmental impact of the built environment.

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I'm thankful to John Straube and Amr elBahrawy, for being my internal and external readers respectively. Their guidance provided important advice on how the thesis can be reframed, connecting better with the goal.

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Lastly, I am deeply happy for the relentless love and support of my parents, family, and friends throughout my academic journey. Your encouragement and our shared memorable moments have continually strengthened my resolve.

Dedication

To all those impacted by the harsh realities of climate change, I dedicate this work.



Figure 1. India's deadly heatwaves are getting even hotter (Reuters and CNN, 2023)

Table of Contents

Author's Declaration ..... *ii*
Abstract ..... *iii*
Acknowledgements ..... *iv*
Dedication ..... *v*
List of figures ..... *viii*
List of tables ..... *x*
List if illustrations ..... *xi*

1. Introduction **1**
1.1 Background & Inspiration 3
1.1.1 Background 3
1.1.2 Inspiration 5
a. Paul Polman & Ha/f Climate Studio 5
b. A Nascent Stage for Canada 7
1.2 Problem Statement **8**
1.3 Research Objectives **10**
a. Research Framework **11**
b. Report Outline **14**

2. Impacts **16**

2.1 Impacts of Urbanization: Macro **18**
2.2 Impacts of Urbanization: Micro **23**
2.3 SickKids **31**
2.4 Conclusion: Learnings **52**

3. Aluminium Curtain Walls **56**

3.1 Curtain Walls **58**
3.2 Unitised Curtain Wall Facades **63**
3.3 Carbon Footprint **71**
3.4 Conclusion: Learnings **81**

4. Circular Loop **84**
4.1 What is a Circular loop? **86**
4.2 Principles of Circular Loop **88**
4.3 Cradle-to-Grave vs Cradle-to-Cradle. **91**
4.4 Conclusion: Learnings **93**

5. Circular Loop Practice **69**
5.1 Circular Loop in Other Industries **97**
5.2 Circular Loop in Construction Industry **99**
5.2.1 Introduction 97
5.2.2 Market Developments & Stakeholders 107
5.2.3 Circular Building Construction Model 110
5.2.4 Circular Loop Obstacles 111
5.2.5 Circular Loop Strategies 114
5.2.6 Conclusion 120
5.3 Circular Loop in Facade industry **120**
5.3.1 Introduction 120
5.3.2 Results 126
5.3.2.1 Build Less! 127
5.3.2.2 Build Intelligently! 128
5.3.2.3 Build for the Future! 130
5.3.3 Challenges & Opportunities 133
5.3.4 Recommendations and Conclusion **139**

6. Case studies **143**
6.1 What's happening in North America? **146**
6.2 What's happening in United Kingdom? **158**
6.3 What's happening in Europe Union? **168**

7. Design for Disassembly **182**
7.1 A Simple Idea! **184**
7.2 Good, but Hard **185**
7.3 The Action Plan **187**
7.4 Circular Impact **200**
7.5 The Future of Curtain Walls **209**

8. Conclusion **213**

References **215**

Appendix **217**

List of Figures

Figure 1. India's deadly heatwaves are getting even hotter (Reuters and CNN, 2023) ..... **v**
Figure 2. Curtain wall facade of Seagram Building (David Masello, 2015) **3**
Figure 3. Transition from linear to circular economy (PBL, 2017) **4**
Figure 4. Taglines of companies for circularity (Adapted from "Net positive" book) **5**
Figure 5. Study of four wall assemblies and breakdown of their embodied carbon footprint (ha/f studio, 2021) **6**
Figure 6. Conceptual framework of circular economy (adapted from Materialflows.net, 2021) **7**
Figure 7. Global GHG emissions by sector (Architecture 2030, 2017) **8**
Figure 8. Why pay to Dispose Old Windows? (Momentum Recycling, 2022) **9**
Figure 9(left-to-right). Share of Global energy (United Nations Environment Programme, 2021) **9**
Figure 10. Raw materials use (Metabolic et al., 2019) **9**
Figure 11. Distribution of CO_2e/m^2 overall life of stages (WBCSD, 2020) **9**
Figure 12. Design for Disassembly approach (adapted from Teeuwen, 2023) **10**
Figure 13. Research stages for the thesis (Created by the author, 2024) **11**
Figure 14. Breakdown of chapters and its further branches (Created by the author, 2024) **14**
Figure 15. St. Micheals' Hospital from 1895(St. Michael's Hospital Archives, 1910) **25**
Figure 16(left-to-right). A mother looks at her child in an isolation cubicle in this 1916 photo.; The Lakeside Home for sick kids from pre-1900(SickKids Archives, 2017) **32**
Figure 17(left-to-right). Conceptual Phase Redevelopment- a. SickKids Identity: The University Avenue Landscape; b. The Patient Support Centre: Demolish Existing McMaster Building; c. Conceptual Circulation Diagram (SickKids, 2015) **33**
Figure 18(left-to-right). Project Horizon- Render visualisation of Patient Support Centre and Patient Care Centre, Toronto (SickKids, 2015) **33**
Figure 19(left-to-right). Patient Support Centre- a. Draft Official Plan Amendment; b. Site Plan (City of Toronto, 2018) **34**
Figure 20. Elizabeth McMaster Building when opened in 1986 (The Globe and Mail, 2020) **35**
Figure 21. Demolished materials from Elizabeth McMaster Building (SickKids, 2019) **35**
Figure 22. Demolition of SickKids' old bridge (SickKids, 2019) **36**
Figure 23. Artist Rendering of the Patient Support Centre (B+H Architects, 2023) **36**
Figure 24. A glass-enclosed bridge connected to SickKids PSC with the main hospital. (The Globe and Mail, 2020) **37**
Figure 25(left-to-right). Patient Support Centre- a. West Elevation; b. South Elevation; c. East Elevation; d. North Elevation; (City of Toronto, 2018) **37**
Figure 26. Demolition at the North elevation's facade of the Elizabeth McMaster Building (Forum contributor Red Mars, 2019) **38**
Figure 27. Demolition of Elizabeth McMaster Building' core (Urban Toronto, 2019) **39**
Figure 28. Unitised curtain walls on lower levels of PSC(Johnny Au, 2022) **39**
Figure 29. Final installation of Aluminium spandrels and grills (Urban Toronto, 2022) **44**
Figure 30. A render visualisation of varied facades for high-rise buildings(Created by author, 2024) **58**
Figure 31(left-to-right). A render visualisation of: a. Curtain wall components on a façade; materials involved in these facade systems(Created by author, 2024) **59**
Figure 32. Boley Clothing Company building, Kansas City (Allana, 2012) **59**
Figure 33. Curtain wall requirements (adapted from Knaack, Auer et al., 2014) **60**
Figure 34. A render visualisation of under construction of Curtain walls on a mid-rise building(Created by author, 2024) **61**
Figure 35. Stick curtain wall system (adapted from Murray, 2009) **62**
Figure 36. Unitised curtain wall system (adapted from Murray, 2009) **62**

Figure 37. Unitised curtail wall components visible during installation on PSC building (Urban Toronto, 2021) **63**
Figure 38. Details of elements involved in a curtain wall(Ntailianas, 2019) **63**
Figure 39. Exploded Isometric mullion-transom connection (Ntailianas, 2019) **64**
Figure 40. Varied materials used in anchors (Halfen, 2019) **65**
Figure 41(left-to-right). a. Anchors on the side of a concrete slab(on site); b. Visual representation of anchors on the side of a concrete slab; c. Anchors on the top of a concrete slab(on site); d. Visual representation of anchors on the top of a concrete slab(Halfen Ntailianas, 2019) **65**
Figure 42. Main layouts of curtain wall fixation (Adapted from Ntailianas, 2019) **66**
Figure 43. Various elements involved in an Insulated Glass Units (Ntailianas, 2019) **68**
Figure 44. Varied types of spandrel glasses (INTOS, 2024) **69**
Figure 45(left-to-right). Most common insulation materials used in sandwich panels: a. PUR / PIR (Polyurethane); b. EPS (Expanded Polystyrene); c. XPS (Extruded Polystyrene), d. Phenolic; e. Rockwool (Assan Panel, 2019) **69**
Figure 46. Facade's service life(adapted from Kakolyri, 2015) **71**
Figure 47. Upfront carbon emissions(adapted from Teeuwen, 2023) **72**
Figure 48. Carbon distribution for aluminium material, in comparison to others(adapted from Teeuwen, 2023) **72**
Figure 49. Embodied Carbon with glass products (Adapted from ARUP, 2024) **73**
Figure 50. Demolition of curtain wall for Amsterdam Centrum(Created by Universiteit van Amsterdam HuisvestingsOntwikkeling, 2011) **85**
Figure 51. Biological Cycle vs Technical Cycle (Created by Leising, 2016) **90**
Figure 52. CISCO Lifecycle Racetrack(CISCO, 2020) **101**
Figure 53. Philips Circular-Economy-Diagram (Philips, 2022) **101**
Figure 54. Value Hill (Created by Metabolic, 2023) **103**
Figure 55. Circular Economy for a Sustainable Built Environment (Adapted from Klein, 2013) **104**
Figure 56. Shearing layers of change (Adapted from Brand, 1994) **105**
Figure 57. Life-cycle stages according to the EN standard (Adapted from OneClick LCA, 2023) **105**
Figure 58. Hierarchical range of building products(Adapted from Eekhout, 2008) **107**
Figure 59. Linking model: Circular Economy principles by EMF(Adapted from EMF, 2013b) **108**
Figure 60. Design domain - Circular building design principles in relation to the circular building product levels (Adapted from Beurskens and Bakx, 2015) **111**
Figure 61. Key stakeholders' participation for decarbonising of buildings **113**
Figure 62. Choice distribution (Adapted from by Teeuwen, 2016) **117**
Figure 63. Categorisation of linear and circular approaches for reducing resource use. Based on, and expanded from (Adapted from Stahel(1994), Braungart et al.(2008)) **120**
Figure 64 & 65(left-to-right). The First Canadian Place, Toronto; Render Visualisation(Roberto Portolese and B+H, 2024) **148-49**
Figure 67.(left-to-right). Movement of suspended platform (B+H Architects, 2012) **150-151**
Figure 68. Close-up of suspended platform (B+H Architects, 2012) **152**
Figure 69. Installation of new insulation (B+H Architects, 2012) **152**
Figure 70. Installation of new spandrel(B+H Architects, 2012) **153**
Figure 71. Conceptual illustration of Citigroup's main tower (Citigroup, 2022) **161**
Figure 72. Dismantling of curtain wall (Scheldebouw, 2023) **162**
Figure 73. Dismantling process in production hall (Scheldebouw, 2023) **163**
Figure 74. The Koningskade 4 Building, Netherland (Biedboek, 2011) **171**
Figure 75. The Natural Pavilion, Netherland (Paula Pintos, 2022) **172**
Figure 76. Removal of curtain wall elements (Teeuwen, 2023) **172**
Figure 77(left-to-right). Old gaskets; Disposal of old gaskets to landfill (Teeuwen, 2023) **173**
Figure 78. Front Elevation of the Natural Pavilion(Paula Pintos, 2022) **174**
Figure 79. Reusing of glass panels (Paula Pintos, 2022) **174**
Figure 80. Do we think about disassembly when assembling a curtain wall? (Urban Toronto, 2022) **189**

List of Tables

Table 1. Varied materials used in curtain walls (Adapted from Ntailianas, 2019) **66**
Table 2. Comparison of properties between Aluminium and other materials (Adapted from Kakolyri, 2015) **67**
Table 3. Advantages and disadvantages of Aluminium profiles (Adapted from Fradelou, 2013) **68**
Table 4. Comparison of insulating materials (Created by author, 2024) **69**
Table 5. Key principles of fields of study that are combined in the concept of CE (Created by Leising, 2016) **93**
Table 6. Characteristics between Building, Industrial, and Non-Industrial sectors(Adapted by Noordhuis & Vrijhoed, 2011) **114**
Table 7. Overview of obstacles for implementing CE industry (Adapted from Leising, 2016) **115**
Table 8. Holistic strategies that can be applied in facade industry (Created by author, 2024) **118-19**
Table 9. Slowing Resource Loop strategies (Adapted from Bocken, 2015) **121**
Table 10. Closing Resource Loop strategies (Adapted from Bocken, 2015) **122**
Table 11. Challenges and Opportunities for Unitised curtain walls(Created by Author, 2024) . **136-142**
Table 12. Eight strategies for the Patient Support Centre(Created by Author, 2024) **191**
Table 13. Trade-offs of 'Component-based reuse' (Created by Author, 2024) **199-200**

List of Illustrations

Illustration 1. World level issues involving construction industry(Created by author, 2024) **19**

Illustration 2. Continental and Provincial climate concerns(Created by author, 2024) **21-22**

Illustration 3. Significant growth in Toronto's healthcare sector (Created by author, 2024) **24**

Illustration 4. Healthcare infrastructure redevelopment at Downtown Toronto(Created by author, 2024) **25-26**

Illustration 5. Wall assembly study of SickKids' buildings (created by author, 2024) **28**

Illustration 6. Wall assembly study of Toronto Western Hospital and Camh's building (Created by author, 2024) **29**

Illustration 7. Forensic Architecture of Elizabeth McMaster Building (Adapted from Jack Landau, 2019) **40**

Illustration 8. Forensic Architecture of Patient Support Centre(Adapted from Urban Toronto, 2022) **41**

Illustration 9. Installation of Unitised Aluminium curtain walls on South Elevation (Adapted from Urban Toronto, 2022) **42**

Illustration 10. Layers of Aluminium panels(Adapted from Urban Toronto, 2022) **43**

Illustration 11. Detailed analysis of Elizabeth McMaster Building (Created by author, 2024) **46-47**

Illustration 12(left-to-right). Tree map depicting material's carbon emissions; Building circularity diagram (Created by author, 2024) **48-49**

Illustration 13. Detailed analysis of Patient Support Centre (Created by author, 2024) **50-51**

Illustration 14(left-to-right). Tree map depicting material's carbon emissions; Building circularity diagram (Created by author, 2024) **53-54**

Illustration 15. Life cycle stages involved from Elizabeth McMaster Building to Patient Support Centre(Created by author, 2024) **55**

Illustration 16. Guaranteed and Estimated lifespan(adapted from Teeuwen, 2023) **70**

Illustration 17. Replacement frequency of elements in curtain walls(Adapted from ARUP, 2024) **70**

Illustration 18. 6 out of 16 unitised curtain walls were selected to represent the breadth of European and United Kingdom facade design. (Adapted from ARUP, 2024) **75**

Illustration 19(top-to-bottom). WT-01: Technicalities, Embodied Carbon(EC) generated, and EC by stage(Adapted from ARUP, 2024) **76**

Illustration 20(top-to-bottom). WT-02: Technicalities, Embodied Carbon(EC) generated, and EC by stage (Adapted from ARUP, 2024) **77**

Illustration 21(top-to-bottom). WT-03: Technicalities, Embodied Carbon(EC) generated, and EC by stage(Adapted from ARUP, 2024) **78**

Illustration 22(top-to-bottom). WT-04: Technicalities, Embodied Carbon(EC) generated, and EC by stage (Adapted from ARUP, 2024) **79**

Illustration 23(top-to-bottom). WT-05: Technicalities, Embodied Carbon(EC) generated, and EC by stage; ; (Adapted from ARUP, 2024) **80**

Illustration 24(top-to-bottom) WT-06: Technicalities, Embodied Carbon(EC) generated, and EC by stage (Adapted from ARUP, 2024) **81**

Illustration 25. Total Embodied carbon, between WT-01 to WT-06, over 60 years lifetime(Adapted from ARUP, 2024) **82**

Illustration 26. Embodied carbon by material, between WT-01 to WT-06, over 60 years lifetime(Adapted from ARUP, 2024) **83**

Illustration 27. Embodied carbon by component, between WT-01 to WT-06, over 60 years lifetime(Adapted from ARUP, 2024) **84**

Illustration 28. The Butterfly Diagram (Adapted from EMF, 2013) **92**

Illustration 29. Cradle-to-Grave vs Cradle-to-Cradle(Adapted from Michael, 2016) **94**

Illustration 30. The Inertia Principle(Adapted from Michael, 2016) **96**

Illustration 31. Stakeholders across supply chain of facade industry **125-26**

Illustration 32. Stakeholders interviewed worldwide (Created by Author, 2024) **127-128**

Illustration 33(top-to-bottom). Position of respondents interviewed; Size of their company **129**
Illustration 34. Typical reasons for facade replacement The Inertia Principle **130**

Illustration 35. Knowledge of expected lifespan of Aluminium curtain walls **131**

Illustration 36. Sensibility of components and materials(Created by Author, 2024) **132**

Illustration 37. Potential of locally sourcing the materials(Created by Author, 2024) **133**

Illustration 38. Barrier across supply chain for reusing curtain walls(Created by Author, 2024) **134**

Illustration 39. Stakeholders indicating percentage distribution for each barrier **135**

Illustration 40. Embodied emissions and Building Circularity results with Non-Donor mentality (Created by Author, 2024) **154-155**

Illustration 41. Embodied emissions and Building Circularity results with Donor mentality (Created by Author, 2024) **156-157**

Illustration 42. Life cycle stages for BMO Tower(Created by Author, 2024) **159-160**

Illustration 43. Embodied emissions and Building Circularity results with Non-Donor mentality (Created by Author, 2024) **165-66**

Illustration 44. Embodied emissions and Building Circularity results with Donor mentality (Created by Author, 2024) **167-68**

Illustration 45. Life cycle stages for CitiBank Building(Created by Author, 2024) **170**

Illustration 46. Embodied emissions and Building Circularity results with Non-Donor mentality (Created by Author, 2024) **175-176**

Illustration 47. Embodied emissions and Building Circularity results with Receiver mentality (Created by Author, 2024) **177-178**

Illustration 48. Embodied emissions and Building Circularity results with Donor mentality (Created by Author, 2024) **179-180**

Illustration 49. Life cycle stages regarding Koningskade 4 Building and The Natural Pavilion (Created by Author, 2024) **181-182**

Illustration 50. Options available for Donor building to transfer materials for a second life.(Created by Author, 2024) **187**

Illustration 51. Visual representation of eight strategies on PSC Building's curtain walls (Created by Author, 2024) **192-193**

Illustration 52. Calculation of the 'W5' assembly and its relation to other curtain walls. (Created by Author, 2024) **194**

Illustration 53. Life cycle stages involved in a potential "In-place upgrade" **196**

Illustration 54. Life cycle stages involved in a potential "Panel-Reuse" (Created by Author, 2024) **197**

Illustration 55. Life cycle stages involved in a potential "Panel Refurbishment" **198**

Illustration 56. Life cycle stages involved in a potential "Panel Re-manufacturing" **199**

Illustration 57. Life cycle stages involved in a potential "Component Reuse" **201**

Illustration 58. Life cycle stages involved in a potential "Component Refurbishment" **202**

Illustration 59. Life cycle stages involved in a potential strategy of "Recycling" **203**

Illustration 60. Life cycle stages involved in a potential strategy of "Wastage" (Created by Author, 2024) **204**

Illustration 61. Visual representation of life cycle stages for PSC and a receiver building in 2053 (Created by the Author, 2024) **207-208**

Illustration 62. Circularity scenario 1 (Created by Author, 2024) **209**

Illustration 63. Circularity scenario 2 (Created by Author, 2024) **210**

Illustration 64. Circularity scenario 3 (Created by Author, 2024) **211**

Illustration 65. Circularity scenario 4 (Created by Author, 2024) **212**

Illustration 66. Circularity scenario 5 (Created by Author, 2024) **213**

Illustration 67. Life cycle stages regarding Koningskade 4 Building and The Natural Pavilion (Created by Author, 2024) **214-215**

1. Introduction



1.1 Background & Inspiration

1.1.1 Background

A building and a human being always have a metaphorical interrelation with each other. On one side, the architectural building works due to various components like Structure, Systems, and Envelope, whereas on the other a human body works through its Skeleton, Organs, and Skin. To be more specific, the enclosure of a building and the thin skin of a human have commonalities with each other. Both help to divide, protect, and control the internal environment with the external. A shell of a building is a perfect example to start the conversation about the integration of both, adaptivity and aesthetics. These are called Building envelopes, which serve important functions such as noise and pollution control, protection from climatic factors, and visual connection with the outside. Examples include Ajanta & Ellora (cut stone caves), Exeter Library of Brick-and-Mortar, and Seagram Building's curtain walls(Figure 2).



Figure 2. Curtain wall facade of Seagram Building (David Masello, 2015)

The previous century was marked by speedy industrialization and unceasing economic expansion, but more than anything else, it was defined by impressive technological progress. As a result, it's no wonder that the 21st century is dealing with some of the most pressing environmental issues. Inadequate resources, ecological decline, pollution, and health concerns are just a few examples. One of the strong reasons to know behind this is short-term thinking by companies like fossil-fuel (Mining Watch Canada 2023, 2) and Mining industries (The Narwhal, n.d.). This conveys solely focus on maximising profit today rather than worrying about complicated, systemic issues that take years to solve. A true scenario is when a proposed carbon tax was on the ballot in Washington State in 2018 (Yoder 2018, 5), and it was leading in the polls. Where an oil and gas company called The Western States Petroleum Association, with its lucrative short-term mindset, poured $30 million, into convincing people it would be bad for them, leading the ballot to fail. However, how does this relate to the previous paragraph's discussion on the construction industry and building envelopes? The answer to this is the modern economic system's extract-produce-use-dump material and energy flow model, which is now considered

outdated linear, but can still be observed in our unsustainable construction industry (Korhonen, Nuur, Feldmann, and Birkie 2018, 5).

It is evident that in recent decades, the methods of constructing and demolishing buildings have placed a significant strain on our planet's environmental capacity. Despite its crucial role as an economic driver, the building sector's considerable consumption of raw materials and energy has largely been underestimated (Circle Economy 2015, 26). This industry already accounts for 40% of the materials entering the global economy and produces 40-50% of the world's greenhouse gas emissions and acid rain-causing agents (Khasreen, Banfill, and Menzies 2009, 675). Unfortunately, these materials often do not reach their end-of-life stage within the building's functional lifespan because of the building sector's rapidly changing demands. Buildings lose their function or are demolished for various reasons such as new developments or changes in use. For example, the facade alone typically consists of 25-30% of a building's embodied energy (Oldfield 2019, 193) and ends up in a local landfill along with other building materials. Curtain wall facades, which can produce up to 10-30% of a building's total embodied carbon emissions (Hartwell, Macmillan and Overend 2021, 2), are significant contributors to this waste. This highlights the need for leaders in the construction industry to recognize that profit should be derived from solving the world's issues rather than contributing to them. Using raw materials more efficiently and sustainably is necessary to reduce environmental impact and maintain prosperity (Circle Economy 2015, 14).

As shown in Figure 3, to change this unsustainable trajectory the concept of the Circular Economy is proposed by closing and connecting material loops. In this way, waste is used as a resource again. This approach is gaining traction globally, with many giant firms are increasing material capture (recycling, reuse, and repair) practices. Some of them include: - "Dow Corporates" which pledged to "redefine the role of business in society and facilitate the world's transition to a circular economy." (Dow Corporates, n.d.) and Unilever Sustainable Living Plan [USLP] who are focusing on regenerative practices that primarily use renewable energy from recycled and renewable materials, by which the circular model reuses or recycles all materials in an endless loop (Unilever, 2010, 2). In contrast to this, the circular economics approach is mainly theoretical in building sector knowledge because tools and design solutions need to be developed to make a circular approach possible. Although a large percentage of construction and demolition waste in Canada is already being recycled, this process remains carbon and energy-intensive, especially for aluminium and glass, due to the high temperatures that are required for remelting (Beck 2021, 3). So, is there a better way? What if the whole curtain wall or its components could be reused directly, without a reduction in value?

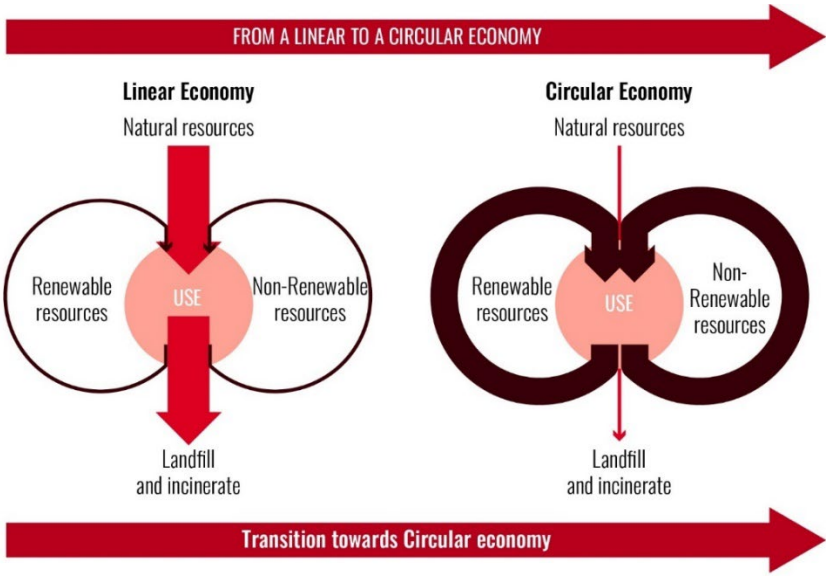


Figure 3. Transition from linear to circular economy (PBL, 2017)

One of the prominent and interesting approaches to it could be through adaptive reuse, direct material reusing, and the high value of recycling a building envelope, which is referred to as a principle of circular economy and is termed a “Regenerative Envelope”. A Regenerative Envelope has numerous benefits for lowering operational CO2 emissions through High-performance systems (Passive House Institute, n.d.), this includes:

- Strengthening resilience: Adapts to changing weather, reducing heating/cooling requirements.
- Enhancing thermal comfort: Maintains a consistent indoor environment, lowering HVAC use.
- Reducing peak energy: Minimizes energy spikes during extreme weather.
- Mitigating grid demand: Lowers energy consumption, reducing strain on the power grid.
- Enabling district energy: Makes the building compatible with shared energy systems
- Circulating energy resources: Captures and redistributes energy within the building.

However, to implement the circularity in the external layers and carbon-intensive materials, it will be interesting to look at technical barriers, trade-offs, and collaborative opportunities in the existing and future buildings.

1.1.2 Inspiration

This thesis is initiated with inspiration attained from leaders like Paul Polman, an ex-CEO of Unilever and Co-author of Net Positive book, who’s is widely recognized for his efforts on promoting sustainable business practices. In specific to our construction industry, ha/f climate studio, aims to mitigate the impact of buildings on climate change. In addition, the regulations in both Canada, but also North America, in terms of sustainability are started adopting by industries and/or governments in many provinces.

a. Paul Polman & ha/f climate design

Paul Polman is a renowned Dutch businessman who has been a trailblazer in the field of sustainability and corporate social responsibility. He held the position of CEO at Unilever for a decade, during which he fervently advocated for sustainable business practices. In his latest book, "Net Positive," he stresses the significance of a circular economy and cites examples of companies (Figure 4) such as IKEA, Patagonia, and Unilever itself (Polman and Winston 2021, 138), who are committed to integrating sustainability into their operations, products, and services, to make positive impact on society and the environment while also driving business growth.

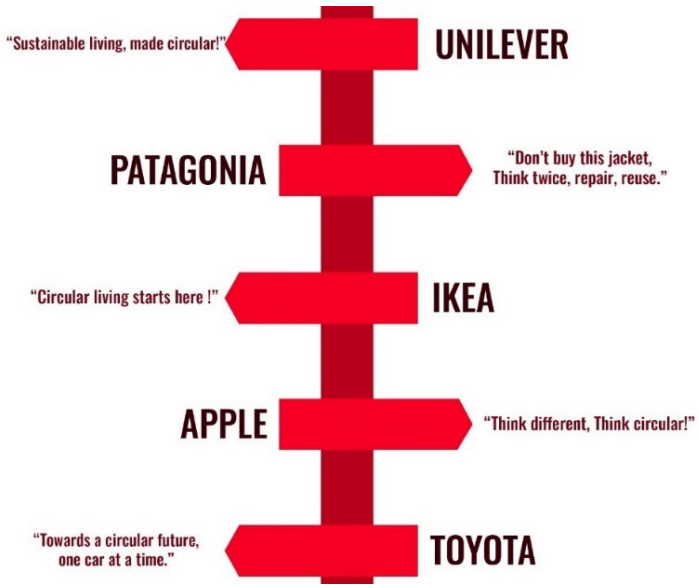


Figure 4. Taglines of companies for circularity (Adapted from “Net positive” book)

Ha/f Climate Design studio exemplifies sustainable leadership with its mission to spark a conversation about the environmental impact of buildings in Canada. The studio was established in 2020, and their research laid the groundwork for the embodied carbon policies recently adopted by the City of Toronto, co-authored by Kelly Alvarez Doran. As shown in figure 5, particularly drawn to the circular design strategies promoted by the studio's ideology increased interest, the whole building Life Cycle Assessment (wbLCA) of various envelope designs and materials used in Toronto (Ha/f Climate Design 2023, 5) caught the author's attention. The high embodied carbon intensity on a mass/volume basis in wall assemblies like Aluminium Curtain Walls piqued the interest in exploring carbon reduction opportunities in current and future building enclosures.

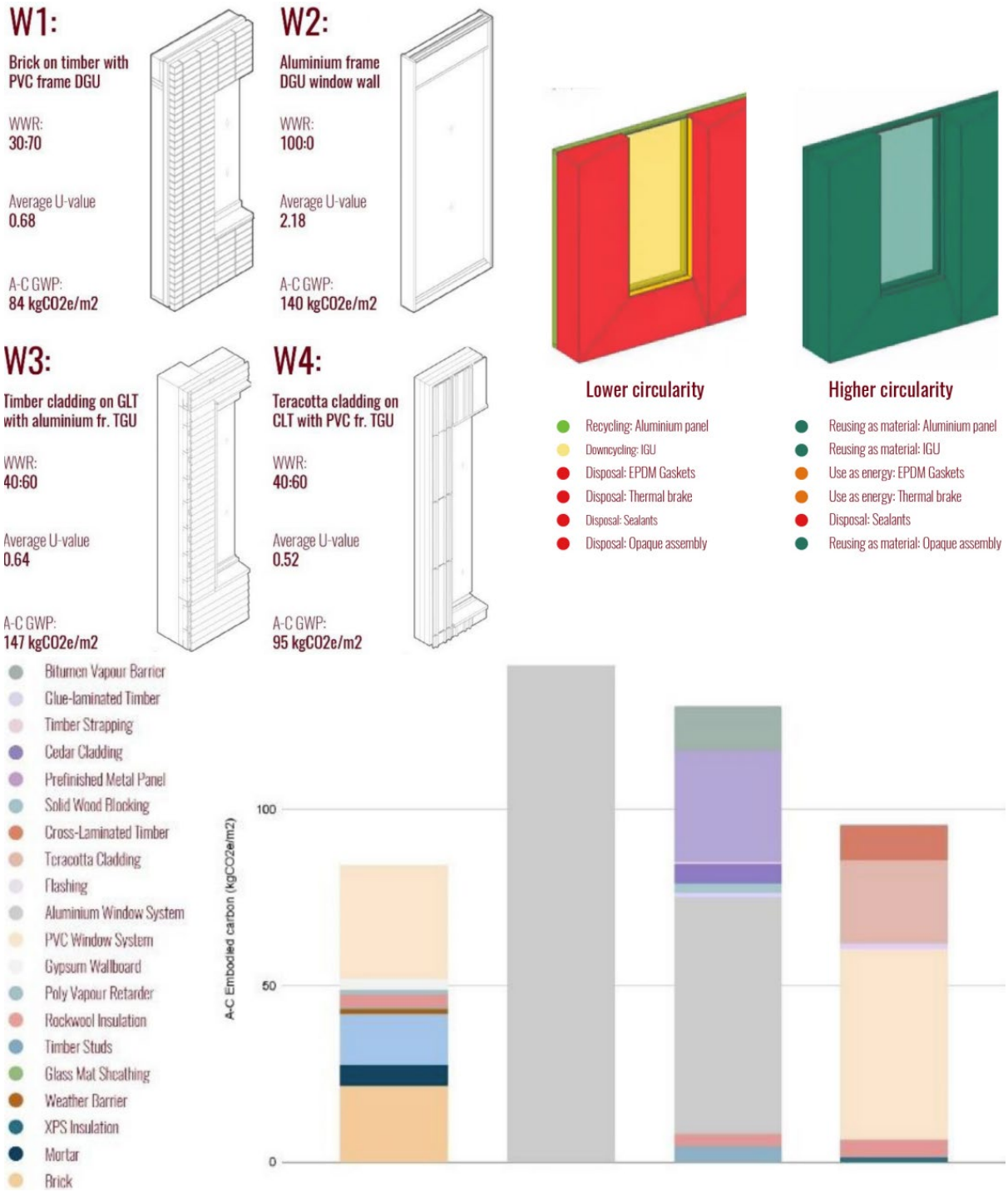


Figure 5. Study of four wall assemblies and breakdown of their embodied carbon footprint(ha/f studio, 2021)

b. A *nascent* stage for Canada

In the early 2000s, organizations like the Canada Green Building Council and the CSA Group began collaborating on green building initiatives, including efforts to align with standards like Leadership in Energy and Environmental Design (LEED). Since 1995, the CSA Group has developed three standards relevant to Canada's circular economy practices in the built environment sector: "CSA S478:19" for Durability in Buildings (CSA Group 2019), "Z782-06" for Design for Disassembly and Adaptability in Buildings (CSA Group 2006), and "Z783-12" for Deconstruction of Buildings and their Related Parts (CSA Group 2012). Several examples of circular construction initiatives and businesses are active in Canada, with provinces like British Columbia, Quebec, and Ontario serving as hubs for innovation (Hartwell, Macmillan and Overend 2021, 13). Key stakeholders, including governments, regulators, educational institutions, industry associations, and non-profits, are focused on embedding circular practices. Challenges remain due to the fragmented nature of the construction sector, requiring efforts to overcome system barriers and inertia. The National Zero Waste Council estimates that disassembling and reusing buildings could avoid 1.3 million tonnes of embodied carbon annually in Canada (Hartwell, Macmillan and Overend 2021, 12). This trend towards deconstruction not only presents economic opportunities but also prompts a rethink of how buildings are designed, managed, and maintained. It also highlights the potential for recovering construction materials and resources to eliminate waste. After considering various aspects of Design for Disassembly (DfD), it was mindful to focus on deconstruction practices (Figure 6), particularly aluminium curtain walls, due to personal interest and their research potential.

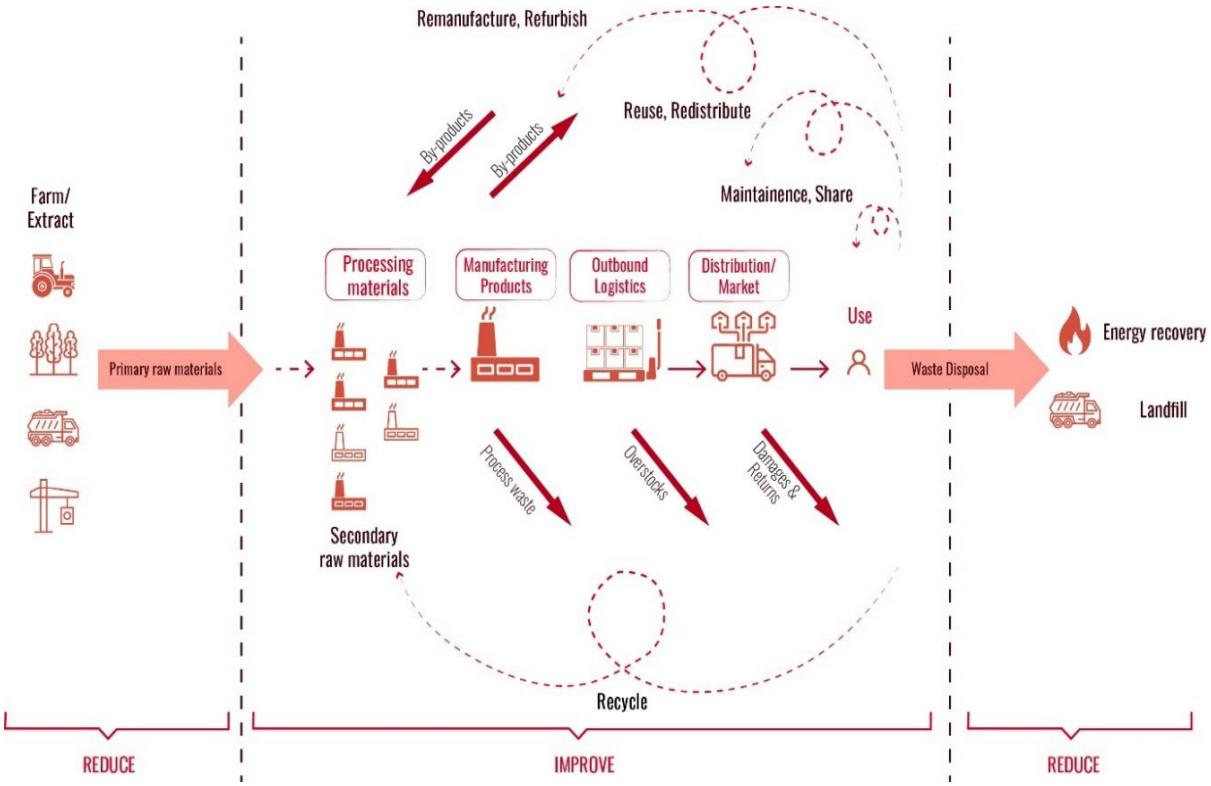


Figure 6. Conceptual framework of circular economy (adapted from Materialflows.net, 2021)

1.2 *Problem* Statement

Despite the growing awareness of the environmental impact of buildings, progress towards mitigating these effects has been slower than needed. By the third decade of the 21st century, the world continues to face with the alarming effects on the natural world. This includes issues like global warming, deforestation, pollution, plastic waste, disruptions to nitrogen cycles, and freshwater depletion, with six out of nine planetary boundaries already exceeded. Annually, as depicted in Figure 7, the building industry accounts for 40% of carbon emissions, with embodied carbon representing for 11% of global greenhouse gas (GHG) emissions and 28% of emissions from the global building sector (World Green Building Council 2019, 16). Projections indicate the embodied carbon will contribute to almost half of all new construction emissions between now and 2050. Additionally, raw material extraction for construction consumes half of all resources, and construction and demolition waste make up 40% of urban solid waste, with the construction industry accounting for 11% of global energy-related GHG emissions. By 2025, it is estimated that 2.2 billion tonnes of construction waste will be generated worldwide, nearly double the amount produced in 2018. Let's now take a closer look at the situation in North America (Beck 2021, 9-10).

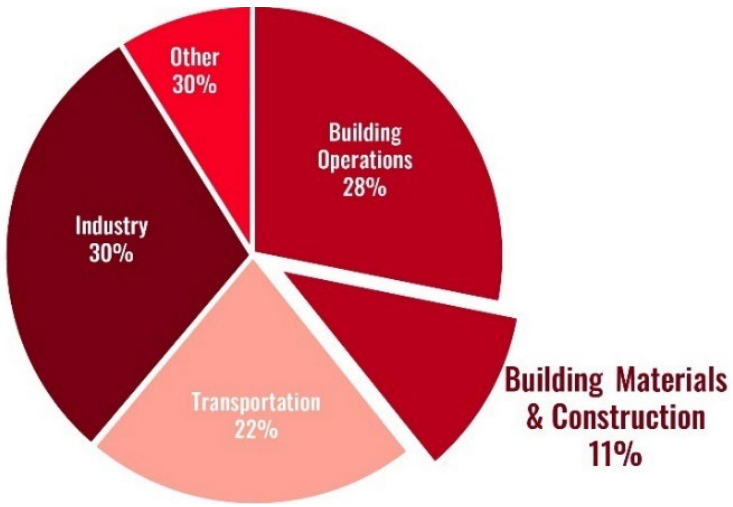


Figure 7. Global GHG emissions by sector (Architecture 2030, 2017)

Starting with the USA, it has been observed that over 100 billion tons of raw materials are converted into new products annually worldwide. However, only 8.6% of these materials are cycled back into the economy after use, with two-thirds ending up as waste or pollution in the environment (Hartwell, Macmillan and Overend 2021, 5). Moving to Canada, the construction sector is a significant contributor to the economy, generating $141 billion in GDP in 2020. However, it also produces one-third of the country's total solid waste (Figure 8), amounting to over 4 million tonnes per year. This waste represents a loss of valuable resources from Canada's economy (Hartwell, Macmillan and Overend 2021, 5). The construction industry in Canada is one of the largest consumers of raw materials and energy, and it contributes significantly to the waste stream, with 3.4 million tonnes of construction materials sent to landfills annually, including an estimated 1.8 million tonnes of embodied carbon (Hartwell, Macmillan and Overend 2021, 12). This linear economy, where resources are extracted, used, and then discarded, puts immense pressure on ecosystems and worsens social inequalities. It also represents missed economic opportunities by not reclaiming the value of these materials. Additionally, rapid urbanization is driving up global demand for resources and infrastructure, further straining the construction industry and its supply chain.



Figure 8. Why pay to Dispose Old Windows? (Momentum Recycling, 2022)

As highlighted by the UN's Intergovernmental Panel on Climate Change, CO2 emissions must be halved by 2030 to align to limit global warming to 1.5°C (IPCC 2022, 53). The thesis focuses on finding circular strategies to achieve this goal, with a particular emphasis on the facades of buildings(Figure 9-11), metaphorically referred as the building's "cocoon." Facades are a substantial driver of energy consumption in buildings, both in terms of embodied carbon (the carbon footprint associated with construction) and operational energy use. Complex geometries can worsen this by increasing the surface area of the facade, leading to higher energy demands and a larger carbon footprint. The challenge is that, unlike the building's structure, which can last a very long time, facades often require substantial maintenance and eventual replacement due to their role as the building's climate barrier. Materials with high carbon intensity, such as aluminium, glass, gypsum, and insulation, contribute a large portion of the total lifecycle greenhouse gas emissions in most buildings, sometimes exceeding 50% of the total lifecycle emissions (United Nations Environment Programme and Yale Center for Ecosystems + Architecture 2023, 41–60).

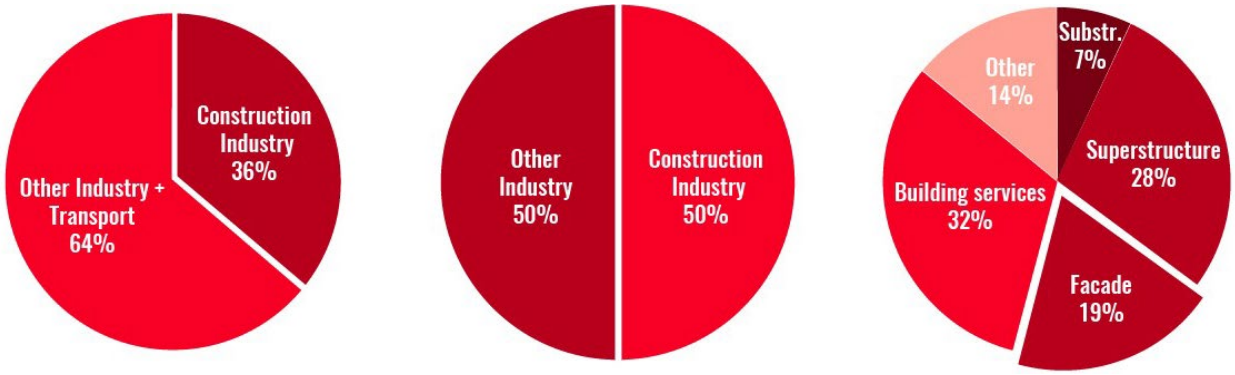


Figure 9(left-to-right). Share of Global energy (United Nations Environment Programme, 2021); Figure 10. Raw materials use (Metabolic et al., 2019); Figure 11. Distribution of CO_2e/m^2 overall life of stages (WBCSD, 2020)

This trend is also observed in Ontario's healthcare facilities, where past, present, and future buildings exhibit similar characteristics. At present, one of the primary reasons for this could be the economic pressure facing the provinces. Such as nearly half of Ontario's hospitals are in bad condition because there is a repair backlog in areas that haven't undergone substantial renovations, a situation surpassing the worst state of other infrastructures like roads and bridges (Perkel 2020). While portions of these hospitals, like Toronto General Hospital, may have older sections dated back to early 1900s, they underwent significant additions and renovations in the 1970s. The collective impact of age and ongoing expansions has led to a need for comprehensive evaluation and potential upgrades to their building

envelopes. This is particularly relevant for hospitals like Scarborough General and Birchmount, where most construction occurred during that era.The challenges faced, especially by Toronto's hospitals, might raise pressing questions like:

- *What are the environmental and economic costs of discarding unitised curtain walls or their components?*
- *What are the specific performance limitations that make the disassembly and reuse of unitised aluminum curtain walls difficult? How does this affect the potential for sustainability in the building envelope?*
- *How can circular economy strategies help reduce the impacts of older unitised curtain walls? What potential alternative facade systems could offer better disassembly and reuse capabilities in the future.*

To address these questions, a thorough understanding of the opportunities, potential, and constraints inherent in these components is required. For example, current facade systems like unitised curtain walls lack a Design for Disassembly (DfD) approach. It's crucial to explore how new systems can efficiently incorporate this practice. The thesis will delve into reusing and recovering curtain wall components and explore circularity techniques for future buildings like Camh or SickKids.

1.3 Research *Objectives*

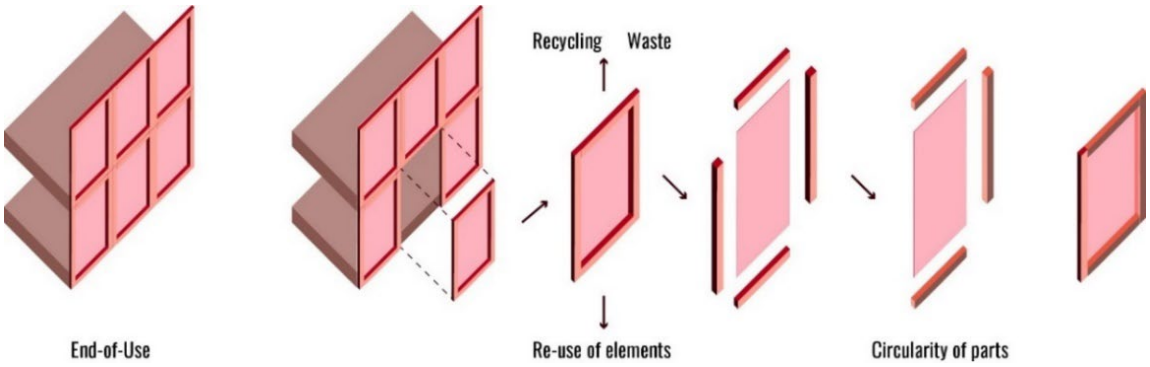


Figure 12. Design for Disassembly approach (adapted from Teeuwen, 2023)

Following the problem statement, the holistic objective of this research is to ***investigate the possibilities and limitations of Design for Disassembly (DfD) strategies(Figure 12) for Unitised Aluminium curtain walls and its components in the Circular Economy.*** While this objective is complex and cannot be fully addressed by this research alone, it aims to contribute to the broader understanding through manageable objectives. To support a comprehensive approach, the granular objectives of this research on aluminium curtain walls will include:

-1: **Clarity**

To assess the associated challenges and opportunities for circular economy scenarios, aligning with current construction practices.

0**: Comparability**

To understand the extent to which circular economy principles can be applied to existing unitised curtain walls and their components, identifying criteria for evaluating and selecting better alternatives for future facades.

+1**: Practicality**

To recommend strategies for enhancing the circularity potential of present and future facade components through the application of DfD, identifying key performance indicators for assessing circularity, and exploring alternative facade systems that better support circular economy principles.

These objectives are designed to guide the research towards a thorough exploration of the topic, contributing valuable insights to the field of sustainable construction practices.

Research *Framework*

The research framework(Figure 13) comprises five key steps: Literature review, Interviews, Case studies, Outcomes & Strategies, and Recommendations. Each of these sections will outline the research questions and methodology, visually represented in the figure below.



Figure 13. Research stages for the thesis (Created by the author, 2024)

While each section has its objectives and micro-research questions, the overarching goal of the entire research framework is to answer a central question:

" How can the circularity of unitised aluminium curtain walls be maximized through the application of Design for Disassembly principles, considering the material's lifecycle, economic factors, and environmental impacts?"

1.3.1 Literature Review

The Literature Review is structured into two phases. The first phase has been focused on understanding the carbon footprint and technical aspects of aluminium curtain walls. In this study, the technical aspects revealed barriers within the facade supply chain that hinder reusability. The second phase built upon the errors in the previous phase, examined best regenerative practices and circular economy principles in

the construction industry. It explored practices such as deconstruction and design for disassembly, emphasizing reuse, remanufacture, and refurbishment.

Throughout the Literature Review, the following micro-research questions are addressed in Chapter 2, Chapter 3, and Chapter 4:

1) *What defines the essential attributes of unitised aluminium curtain wall facades?*
2) *How is the analysis of a unitised aluminium curtain wall facade's lifespan carried out in contemporary practices?*
3) *What are the barriers behind the loss of functionality in unitised curtain walls?*
4) *What are the innovative approaches are involved in transitioning the construction industry towards circular practices?*

These questions aim to provide a comprehensive understanding of the subject, setting the stage for further research and advancements in the field.

1.3.2 Interviews

Engaging stakeholders from around the globe, the investigation conducted insightful video conference interviews with 33 individuals, spanning various backgrounds. Lasting between 30 to 60 minutes each, these interviews aimed to evaluate the applicability of three pivotal criteria in today's professional practices. Inspired by Ha/f Climate Studio's philosophy, the focus was on "Build Less," "Build Intelligently," and "Build for the Future." Also, enhancing our comprehension of aluminium curtain walls the semi-structured meetings revolved around a set of similar research questions as mentioned below: -

1) *What factors influence the choice of materials for unitised aluminium curtain walls?*
2) *Why are locally sourced materials not being considered to reduce embodied carbon?*
3) *What obstacles hinder the reuse of components from older buildings in new constructions?*
4) *Can unitised aluminium curtain wall components be better designed for remanufacturing rather than reusing, and what alternatives for future envelopes can be discovered with maximum circularity?*

Moreover, these micro-research questions are addressed in Chapter 2, Chapter 3, and Chapter 4.

1.3.3 Case studies

The case studies were carefully selected based on their diverse geographic locations, varying scales, and different approaches to implementing circularity principles in the design and construction of aluminium curtain wall facades. This deliberate selection aimed to provide a comprehensive understanding of reuse, reduce, and renewal strategies applicable to different contexts. The chosen projects showcase the principles in action, offering valuable lessons and conclusions for sustainable building practices. The selected case studies are:

i. BMO Tower, Toronto, Canada
ii. Citibank, United Kingdom, London
iii. Koningskade-4 & The Natural Pavilion, Amsterdam, Netherlands

Understanding the limitations of existing case studies and the scarcity of precedents for unitised curtain wall disassembly, the following micro-research questions are addressed in Chapter 5:

1) *What specific strategies were used to tackle the challenges of disassembly and reuse?*
2) *To what extent can we see a successful demonstration of the feasibility of circular economy principles for unitized or similar wall components?*
3) *What lessons can we learn to guide the development of guidelines for the design and construction of wall systems that prioritize disassembly and reuse?*

1.3.4 Outcomes & Strategies

Outcomes & Strategies are a culmination of literature reviews, interviews, and case studies, that result in the development of optimal circular practices, for unitised aluminium curtain facades or components. This stage involves dissecting and categorizing the strengths, weaknesses, opportunities, and threats identified from a global perspective. These insights are then integrated with the best and most relevant strategies to enhance Canada's circular built environment. The environmental impact is assessed through various analyses, such as Life Cycle Analysis (LCA), and was displayed by a reduction in the embodied carbon in aluminium curtain walls through strategies focused on reduction, reuse, and renewable approaches.

Throughout the outcomes and strategies, the following micro-research questions are addressed in Chapter 6:

1) *How can the circular strategies be derived from the sections to meet the maximum requirements of circularity from curtain walls?*
2) *How can these circular strategies create a cycle of revenue generation for stakeholders?*
3) *For future Canadian window-wall and stick-wall components, what design changes can be made to improve their sustainability and compliance with local building codes?*

1.3.5 Recommendations

The recommendations chapter focused on implementing circular methods and strategies identified in previous research within the Canadian context. Drawing on detailed insights from the "Clarity" phase regarding the SickKids' Patient Support Centre, these suggestions will be tailored for this project. By applying these strategies to create regenerative envelopes, the aim to calculate the estimated reductions in embodied carbon, waste generation, and resource depletion. Through monetisation and analysis, the research will explore the potential benefits of these strategies. Additionally, it will identify and address risks and limitations to pave the way for a more sustainable future in the construction industry.

Throughout the recommendations, the following micro-research questions are addressed in Chapters 7:

1) *What circular methods and strategies can be effectively implemented in the Canadian context?*
2) *What insights from the Patient Support Centre can be applied best to enhance the reusability, remanufacturing potential, and material recovery of complex facade systems?*
3) *What are the potential environmental benefits of implementing these strategies, and how can they be quantified?*
4) *What are the limitations associated with implementing circular strategies for unitised curtain walls, and how can they be mitigated?*

1.4 Research *Outline*

Report Outline: The methodology diagram(Figure 14) guides the reader for different chapters, and their purpose of distribution.

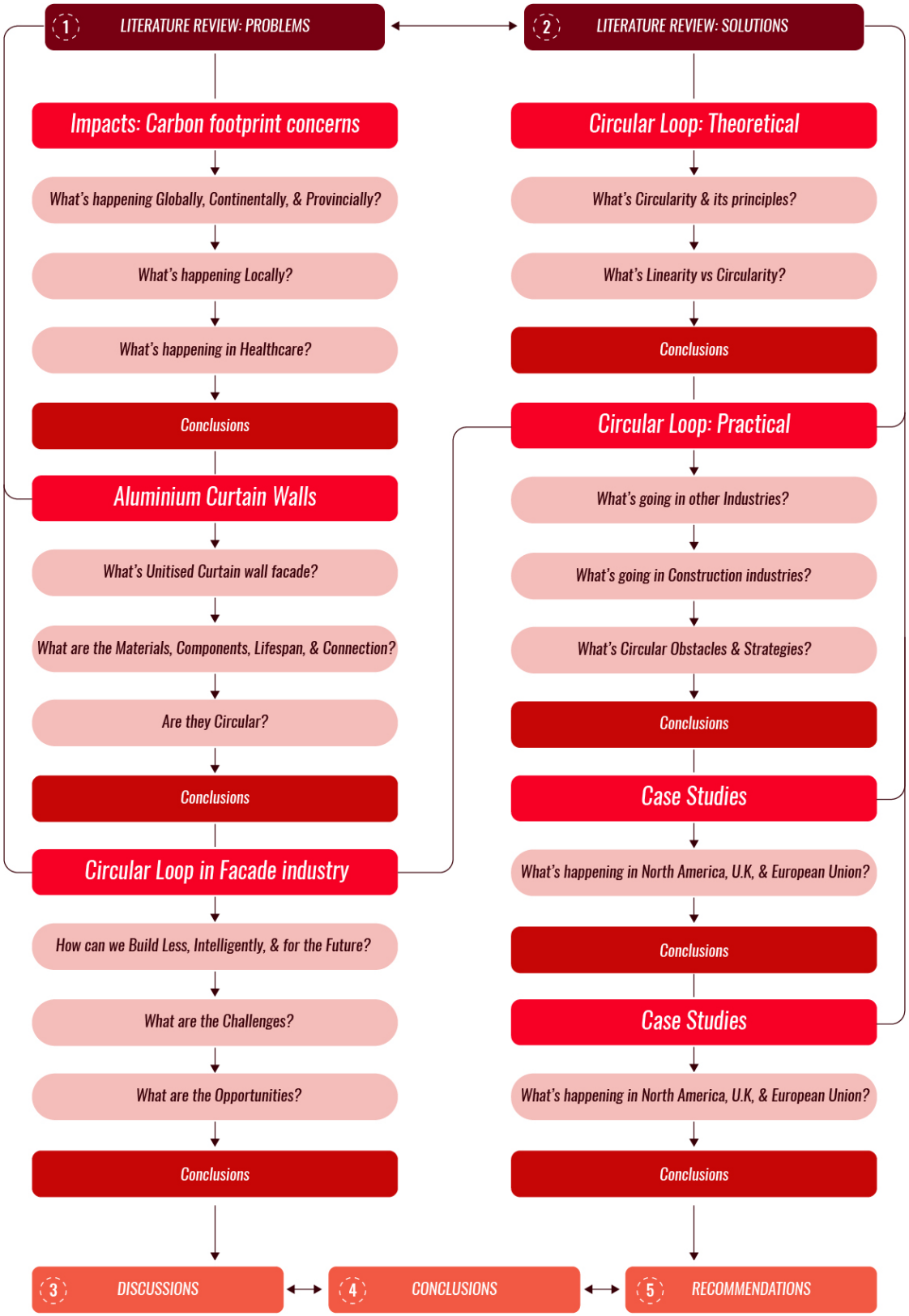


Figure 14. Breakdown of chapters and its further branches (Created by the author, 2024)

2. Impacts


TORONTO

"Buildings are the largest contributor to climate change. With so much attention given to transportation emissions, many people are surprised to learn this fact. In truth, the building sector was responsible for nearly half (46.9%) of U.S. CO_2 emissions in 2009. By comparison, transportation accounted for 33.5% of CO_2 emissions and industry just 19.6%."

Understanding this quote by Edward Mazria (B+H Architects 2017, vii), it's crucial to recognise the significant impact of the construction industry on global, continental, provincial, and local carbon footprints. The construction industry has been a major contributor to the staggering carbon footprint, making it one of the leading causes of Earth Overshoot Day each year (Global Footprint Network 2024). This section on impacts will thoroughly explore the link between carbon footprint and buildings, with a particular focus on their envelope typologies.

2.1 Impacts of Urbanisation: *Macro*

2.1.1 Globally: World

The construction industry has a massive environmental footprint, primarily due to its excessive resource consumption and carbon emissions(Illustration 1). By 2050, global material consumption is expected to reach an unsustainable 90 billion tons, a 125% increase since 2010 (UNEP 2018). Alarmingly, new buildings will be the source of half of the construction sector's carbon emissions by then (Adams, Burrows and Richardson 2019).

The built environment sector, encompassing buildings and infrastructure, is the largest emitter of greenhouse gases, responsible for at least 37% of global emissions (United Nations Environment Programme and Yale Center for Ecosystems + Architecture 2023). While efforts have been made to reduce operational carbon emissions from building operations, the focus now shifts to tackling the substantial embodied carbon emissions tied to the production and transportation of building materials.

The increasing global demand for raw materials, driven by economic growth and improving living standards, is projected to nearly double by 2060 (OECD 2019, 19). To put this in perspective, the world is constructing the equivalent of a new city the size of Paris every five days! Since 1980, the extraction and consumption of raw materials have increased by 60%, with a substantial 20% ending up as waste, totaling 12 billion tons annually (OECD 2015, 10). This linear consumption model, where resources are extracted, used, and disposed of, is unsustainable and worsens pollution and climate change. Moreover, with the anticipated doubling of dependence on raw materials by 2060, annual waste generation is estimated to reach a troubling 70% by 2050 (World Bank Group 2018).

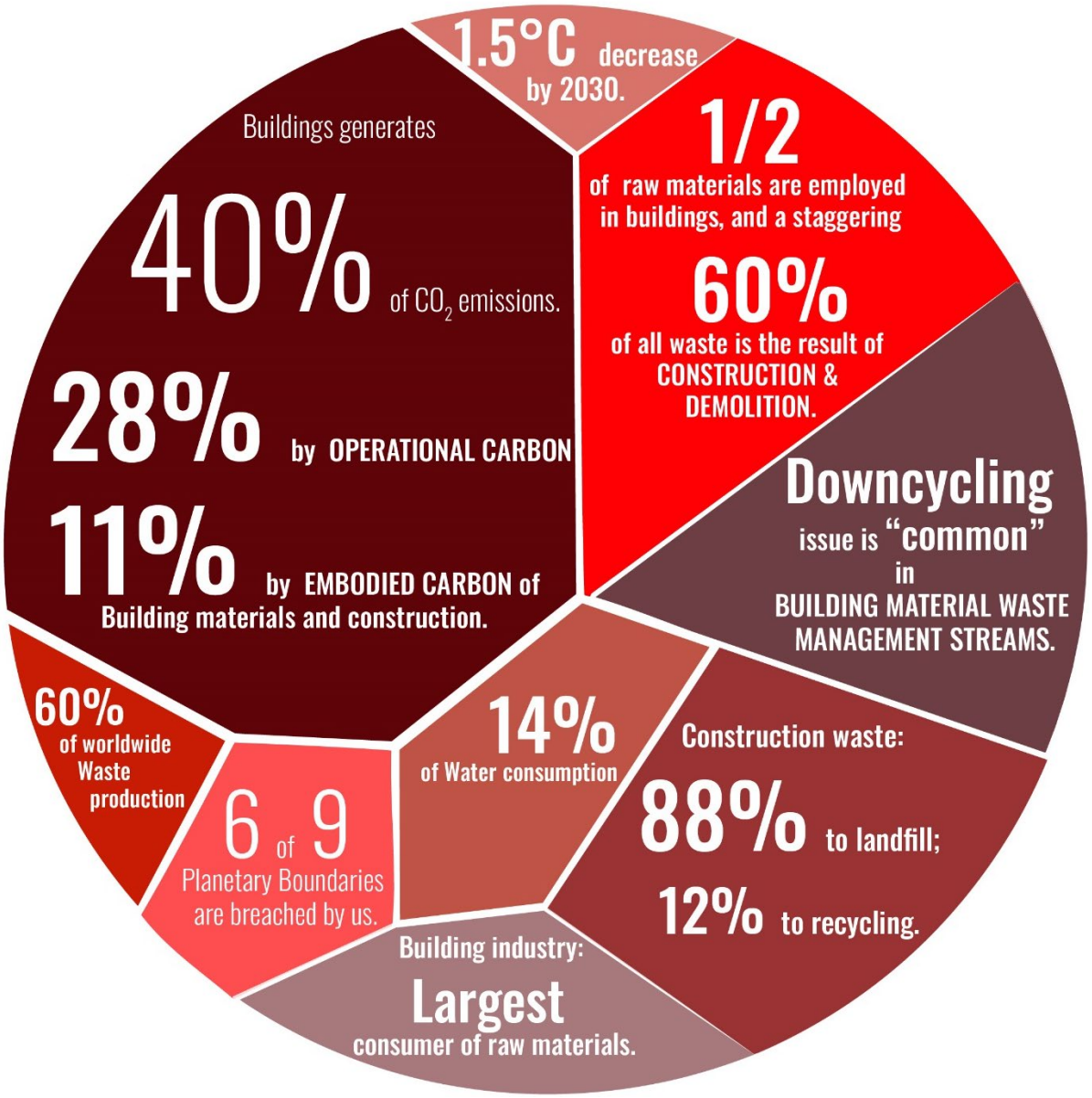


Illustration 1. World level issues involving construction industry(Created by author, 2024)

The global shift towards a circular economy is aimed at addressing pressing environmental issues. This model focuses on conserving resources, reducing waste, and disconnecting economic activity from the consumption of finite resources. The circular economy, drawing inspiration from the Cradle-to-Cradle design philosophy (McDonough and Braungart 2002) differentiates between technical and biological cycles. with biological materials designed to reintegrate into natural systems and technical materials being reused, repaired, or recycled to extend their lifespan and minimise waste. Implementing circular economy principles can help the construction industry minimise its environmental impact and pave the way for a more sustainable future. While the construction sector has made progress in reducing operational carbon emissions through energy efficiency measures, it now faces an urgent need to tackle embodied carbon emissions. These emissions, stemming from the production and transportation of building materials, can make up over 50% of a building's total lifecycle greenhouse gas emissions (Labaran, Mathur, Muhammad and Musa 2022, 4). As buildings become more energy-efficient and energy sources become less carbon-intensive, the significance of embodied carbon will only grow. To

summarize, the construction industry has a substantial and multi-faceted impact on the environment. Embracing a circular economy, prioritizing sustainable materials, and reducing waste are essential steps towards creating a greener and more resilient built environment.

2.1.2 Continentally and Provincially: Countries and Canadian Provinces

The Illustration 2 highlights the significant impact of urbanisation on resource consumption, greenhouse gas emissions, and waste generation across different continents and countries. The construction industry's impact on the environment is a pressing global concern, with significant consequences for resource depletion, waste generation, and carbon emissions. This issue extends beyond individual countries, as evidenced by the following examples:

- **Canada: Alberta**

Alberta's electricity grid relies on fossil fuels for approximately 87% of its generation, with coal accounting for a significant portion (Canada Energy Regulator 2024). This results in an estimated 65% of the province's total greenhouse gas emissions coming from the energy sector (United Nations Climate Change 2020, 22).

- **Canada: Ontario**

In Ontario, buildings account for approximately 24% of the province's greenhouse gas emissions (Office of the Auditor General of Ontario 2020, 3). Of this, operational emissions from buildings represent around 30%, while embodied carbon associated with construction materials and processes accounts for the remaining 70% (Ontario Association of Architects. n.d.).

- **USA**

The United States generates an estimated 292 million tons of construction and demolition waste annually (US Environmental Protection Agency 2023), a significant portion of which ends up in landfills. This waste stream represents a substantial loss of valuable materials and contributes to environmental pollution.

- **Europe**

Europe consumes approximately 40% of the world's natural resources, including minerals, metals, and fossil fuels (European Environment Agency 2019, 33). The continent is responsible for roughly 10% of global greenhouse gas emissions, with the energy sector being a major contributor (European Commission n.d.). Furthermore, Europe generates an estimated 2.5 billion tons of waste each year, a significant environmental challenge (Eurostat Statistics Explained 2023).

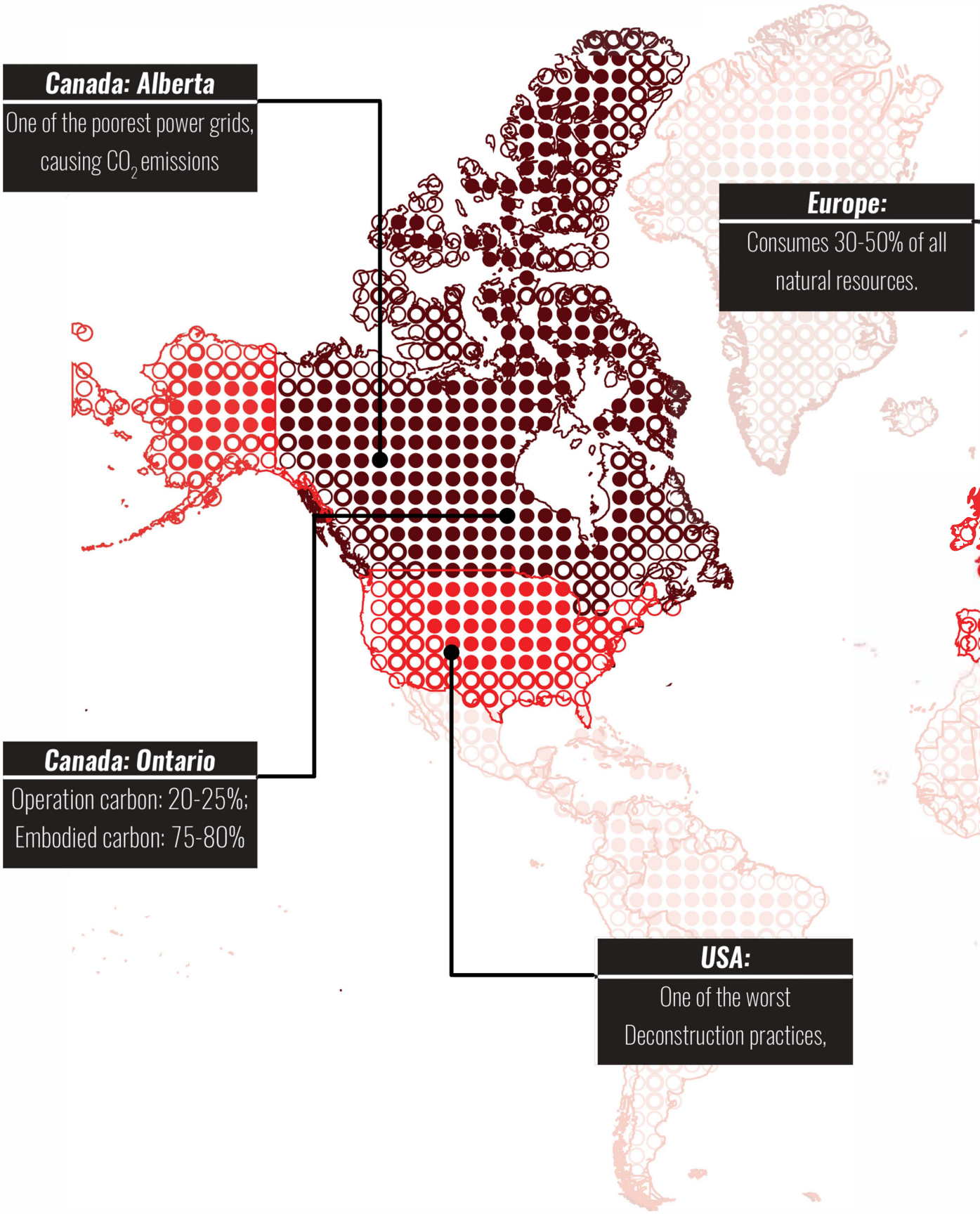
- **Australia**

Australia's construction and demolition waste accounts for around 40% of the total waste generated annually (Australian Government, DCCEEW 2021). The deconstruction rate in Australia is relatively low, with less than 1% of buildings being deconstructed (Pickin, Randell, Trinh and Grant 2017, 30), leading to the loss of valuable materials and increased environmental impact.

- **New Zealand**

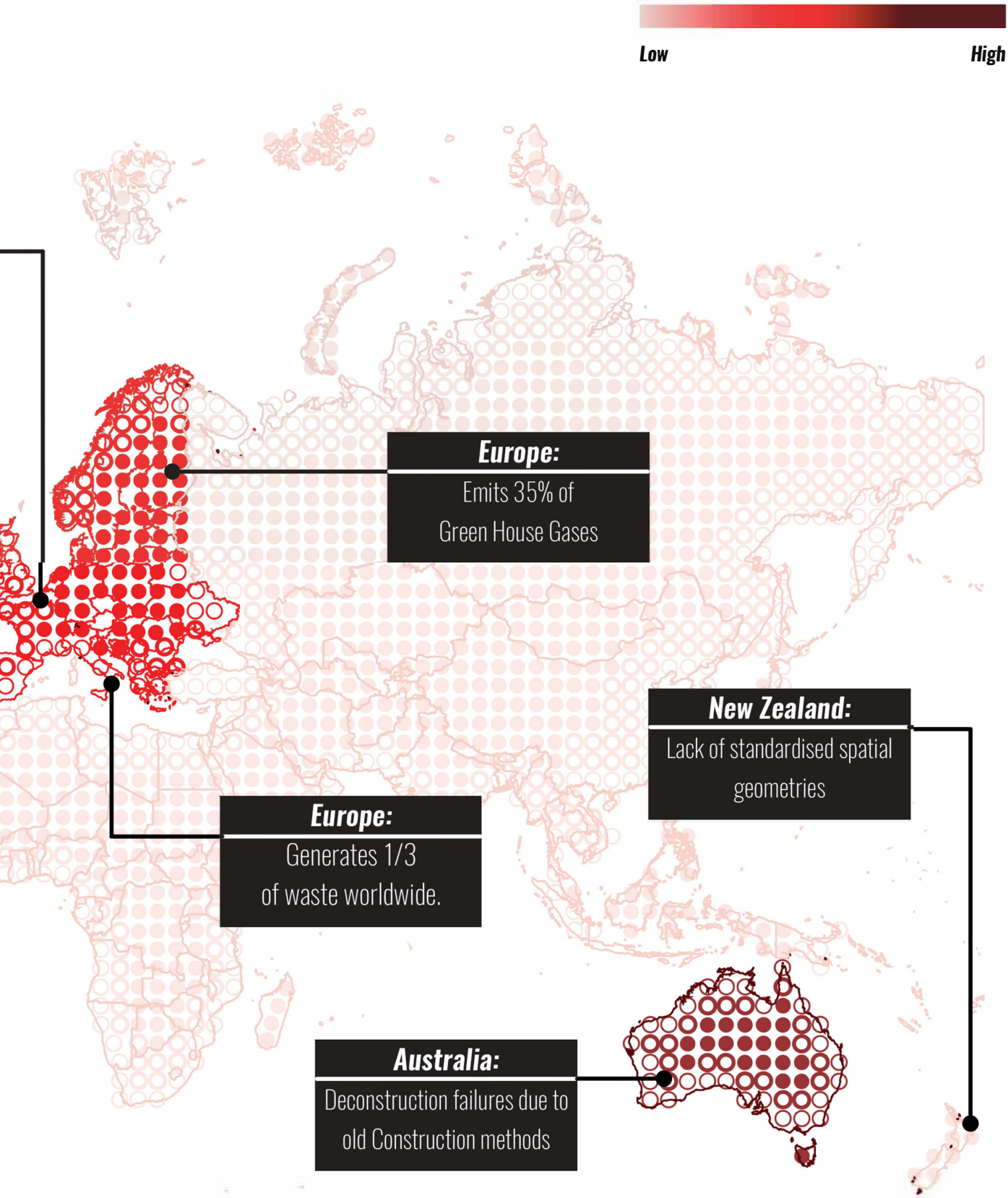
While there is no specific percentage available for the lack of standardised spatial geometries in New Zealand, the issue is widely acknowledged in urban planning discussions and reports (Ministry for the Environment 2020, 339). This lack of standardisation can lead to inefficiencies in land use, infrastructure planning, and resource management.

Continental and Provincial Impact of Urbanization



"-1": CLARITY

"0": COMPAR


Low
High
Europe:
Emits 35% of
Green House Gases
New Zealand:
Lack of standardised spatial
geometries
Europe:
Generates 1/3
of waste worldwide.
Australia:
Deconstruction failures due to
old Construction methods

These statistics highlight the urgent need for sustainable practices across the globe. The construction industry's current linear model, characterized by resource extraction, use, and disposal, is unsustainable. Transitioning to a circular economy, where materials are reused, repaired, and recycled, is crucial to mitigate the industry's environmental impact. In developed economies, repurposing existing materials, such as the vast amount of failing reinforced concrete infrastructure, can help reduce the demand for new resources.

However, many contemporary buildings are "designed for obsolescence" (Pervez 2017, 5), with limited lifespans and complex assemblies that hinder disassembly and reuse. The urgency of addressing embodied carbon emissions in construction is underscored by the fact that they can account for over 50% of a building's total lifecycle greenhouse gas emissions (Cutler, Dayton, Grant, Mahomed and Ojetayo 2022), especially as energy efficiency improves and energy sources become less carbon intensive. In the UK (Climate Change Committee n.d.), for example, buildings are responsible for 59% of annual carbon emissions. The European construction industry (Gerrard 2023) also faces challenges, generating 37% of the continent's waste.

2.2 Impacts of Urbanisation: *Micro*

2.2.1 Locally: Toronto

In 2023, Toronto had the largest number(238) of cranes in North America (Rider Levett Bucknall 2023) and had given the green light for the high level of construction activity. In Toronto, buildings are responsible for 76% of greenhouse gas emissions, with commercial and residential buildings contributing to 60.9% of this total. As a result, these buildings must continue adhering to the stringent environmental regulations outlined in the Ontario Building Code (OBC) and the Toronto Green Standard (TGS) for new developments in the city (City of Toronto 2022). These regulations cover requirements for operational energy use and greenhouse gas (GHG) emissions but do not currently address embodied energy or GHG emissions. Even though approximately 80% of proposed and under-construction buildings in major North American cities are high-rise residential buildings, there is a lack of research on the trade-offs between embodied and operational impacts for this building type (Rivera, MacLean and McCabe 2021, 2).

This research gap is particularly crucial for Toronto, where high-rises are increasingly reshaping the urban landscape due to rapid population growth and densification policies. Understanding these trade-offs is essential for making informed decisions that minimize the overall environmental footprint of these buildings in the Toronto context. Furthermore, in 2007, the City of Toronto established a framework to reduce GHG emissions, setting targets to achieve a 30% reduction in emissions below 1990 levels by 2020 (Slater et al. 2022, 6). As shown in Illustration 3, the healthcare sector in Toronto is also experiencing significant growth, with demolitions, refurbishments, and new infrastructures being developed.



Illustration 3. Significant growth in Toronto's healthcare sector (Created by author, 2024)

2.2.2 Healthcare sector

The history of healthcare infrastructure in Toronto is extensive and intricate, characterised by periods of remarkable growth and development as well as challenges and setbacks. In the early 19th century, healthcare in Toronto was mainly provided by private practitioners and small, charitable hospitals. The Toronto General Hospital, founded in 1819, marked a significant milestone as the first major hospital in the city (University Health Network. n.d.). Other early hospitals included St. Michael's Hospital (Figure 15a & b) from 1895, established by the Sisters of St. Joseph, and Women's College Hospital (1907), which was the first hospital in Canada where women were recognized as practicing medical professionals (Unity Health Toronto 2024).

Throughout the 20th century, Toronto experienced significant growth and advancement in its healthcare infrastructure. This progress was driven by factors such as population increase, advancements in medical technology, and the establishment of universal healthcare in Canada during the 1960s (City of Toronto. n.d.). New hospitals like Sunnybrook Health Sciences Centre (1948) and Mount Sinai Hospital (1954) were built during this time, and existing ones underwent substantial expansions and renovations.

The healthcare sector in Toronto has faced challenges such as funding limitations, staff shortages, and overcrowding. Concerns have also been raised about the aging infrastructure of many hospitals in the city in recent Today, Toronto is home to a world-class healthcare system, comprising a diverse range of hospitals, clinics, and other healthcare facilities. However, ongoing challenges persist, including the need for sustained investment in infrastructure and the necessity to adapt to the changing needs of the population. The future of healthcare infrastructure in Toronto is expected to be shaped by factors such as technological advancements, shifting demographics, and the ongoing requirement to provide high-quality care to all residents (RCCAO 2016, 23). Illustration 4 depicts Toronto's healthcare infrastructure,

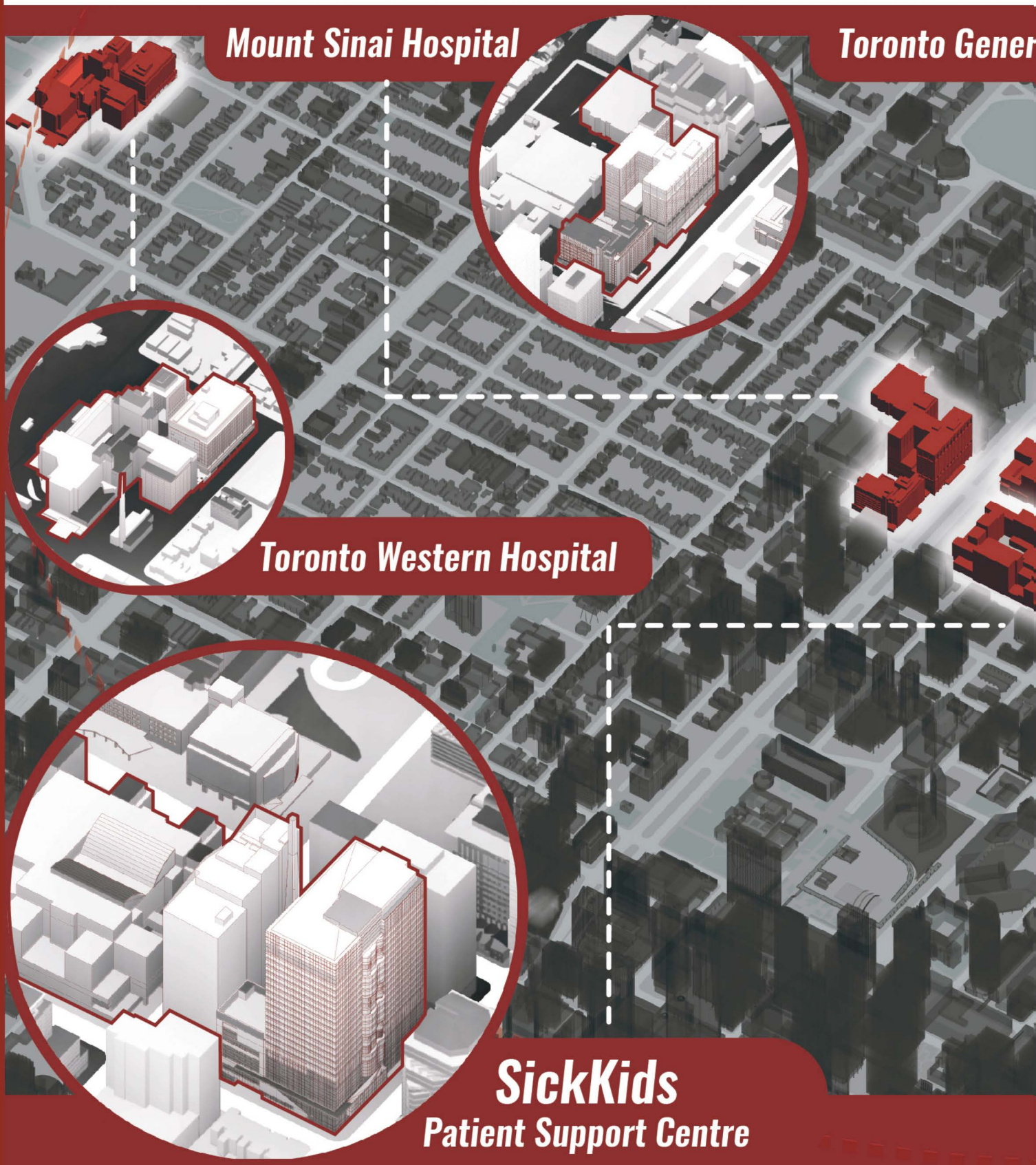
undergoing a significant transformation with major redevelopment projects underway, at numerous hospitals established in the late 20th century.



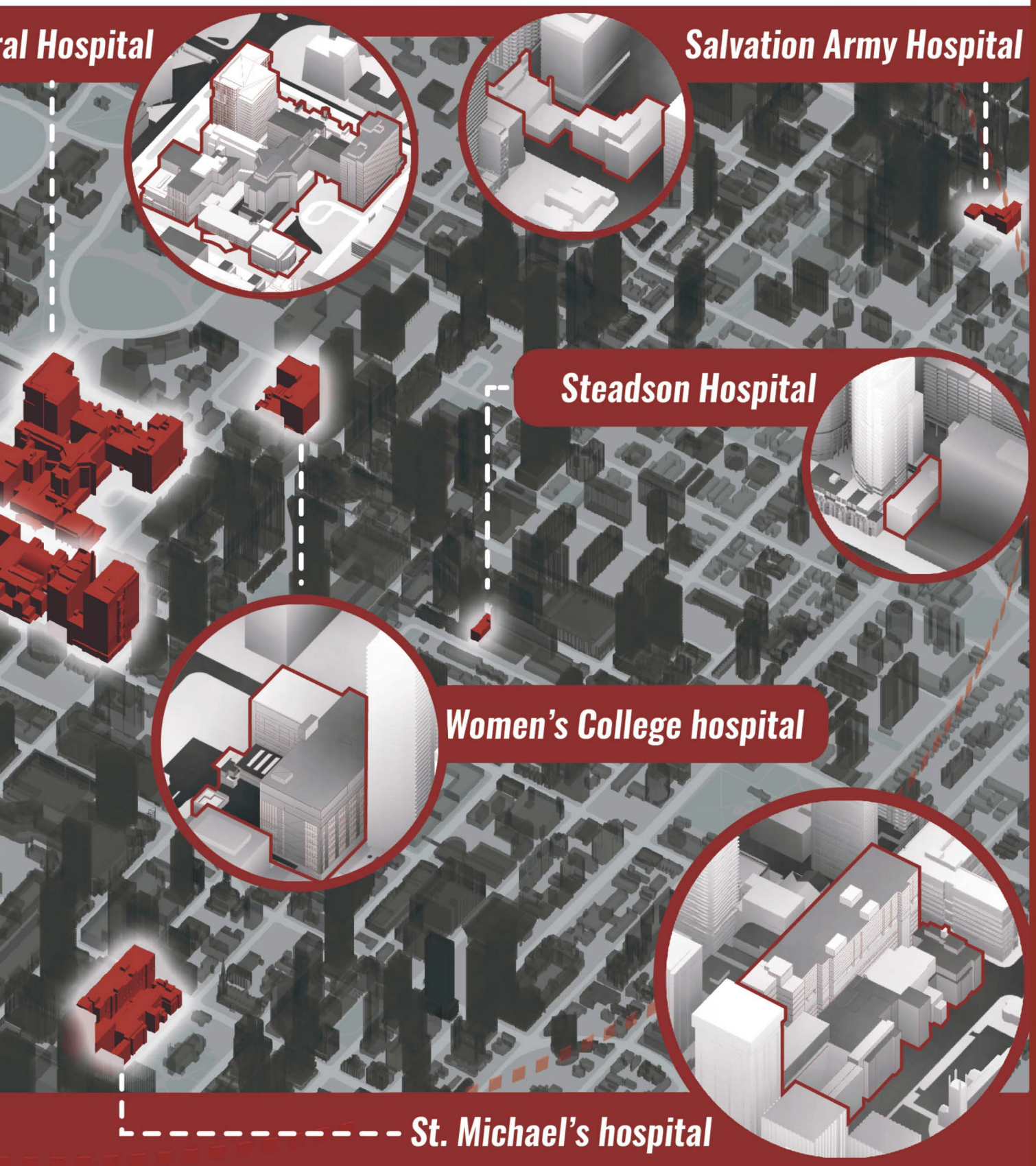


Figure 15a & b. Evolution of St. Micheals' Hospital from 1895 to Recent(St. Michael's Hospital Archives, 1895 and Infrastructure Ontario, 2023)

Local Impact of Urbanization



Mount Sinai Hospital	SickKids	Women College Hospital	Toronto Western Hospital
1954	**1983**	**1988**	**1976**
2145 m^2 28000 m^3	**1740 m^2** **242500 m^3**	1275 m^2 59000 m^3	1350 m^2 193850 m^3



Toronto General Hospital	St. Michael's Hospital	Salvation Army Hospital	Steadson Hospital
1971	**1973**	**1981**	**1970**
2950 m^2 34450 m^3	1710 m^2 173250 m^3	545 m^2 6550 m^3	275 m^2 14500 m^3

Mount Sinai Hospital is presently undergoing a total redevelopment in the name “Renew Sinai” (Mount Sinai Hospital. n.d.) of 274,500 m², with an envelope area of 2,145 m² being specifically developed, being largest one after 1973. SickKids is also evolving and adapting, with ongoing major redevelopment: “Project Horizon” (SickKids n.d.) after 1983, with a total redevelopment area of 242,500 m² and an envelope area of 1,740 m² (Illustration 5). Women's College Hospital is seeing a redevelopment after 1988 of 59,000 m², with 1,275 m² dedicated to the building envelope (Women’s College Hospital 2013). Toronto Western Hospital's redevelopment after 1971 encompasses 193,850 m², with 1,350 m² for the envelope (Illustration 6) (University Health Network 2023). Toronto General Hospital is focusing on a redevelopment after 1971 of 34,450 m², including 2,950 m² for the envelope (H.H. Angus & Associates 2005). St. Michael's Hospital's redevelopment project after 1973 covers 173,250 m², with 1,710 m² allocated to the envelope (Urban Toronto n.d.). Additionally, both Salvation Army Hospital and Stevenson Memorial Hospital, after 1981 and 1970, are undergoing smaller-scale redevelopments, with total areas of 6,550 m² and 14,500 m² respectively, and envelope areas of 545 m² and 275 m² respectively (Stevenson Memorial Hospital n.d.). These ambitious projects, including Camh (Illustration 6), highlights Toronto's commitment to modernizing its healthcare infrastructure and providing state-of-the-art facilities for its residents.

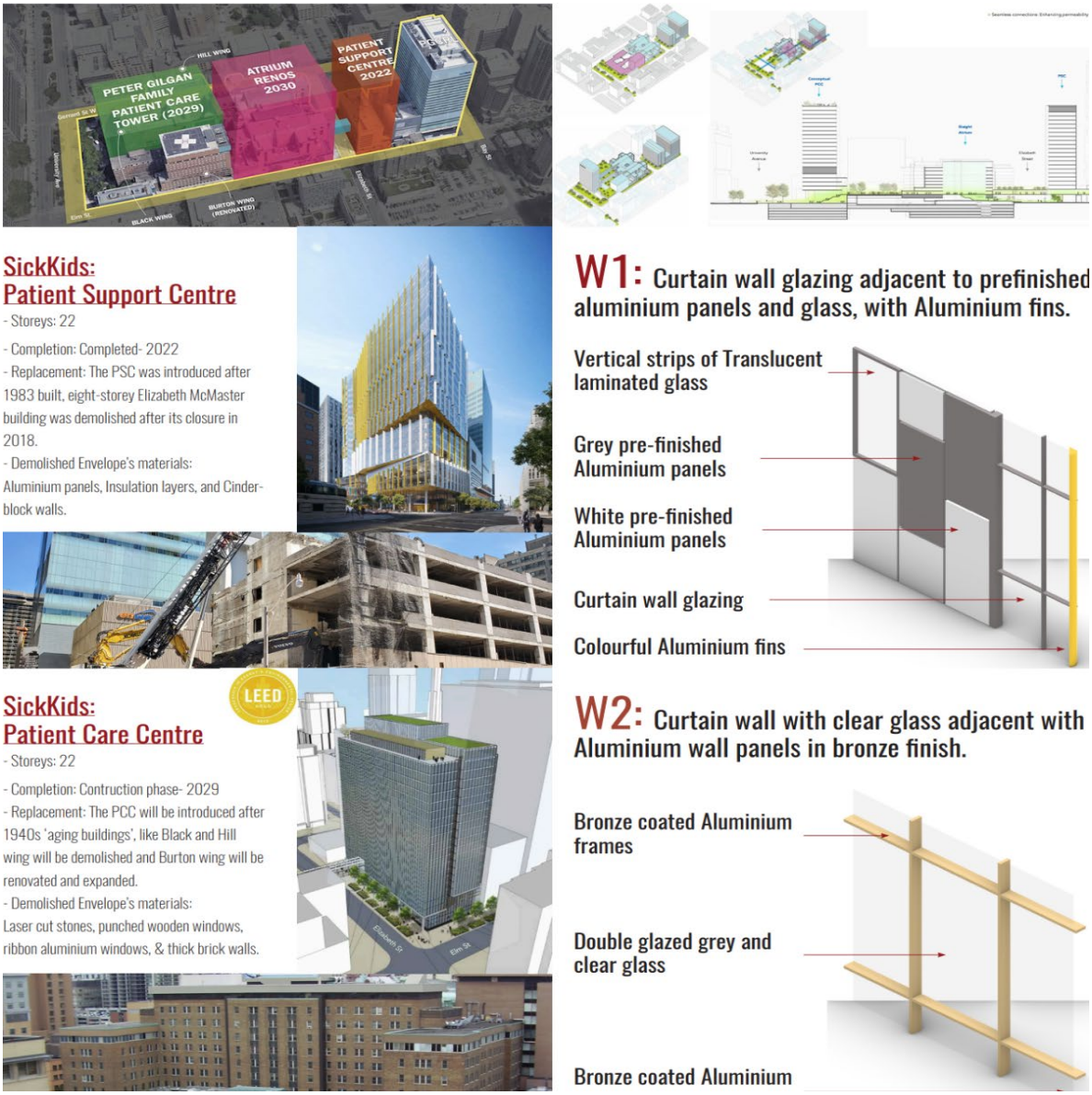


Illustration 5. Wall assembly study of SickKids’ buildings (created by author, 2024)

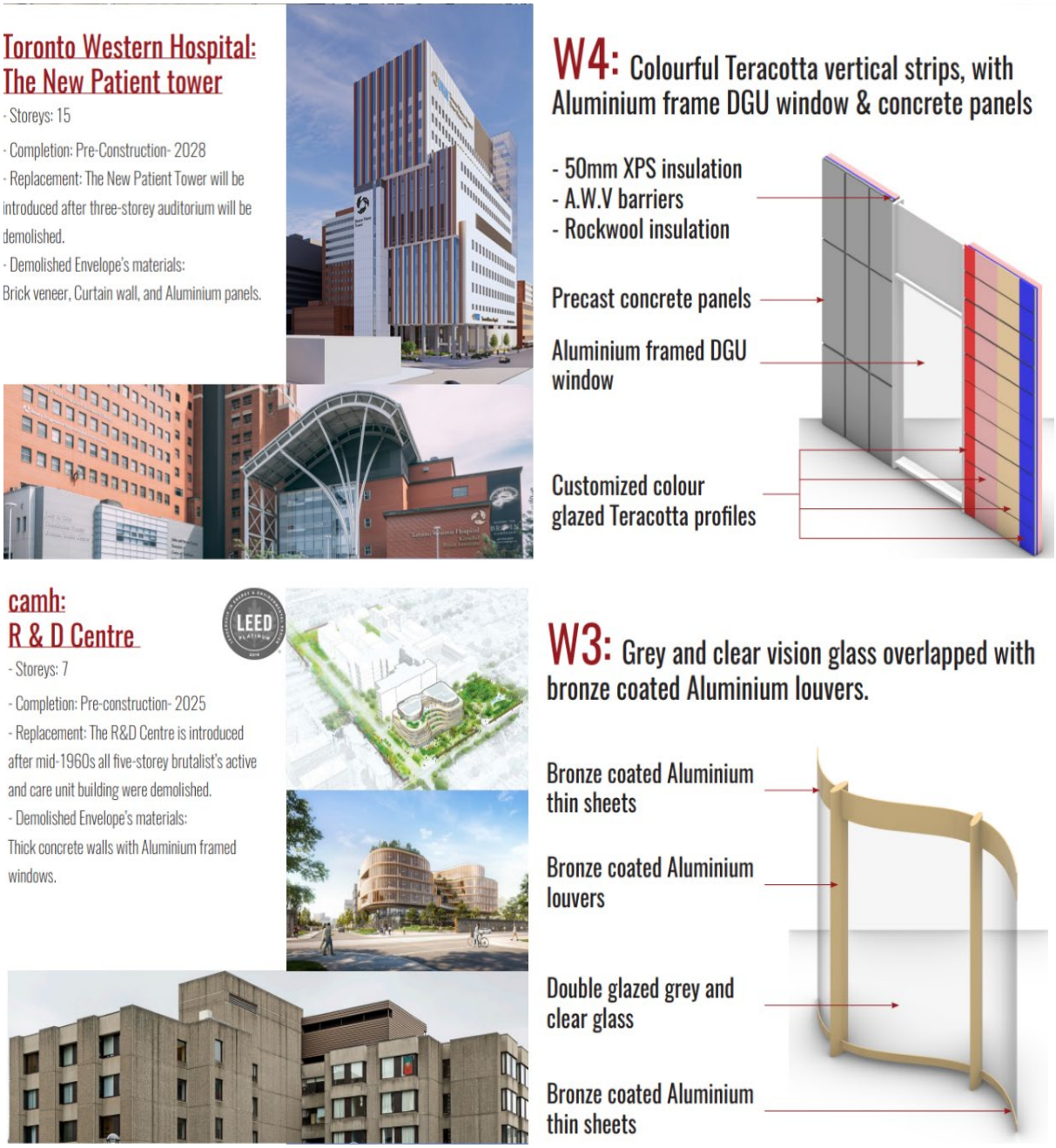


Illustration 6. Wall assembly study of Toronto Western Hospital and Camh's building (Created by author, 2024)

The Toronto Hospital construction projects primarily utilised aluminium and glass in their building designs. Aluminium was commonly used for frames, fins, and panels, providing flexibility and a contemporary look. Double-glazed glass was often used to enhance energy efficiency while offering natural light and views for patients and staff. Additionally, some projects incorporated unique materials such as colourful terracotta and bronze-coated aluminium to add visual interest. While these materials offer aesthetic and functional benefits, it's important to consider their embodied carbon footprint in the context of sustainable construction practices. Further discussion in the subsequent sections of the chapter will delve into the embodied carbon footprint associated with these material choices, offering valuable insights for future hospital projects seeking to minimize their environmental impact.

2.2.3 Why focus on the Healthcare sector?

1: The Healthcare Crisis

The term "Healthcare Crisis" signifies the significant challenges faced by the healthcare system in Toronto, Ontario, and across Canada in the post-pandemic era. These challenges have prompted both the public and the government to recognize the pressing issues within Toronto's healthcare infrastructure. These issues encompass several key areas. Firstly, many of the healthcare facilities in Toronto are aging and urgently require maintenance, updates, and modernisation. Addressing this backlog of overdue maintenance necessitates a substantial investment. Secondly, the growing population and the increasing demand for healthcare services are straining the existing infrastructure, resulting in overcrowding, longer wait times, and difficulties in delivering timely care. Therefore, the concept of "Healthcare Crisis" serves as a call to action to prioritize the enhancement of healthcare facilities in Canada and to explore how stakeholders in the construction industry can contribute to improving the situation.

2: The Elephant in the Room

"The Elephant in the Room" of the healthcare crisis is the distinct mismatch primarily between rapid advancements in healthcare technology and the failing state of many buildings in Toronto. These aging structures are incapable of housing modern medical equipment and systems, hindering advancement in patient care and highlighting a difference in priorities between government-led infrastructure and privately-owned projects. Government-led healthcare projects, such as those focused on research, often prioritise long-term benefits and sustainability. In contrast, privatised companies and owners prioritise short-term financial gains, leading to practices like the demolition of window-wall components rather than embracing circular practices within the construction industry.

This opposite approach is evident in the financial constraints faced by the healthcare sector, which make large-scale renovations or new construction challenging. However, there is a potential solution that aligns with the government's long-term vision: emphasizing sustainable construction methods and resource reuse. For example, focusing on the curtain wall system, often rich in valuable aluminium with high embodied energy, could help offset renovation costs. By prioritizing circular practices, such as repurposing materials and extending the lifespan of building components, the healthcare sector can move towards a more sustainable and financially viable future, aligning with the government's long-term goals while mitigating the short-term focus of the private sector.

1 + 2 = 3

In both "The Healthcare Crisis" and "The Elephant in the Room," it is evident that the healthcare sector is facing a dilemma. There is an urgent need to address healthcare facility issues quickly while also struggling to keep up with new technologies, energy-efficient buildings, and other advancements due to financial constraints in Toronto, Ontario, and Canada as a whole. To improve this situation, the thesis proposes implementing economic practices in the present and future, allowing for more effective fund allocation. One such practice involves the reutilisation of building materials, particularly curtain wall components such as aluminium, glass, steel, connectors, and thermal insulation. These materials can be reused by deconstructing older building envelopes or by planning to dismantle materials from curtain walls in new buildings approximately 30 years from now, resulting in significant cost savings. These savings can be categorized as typical (20-40% cost savings) or potential (up to 50% or more savings with high-quality materials and efficient deconstruction processes) (Borson 2013). Discussions with

stakeholders, including architects, material processors, and engineers, have highlighted the benefits of reusing materials rather than purchasing new ones. For instance, a standard aluminium unitised curtain wall (4mx1.5m) costs about $3500/piece, whereas reusing materials can lead to substantial cost reductions in building envelopes, potentially freeing up funds for specialized equipment such as cancer treatment machines, diagnostic tools, and research facilities at institutions like SickKids. Ultimately, these cost savings will directly benefit patients and enhance the hospital's ability to provide advanced care.

Is there a difference in the curtain walls of healthcare buildings compared to other types of buildings?

Patient care facilities incorporate a variety of structures beyond just hospitals, including administration and research buildings such as the SickKids Patient Support Centre and the Peter Gilgan Centre for Research and Learning. However, after consulting with stakeholders in the construction industry worldwide, it becomes evident that there isn't a significant distinction between these healthcare buildings and other commercial buildings with similar exterior envelopes. Whether considering materials, installation, acoustical performance, or impact resistance, healthcare buildings typically do might not differ by more than 10-15% compared to high-rise commercial or residential buildings with curtain walls. This indicates that any case studies and forensic analyses regarding the embodied carbon footprint of curtain walls apply to healthcare facilities as well, making it suitable to study them for this thesis. These findings demonstrate that the challenges related to the circular economy practices for unitised curtain walls are universal across building types. Given the complexities involved in the A1, A2, and A3 stages (Healthcare crisis, the elephant in the room, and 1+2) of curtain wall systems and the unique functions within healthcare settings, such as hospitals, administrative buildings, and research facilities, this research area aligns with the personal interest and expertise of the author, further justifying the focus of this thesis.

2.3 *SickKids*

2.3.1 History

The Hospital for Sick Children (SickKids) in Toronto boasts a long legacy of excellence in paediatric healthcare, research, and education. Founded in the late 19th century in a rented house on University Avenue through the efforts of Elizabeth McMaster and a group of Toronto women, SickKids saw significant developments in the early 20th century with the establishment of the purpose-built Victoria Hospital for Sick Children at College and Elizabeth Streets (Heritage Toronto n.d.). This period also marked pioneering medical advancements, including the first Canadian milk pasteurization plant, blood transfusions for children, and the invention of Pablum (SickKids n.d.). In 1951, SickKids moved to its current location at 555 University Avenue, followed by the founding of the SickKids Research Institute in 1954. Throughout the mid-20th century, SickKids continued to lead in medical breakthroughs, such as the Salter operation and the Mustard procedure. The establishment of one of North America's first paediatric intensive care units (PICU) at SickKids in 1968 further solidified its position as a leader (Figure 16) in paediatric healthcare (SickKids n.d.). As it moved into the late 20th century and beyond, the SickKids Foundation was established in 1972, and 1989, researchers at SickKids achieved a groundbreaking discovery by identifying the gene responsible for cystic fibrosis (SickKids n.d.).



Figure 16(left-to-right). A mother looks at her child in an isolation cubicle in this 1916 photo.; The Lakeside Home for sick kids from pre-1900(SickKids Archives, 2017)

However, in the 21st century, significant changes, such as “Project Horizon” (Figure 17), have taken place at SickKids. Their objective is to establish a cutting-edge academic health sciences centre, restore healthcare delivery, and involve patients and their families as active participants in their care. The initiative includes the development of a modern acute care hospital, patient support centre, and learning institute, worked in several phases: -

Phase 1: Patient Support Centre (PSC): This phase has been successfully completed with the inauguration of the 22-story PSC(Figure 18) on Elizabeth Street. The PSC consolidates administrative and educational functions, freeing up space on the current campus for future expansions.

Phase 2: Peter Gilgan Family Patient Care Tower: This phase involves the construction of a new acute care hospital on University Avenue. The tower(Figure 18) will accommodate inpatient units, operating rooms, diagnostic and treatment areas, and other essential services.

Phase 3: Outpatient Tower: This phase will focus on constructing a new outpatient facility to offer specialized clinics, ambulatory care, and other services for children and families.

Phase 4: Learning Institute: This phase will include the establishment of a new education and research centre to promote collaboration, innovation, and learning in paediatric healthcare.



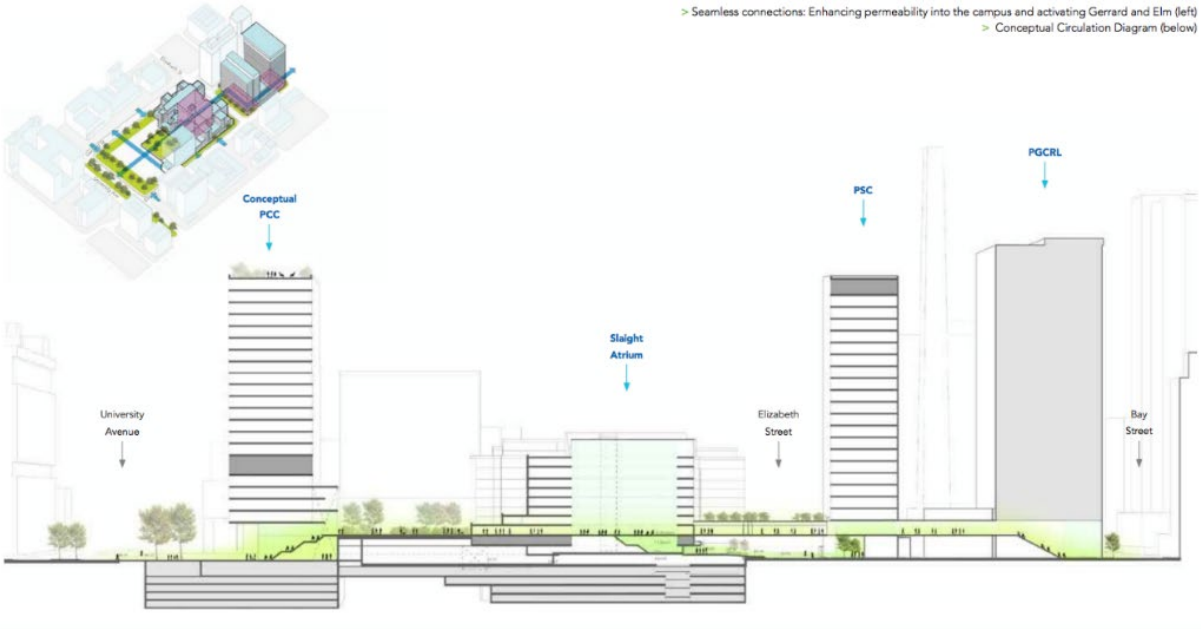


Figure 17(left-to-right). Conceptual Phase Redevelopment- a. SickKids Identity: The University Avenue Landscape; b. The Patient Support Centre: Demolish Existing McMaster Building; c. Conceptual Circulation Diagram (SickKids, 2015)



Figure 18(left-to-right). Project Horizon- Render visualisation of Patient Support Centre and Patient Care Centre, Toronto (SickKids, 2015)

2.3.2 Patient Support Centre, Toronto, Canada

The PSC project marked the initial phase of "Project Horizon," a comprehensive redevelopment initiative for the hospital's campus. As shown in Figure 19, it is situated between Gerrard Street East to the north, Elizabeth Street to the east, Elm Street to the south, and University Avenue to the west, the SickKids campus encompasses various prominent institutions including Toronto General Hospital, Mount Sinai Hospital, Women's College Hospital, the MARS Discovery District, and several University of Toronto health sciences-related faculty buildings.

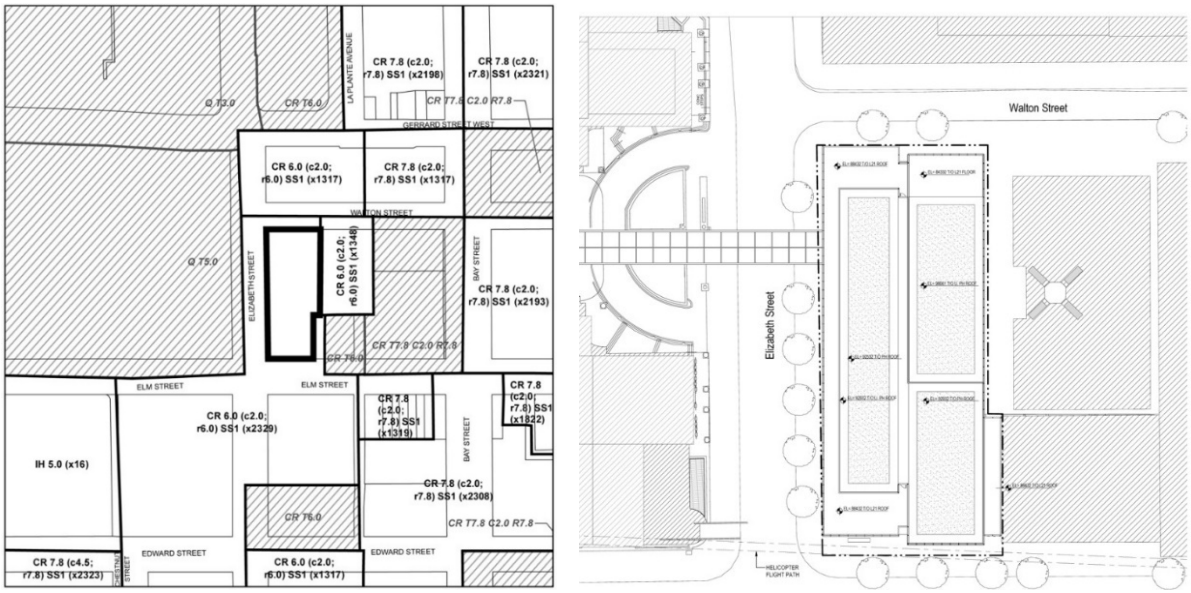


Figure 19(left-to-right). Patient Support Centre- a. Draft Official Plan Amendment; b. Site Plan (City of Toronto, 2018)

In May 2018, SickKids Hospital announced plans to demolish(Figure 21 and 22) the existing 8-storey Elizabeth McMaster Research Building (Figure 20) at 175 Elizabeth Street and replace it with a new Patient Support Centre (PSC) (City of Toronto 2018, 1-3). Positioned directly east of the main SickKids Hospital campus and adjacent to the Peter Gilgan Centre for Research and Learning at 686 Bay Street, the PSC project proposed a new 22-story tower(Figure 23) for institutional use, standing at a height(Figure 25) of 98.66 meters and offering 44,520 m² of non-residential gross floor area with a density of 19.6 times the area of the lot (City of Toronto 2018, 1-3).

The application also included provisions for 183 bicycle parking spaces, with vehicular parking and loading situated off-site (City of Toronto 2018, 1-3). The PSC (Figure 24) was designed to accommodate patient support services, education, and administrative functions for SickKids Hospital. Notably, the building was constructed with 0-meter setbacks along all property lines, and the first two stories were set back 4.1 meters along Elm Street and 3.2 meters along Walton Street. Furthermore, the project involved the demolition of the existing pedestrian bridge (Figure 22) across Elizabeth Street with a new 6.03-meter-wide pedestrian bridge now connecting the PSC with the Slaight Atrium Building to the west at the third story, mirroring the location of the previous pedestrian bridge (City of Toronto 2018, 4).

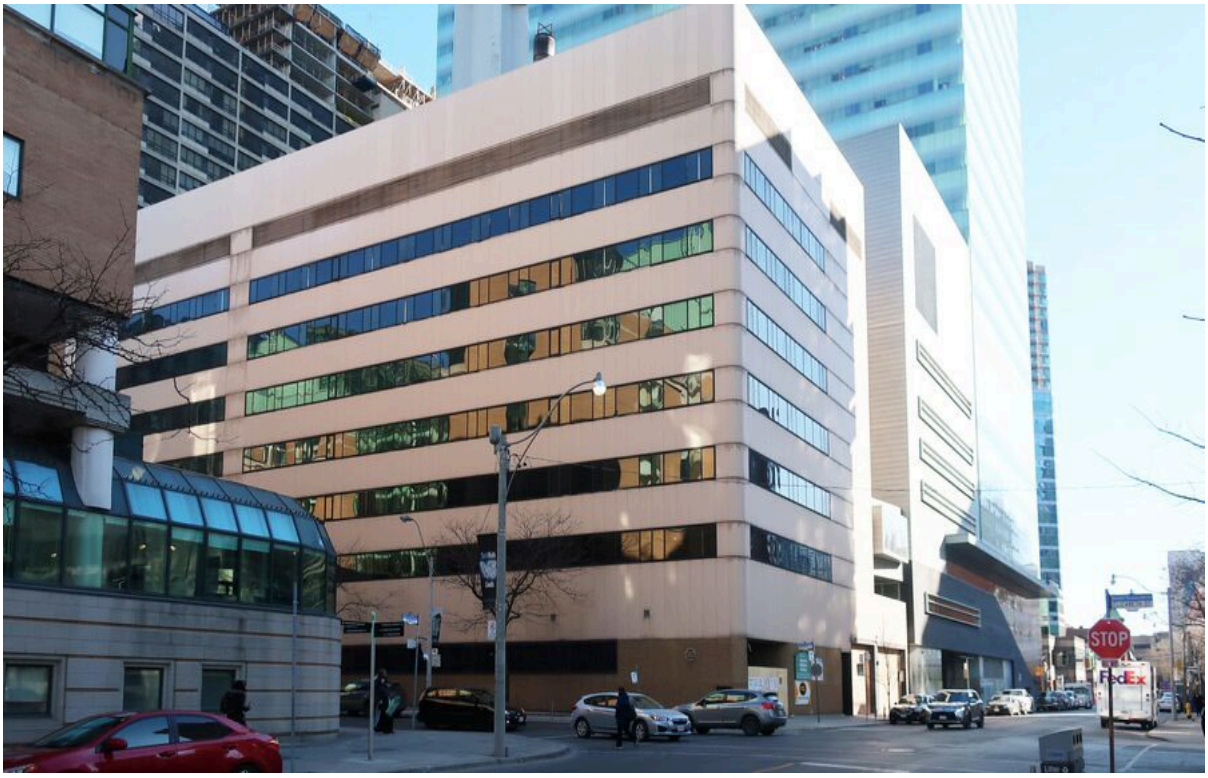


Figure 20. Elizabeth McMaster Building when opened in 1986 (The Globe and Mail, 2020)



Figure 21. Demolished materials from Elizabeth McMaster Building (SickKids, 2019)



Figure 22. Demolition of SickKids' old bridge (SickKids, 2019)



Figure 23. Artist Rendering of the Patient Support Centre (B+H Architects, 2023)



Figure 24. A glass-enclosed bridge connected to SickKids PSC with the main hospital. (The Globe and Mail, 2020)

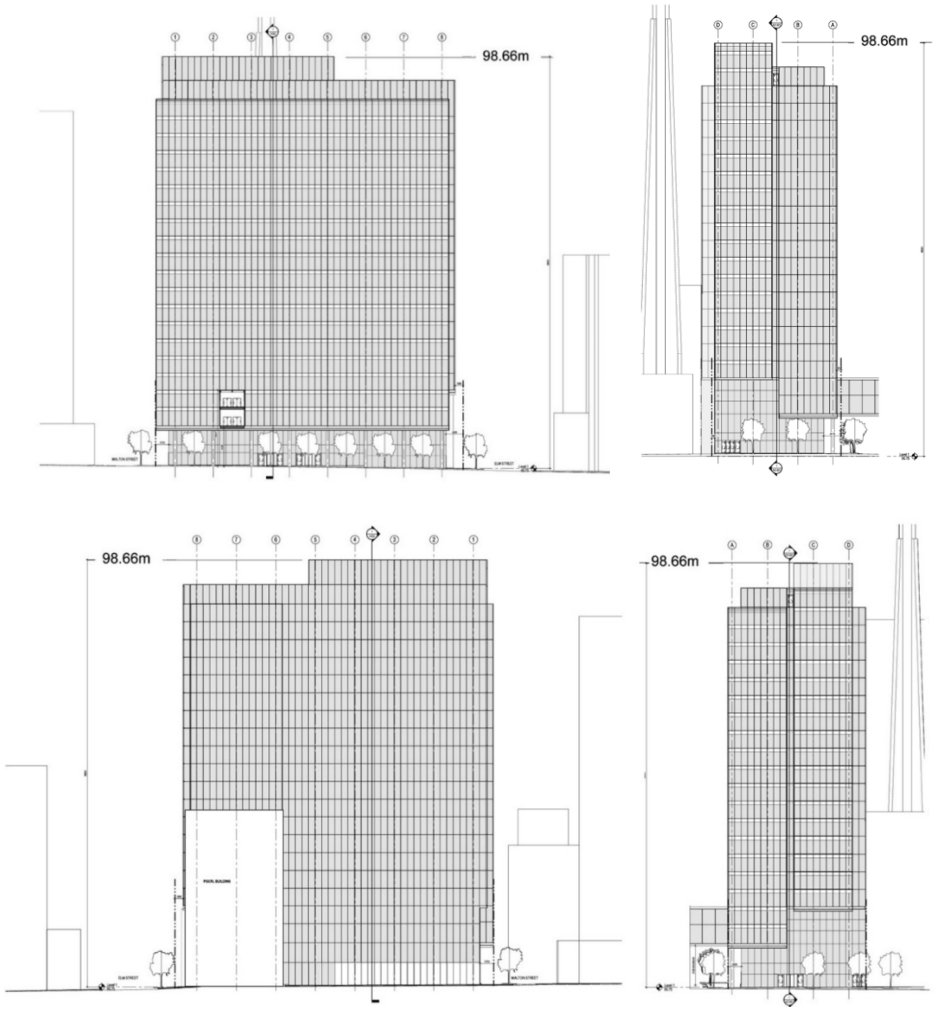


Figure 25(left-to-right). Patient Support Centre- a. West Elevation; b. South Elevation; c. East Elevation; d. North Elevation; (City of Toronto, 2018)

2.3.3 Stages

During Throughout the five-year renovation of the Elizabeth McMaster Building (Figure 26) into the Patient Support Centre (PSC) (Figure 28), a meticulous, multi-stage process was carried out. This process involved the careful demolition of the existing structure (Figure 27), followed by the step-by-step construction of the new building, encompassing its framework, exterior, and interior spaces. To gain a comprehensive understanding of the site's transformation, the author of this thesis conducted a thorough forensic analysis during the project's five distinct phases.

The detailed information was obtained by using two methods. Firstly, data was collected from various online sources such as Urban Toronto and reports from the City of Toronto, including user comments. This information helped to define the different types and quantities of building facades. For example, tracking the project's progress, starting from the demolition of the Elizabeth McMaster Building to the new construction of the Patient Support Centre (PSC) from 2017 to 2023. Analysing approximately 370 replies in the 'Building Discussion' section on Urban Toronto's forums provided insights from facade engineers and laymen about the technical and aesthetic aspects of the building. The author also studied periodic photos of the project's progress to understand the materials, installation processes, and step-by-step developments from these discussions.

The analysis of meticulously documenting the typologies, layers, and dimensions of the building elements, provided both quantitative and qualitative insights into the site's evolution over time. Crucially, this in-depth analysis yielded valuable information about the site's embodied carbon and building circularity, shedding light on its environmental impact and potential for sustainable practices. These findings were further explored and elaborated upon in the later section of the report.



Figure 26. Demolition of facade of the Elizabeth McMaster Building (Red Mars, 2019)



Figure 27. Demolition of Elizabeth McMaster Building' core (Urban Toronto, 2019)



Figure 28. Unitised curtain walls on lower levels of PSC(Johnny Au, 2022)

1. STAGE 1: Demolition

The Forensic Architecture investigation centred on the Elizabeth McMaster Building, an eight-story structure erected in 1983 at the intersection of Elm and Elizabeth Streets, was documented by the author. The detailed examination thoroughly documented the building's transition from abandonment to the initial stages of significant renovation. The study was outlined in data from Urban Toronto (2018-2019). This transitional phase involved the removal of the aluminium facade, revealing the underlying insulation and cinderblock walls, effectively inverting the building's spatial configuration by making the formerly dark, vacant interior the new exterior. Through this process, a detailed analysis (Illustration 7) of the building envelope systems identified four distinct typologies, each characterized by unique dimensions and material compositions. These typologies comprised three sizes of aluminium panels (1650 x 600mm, 2100 x 600mm, and 3300 x 600mm) and curved aluminium panels with identical dimensions but incorporating a 600mm radius curve along all four edges. Furthermore, ribbon windows and fixed glass panels measuring 1200mm x 1200mm were integrated into the design alongside 180 aluminium ventilation grills, each measuring 1650 x 600mm. (ShonTron 2019)

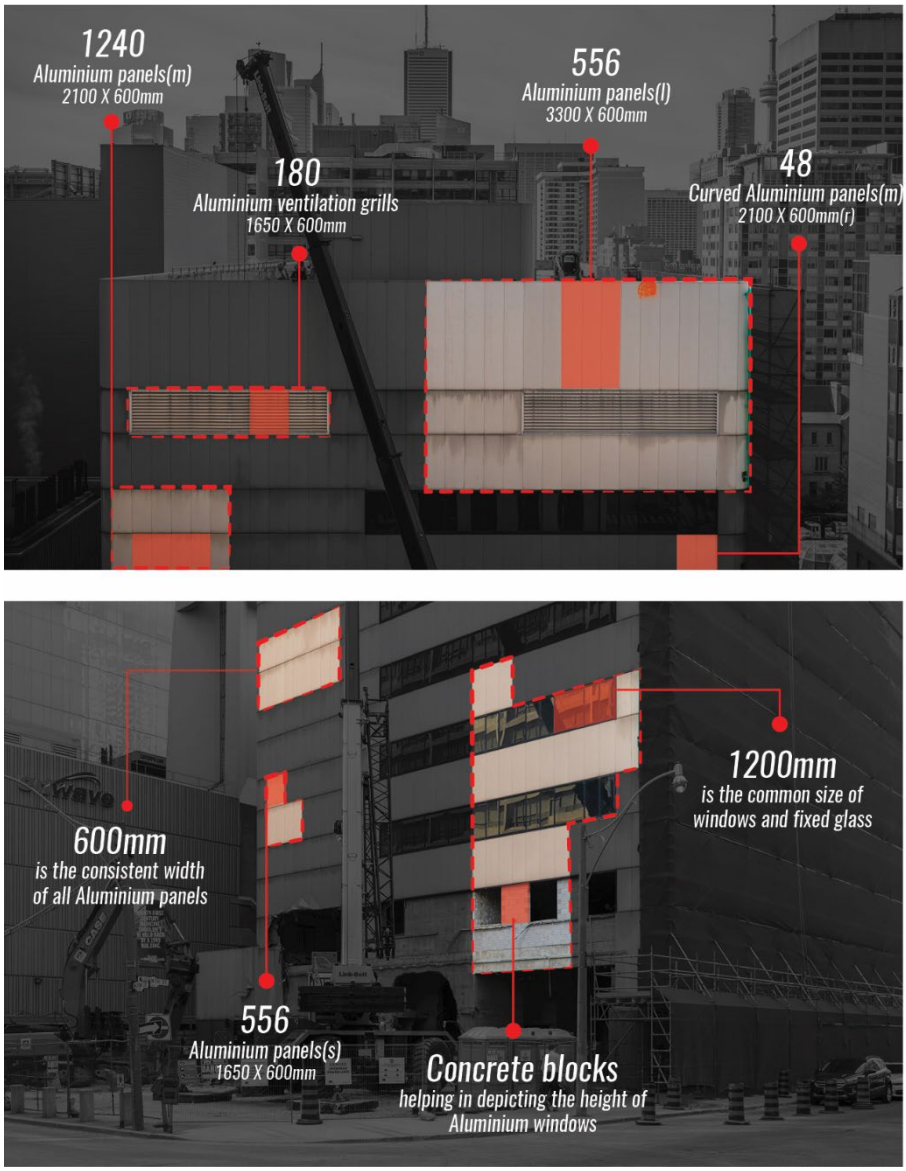


Illustration 7. Forensic Architecture of Elizabeth McMaster Building (Adapted from Jack Landau, 2019)

2. STAGE 2: Material Contribution

The second stage of the forensic architecture analysis focused on the demolition of the Elizabeth McMaster Building, the installation of the core structural members of the PSC, and the timing of the envelope installation in October 2021. This phase(Illustration 8) marked the beginning of our in-depth exploration of the primary focus of this thesis, which includes various types of unitised and stick curtain walls. During the assessment (Benito 2022) of three types of wall assemblies, it was found that 495 curtain wall panels were dual-coated (white and yellow) for shading and aesthetic purposes, 953 curtain wall panels had coatings at the top and bottom, and the materials in the curtain wall (4000mm X 1500mm) included tinted and clear glass, aluminium extrusions such as mullions and transoms, and 100mm glass wool thermal insulation.

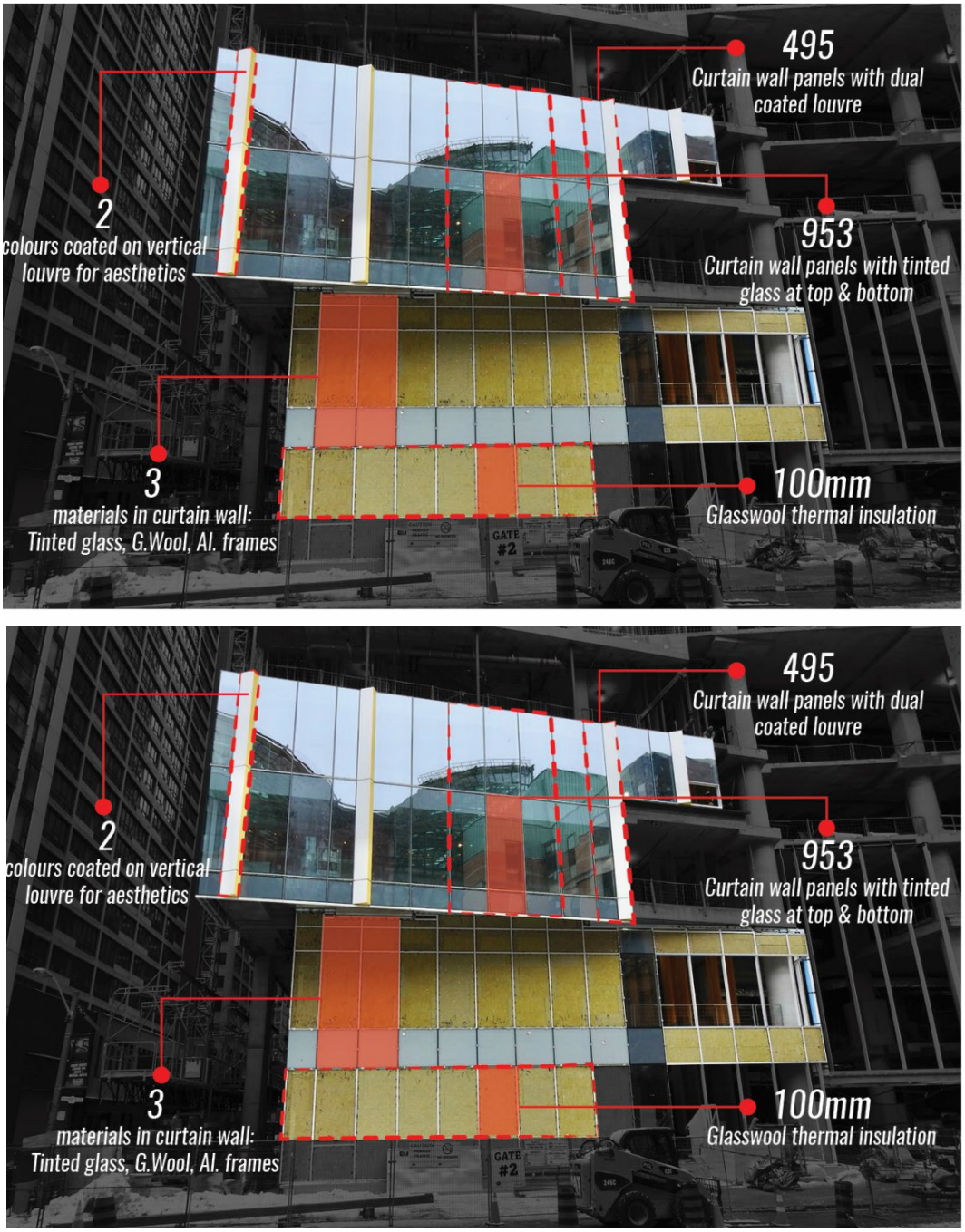


Illustration 8. Forensic Architecture of Patient Support Centre (Adapted from Urban Toronto, 2022)

3. STAGE 3: Component Contribution

As shown in Illustration 9, in the stage 3 of the installation, which was commenced four months later (around December), new stick curtain walls were primarily added to the lower floors, along with several new types of unitised curtain walls at the rear, specifically on the Northeast elevation of the PSC Building (drum118 2022). These included clear unitised curtain walls measuring 3600 x 1200mm, with 174 units, and another type with an additional aluminium strip, totalling 100 units. Both types featured a 1mm thick Blueskin Vapour-Water barrier.

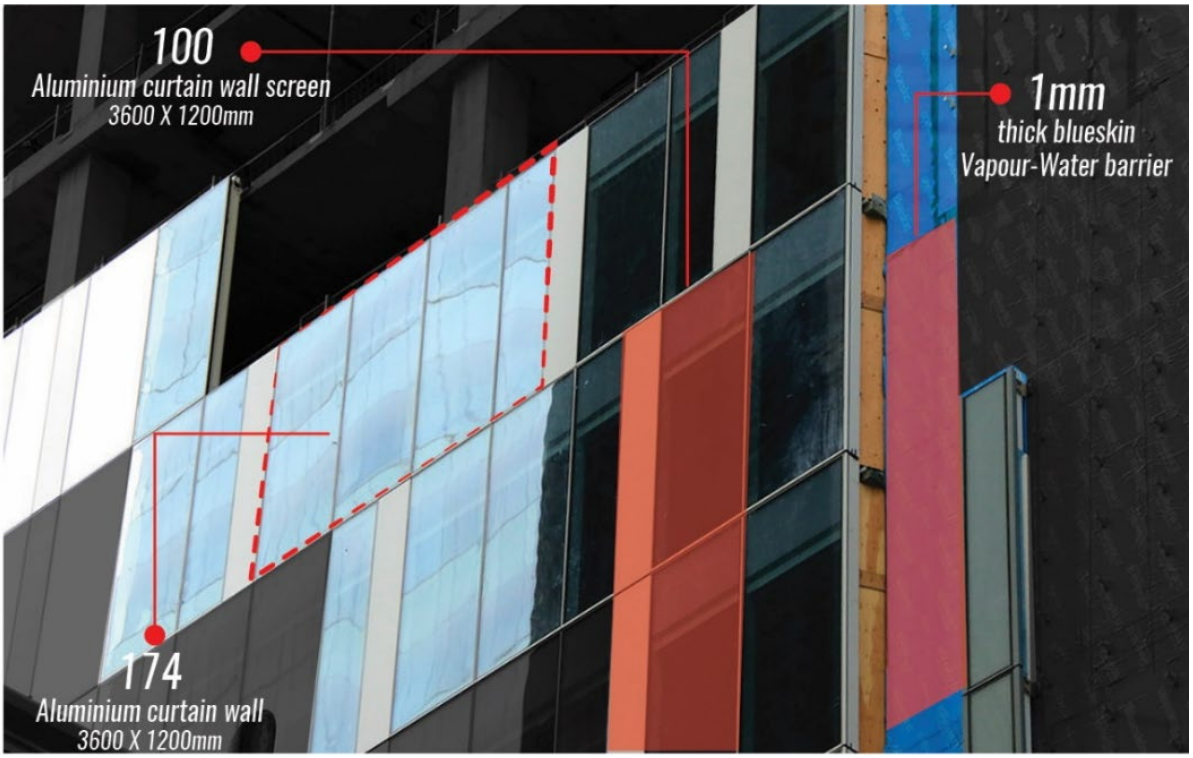


Illustration 9. Installation of Unitised Aluminium curtain walls on South Elevation (Adapted from Urban Toronto, 2022)

4. STAGE 4:

In the second last stage, stage 4, continued using the same wall assemblies as mentioned for the street elevations, with a significant focus on the rear elevation in the North-west. This stage provided a deeper understanding(Illustration 10) of the processes behind the final finish of the building's facades. A key feature was the incorporation of 1682 Coated Aluminium spandrel panels measuring 1800 X 600mm. The layers, from outside to inside, consisted of 600 X 600mm hollow steel sections in a structural grid, serving the purposes of creating air gaps and preventing water and moisture intrusion. Additionally, 12.5mm thick GlassRoc gypsum boards were observed connected with concrete blocks. Furthermore, 276 Coated Aluminium sleek curtain walls were made, with tinted glass measuring 3000 X 600mm in two colours: yellow and dark grey. These curtain walls effectively provided ample natural light to the service areas.

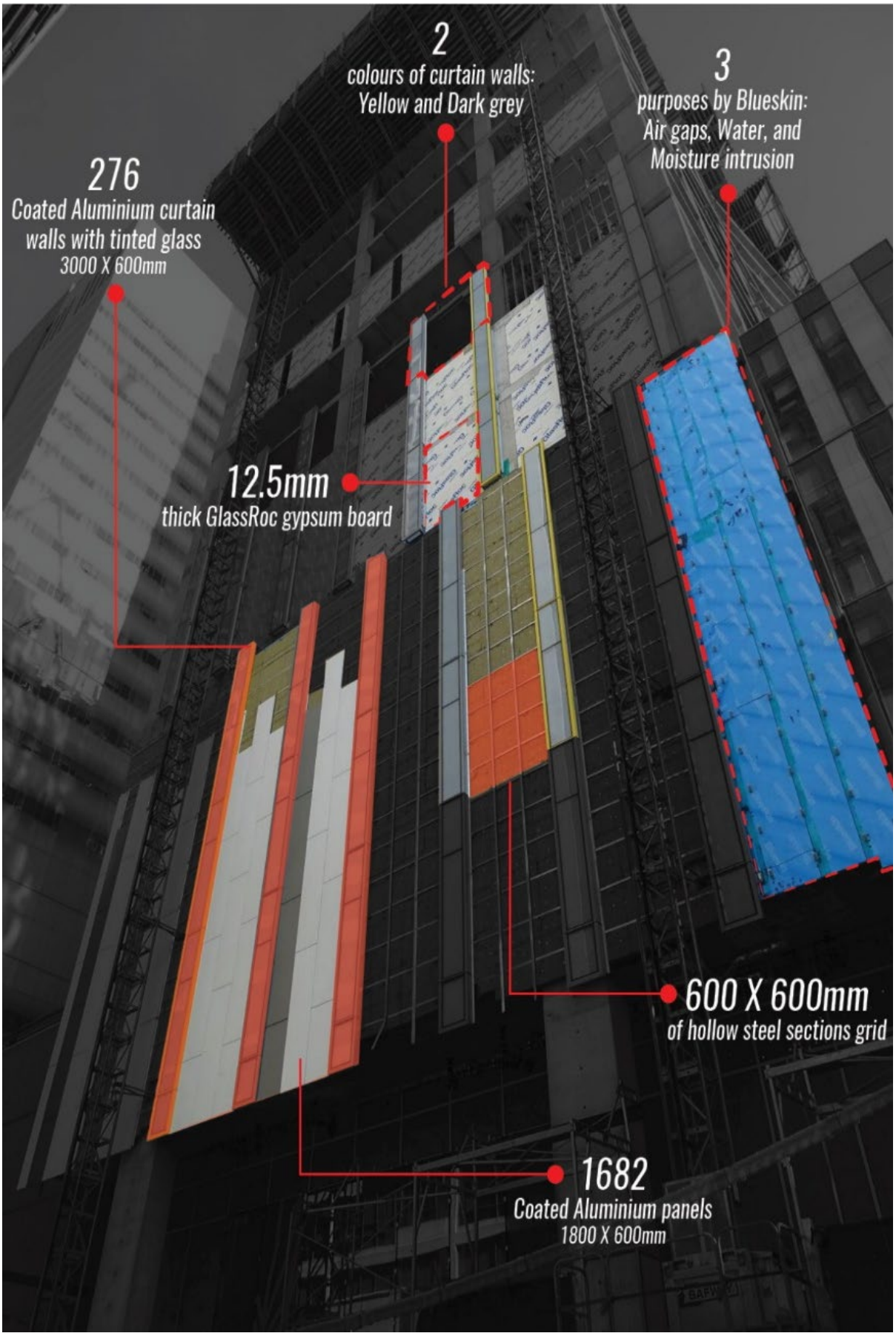


Illustration 10. Layers of Aluminium panels(Adapted from Urban Toronto, 2022)

5. STAGE 5:

In the final stage, two types of aluminium spandrel panels and grills(Figure 29) were used to cover the remaining hidden areas that were not the main focal point. These were coated in grey on the front and rear sides. Additionally, the first six wall assemblies, including the unitised and stick curtain walls, as well as larger aluminium spandrel panels, were completed. The Patient Support Centre was later opened on September 29, 2023.

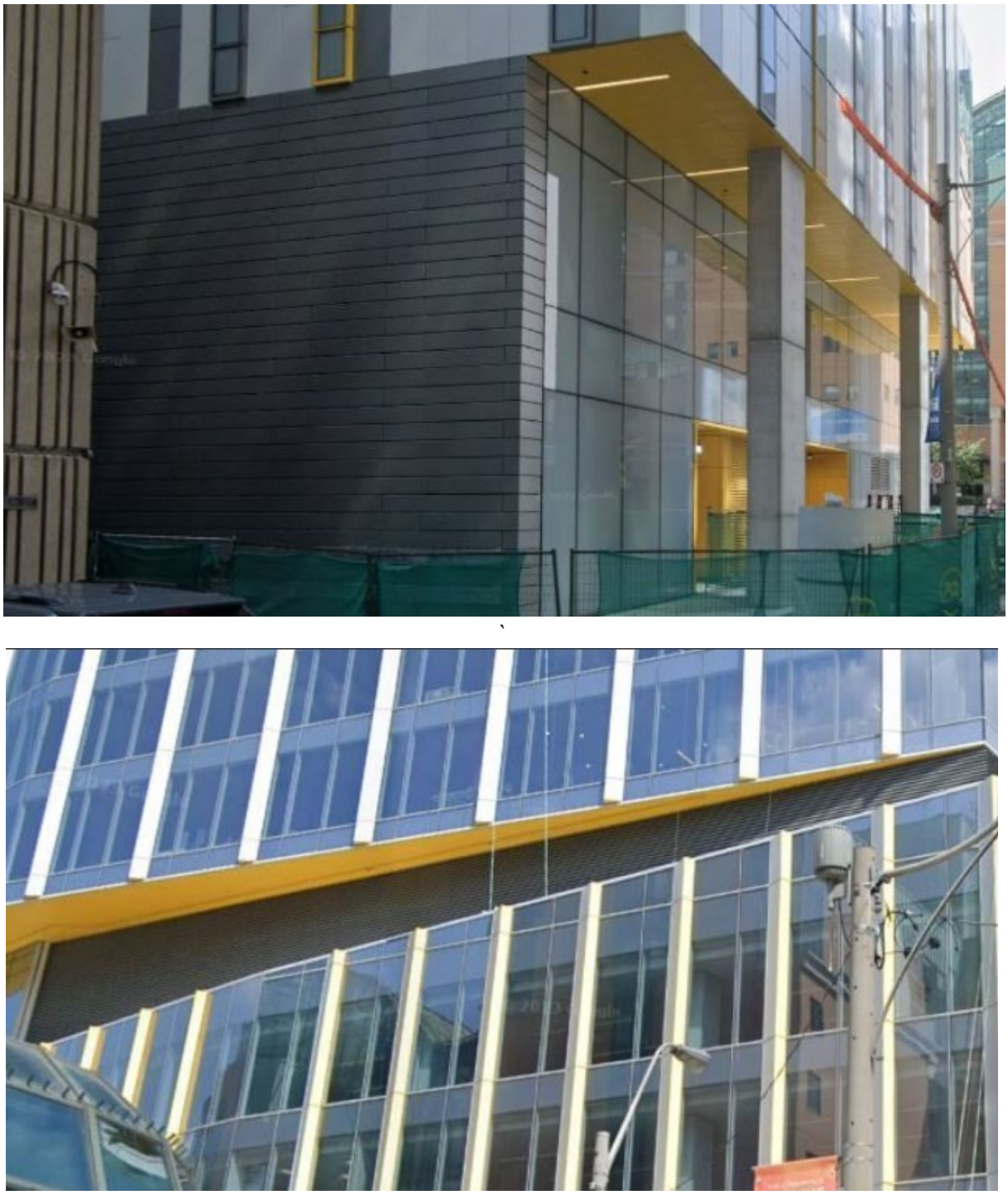


Figure 29. Final installation of Aluminium spandrels and grills (Urban Toronto, 2022)

2.3.4 McMaster & PSC: Forensic Analysis, LCA, and Building Circularity

A. McMaster Elizabeth Building

i. Typologies

The McMaster Elizabeth Building focused primarily on four types of wall assemblies, designated as W1, W2, W3, and W4 as depicted in the Illustration 11. Based on available plans, sections, elevations, images, and specifications, a Revit model of the building envelope was created by the author. The model encompassed the various panels attached to the shell, their insulation layers, air-water-vapor barriers, as well as other ventilation and daylighting components such as grilles and windows. Further details about these assemblies are provided below: -

W1: Aluminium Spandrel panels

There was a total of 3532 wall assemblies, available in three different sizes: small (1.65m X 0.6m), medium (2.1m X 0.6m), and large (3.3m X 0.6m). Each assembly consisted of the following layers, from the outside to the inside: Aluminium panels, thermal insulation, air-vapour barrier, aluminium sheets, and concrete blocks for support.

W2: Windows and Ventilation Grills

This component included 486 openable and fixed aluminium framed single-glazed windows, each measuring 1.65m X 1.2m. These windows were installed as ribbon windows on all eight floors for daylighting and ventilation purposes. Additionally, aluminium ventilation grills were installed parallel to the windows on the top floor.

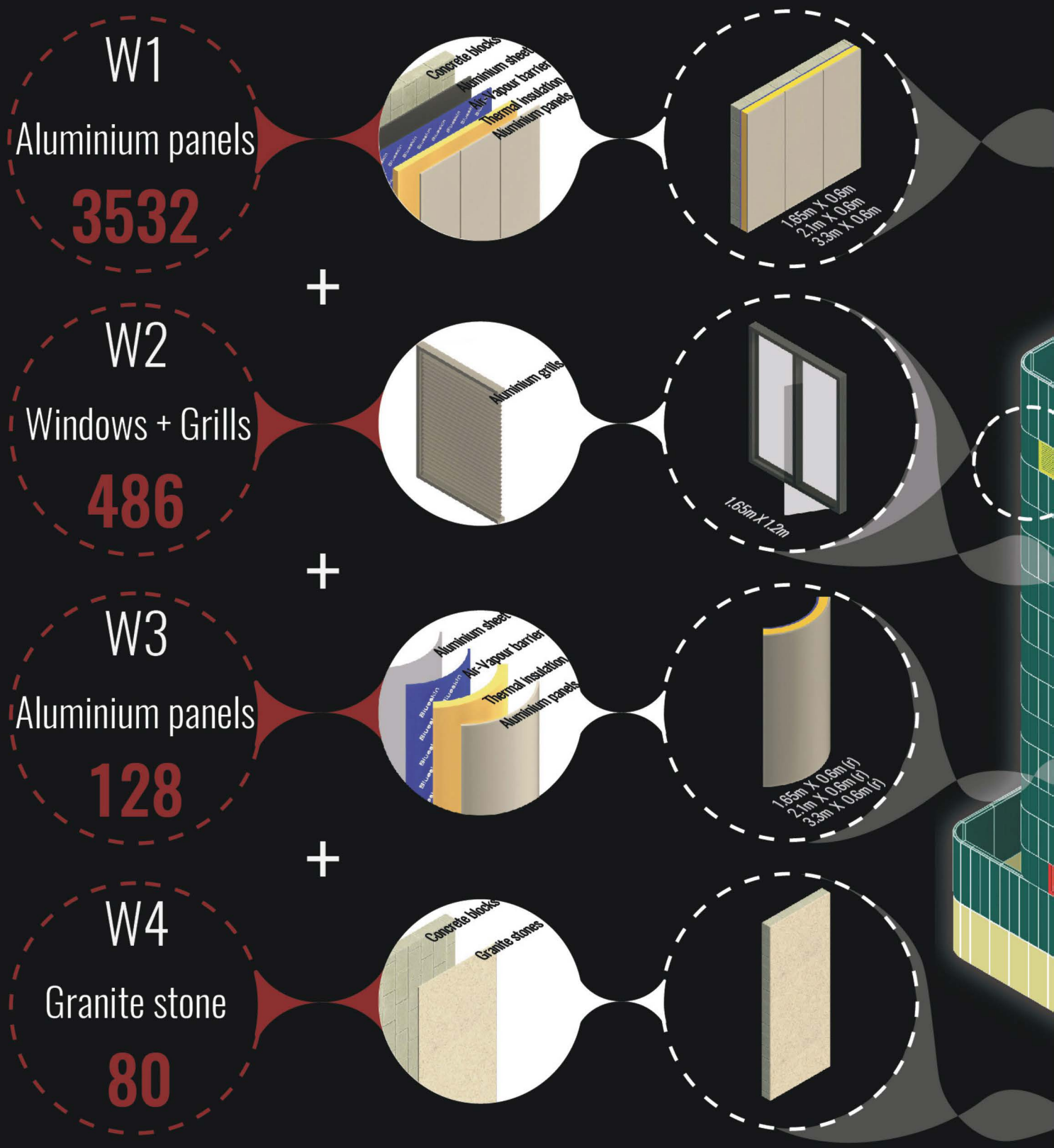
W3: Curved Aluminium Spandrel panels

These aluminium spandrel panels, categorized as W3, were curved in shape and placed at all four corners of the building to enhance the building's aesthetics. There were 128 of these wall assemblies, with the same insulation layers and dimensions as W1, but in a curved form. The dimensions in radius were as follows: small (1.65m X 0.6m (r)), medium (2.1m X 0.6m (r)), and large (3.3m X 0.6m (r)). The layers from the outside to the inside were: Aluminium panels, thermal insulation, air-water-vapour barriers, and aluminium sheets.

W4: Granite stone

The fourth and final wall assembly was made of beige granite stone and was primarily installed on the first floor of the building. There were 80 of these assemblies, with cement and concrete blocks providing support on the backside.

SickKids : Forensic Analysis : McMaster

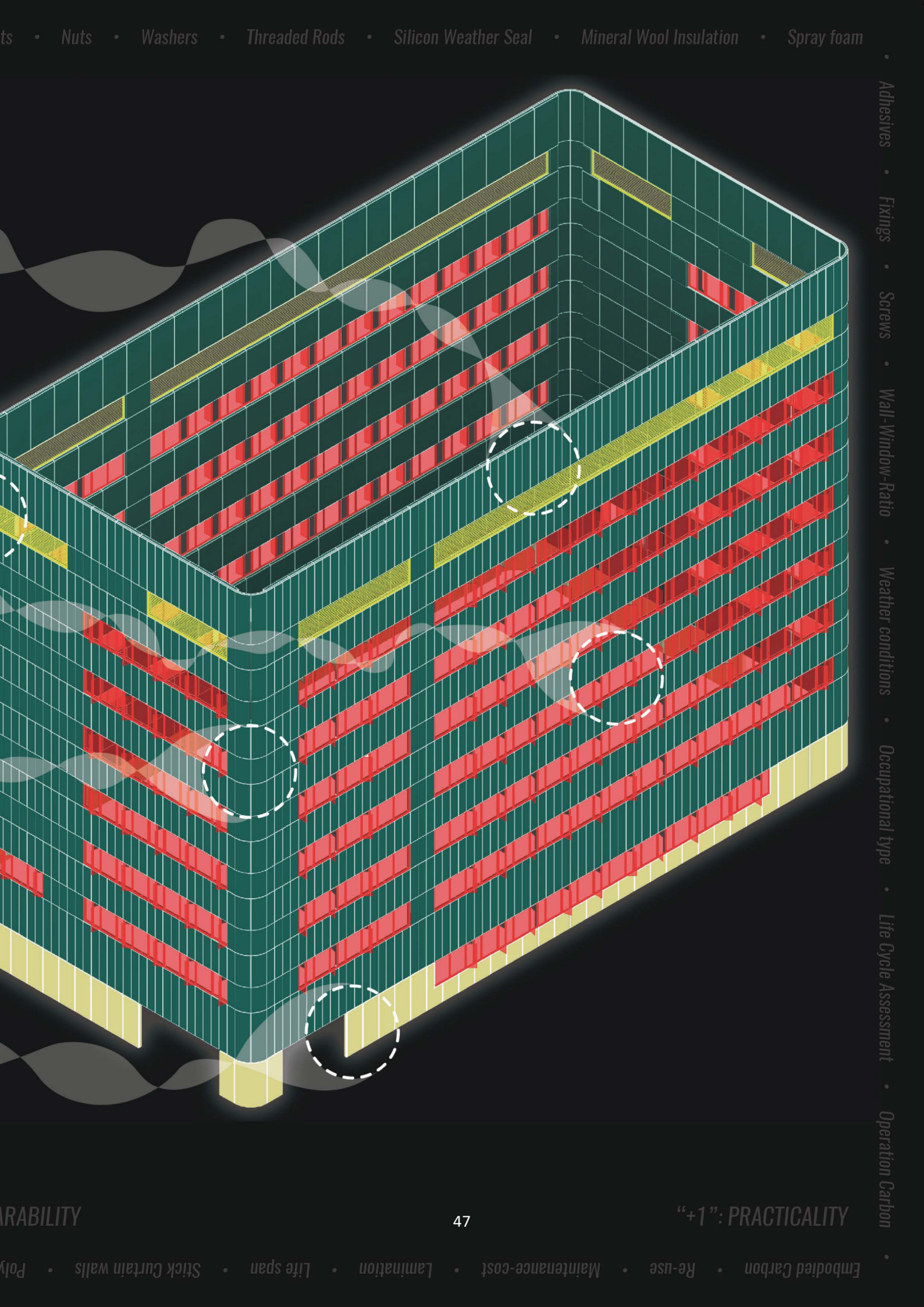


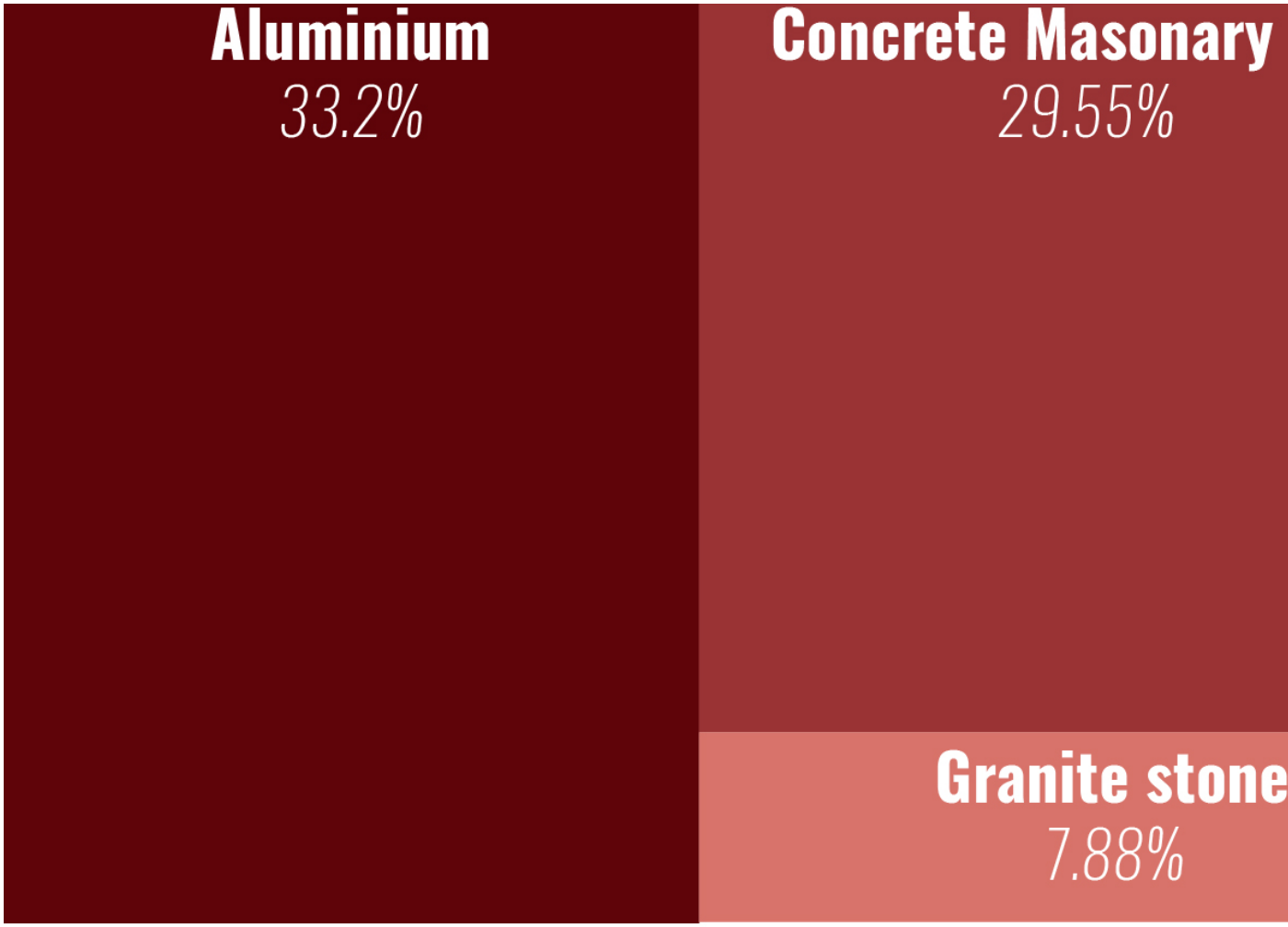
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4226 units

"-1": CLARITY

"0": COMPA

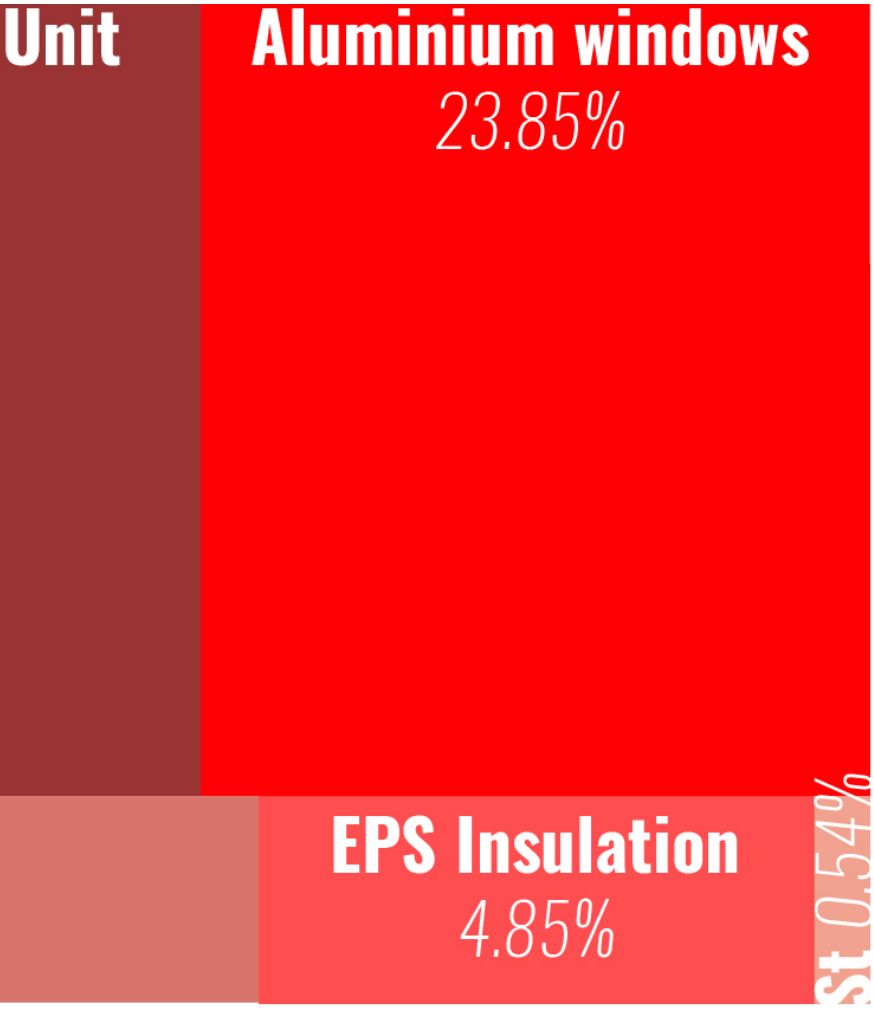

ts • Nuts • Washers • Threaded Rods • Silicon Weather Seal • Mineral Wool Insulation • Spray foam
• Adhesives • Fixings • Screws • Wall-Window-Ratio • Weather conditions • Occupational type • Life Cycle Assessment • Operation Carbon •
ARABILITY
"+1": PRACTICALITY
Poly • Stick Curtain walls • Life span • Lamination • Maintenance-cost • Re-use • Embodied Carbon •



Material covered	1.2%
Virgin	**98.8 %**
Renewable	**0 %**
Recycled	**1.2 %**
Reused	**0 %**
Material returned	3.1%
Reuse as material	**0 %**
Recycling	**3.1 %**
Downcycling	**0 %**
Use as energy	**0 %**
Disposal	**96.9 %**



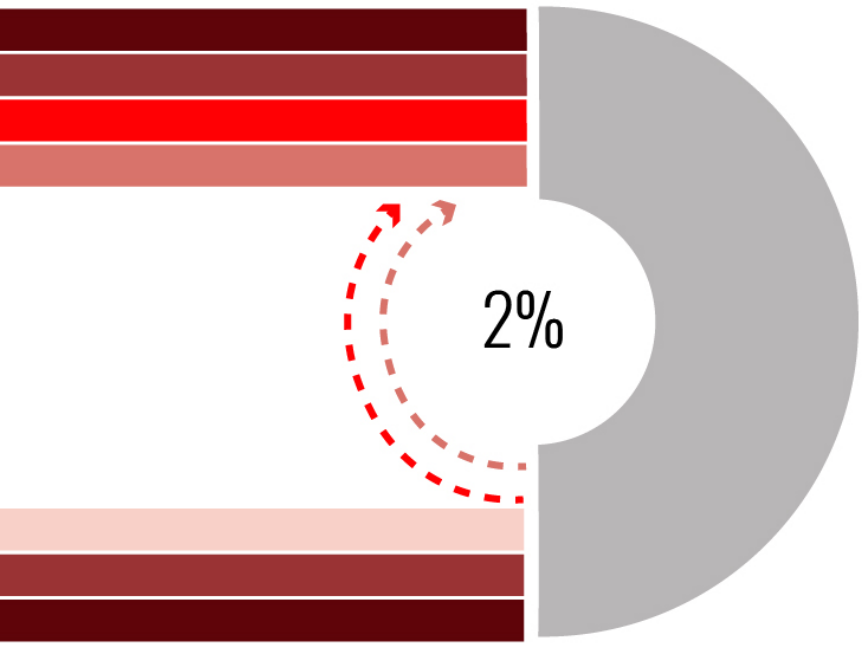
Illustration 12(left-to-right). Tree map depicting material's carbon



Aluminium
+
Glass

57.05%
of facade

6,21,557
CO_2e



68%
of circularity

0%
of Adaptive reusability

emissions; Building circularity diagram (Created by author, 2024)

ii. LCA: Life Cycle Assessment & Building Circularity

In the evaluation of Elizabeth McMaster's building, the second step involved conducting a Life Cycle Assessment. OneClick LCA software was used by the author, for this assessment, providing data on the embodied carbon footprint and building circularity by detailing the materials and their quantities used. The software utilised available EPD (Environmental Product Declaration) reports from North America or nearby areas.

Upon inputting all the necessary data, the tree map (Illustration 12) revealed that materials such as Aluminium and Glass played a significant role, contributing 57.05% of the total embodied carbon in the building, equivalent to 621557 $kgCO_2e$, which is comparable to driving around the Earth's circumference over 60 times! Furthermore, an analysis of Building Circularity focused on examining any approaches taken to minimize waste and maximize the reuse and recycling of materials at the end of their lifecycle. The findings indicated that approximately 98.8% of the materials used in the construction of the building were virgin, and during the demolition of the envelope, only 3.1% could be recycled, while the remaining materials were disposed of or downgraded. This suggests that due to the lack of a 'Circular' mentality in the construction industry, there was a missed opportunity to reuse, remanufacture, and refurbish high-potential materials like Aluminium, and no consideration was given to avoiding direct landfilling of materials like glass. This concept highlights the absence of a mindset (0%) focused on an adaptive reusability vision for building materials, leading to a continuous increase in embodied carbon.

B. Patient Support Centre

i. Typologies

The recently completed Patient Support Centre featured several advanced wall assemblies with intricate connections compared to the Elizabeth McMaster Building. The building focused on six types of wall assemblies, labelled as W1-W6, as shown in Illustration 13. A new Revit model was created by the author, based on the available drawing sets provided by B+H Architects and involved consultants, images and specifications available online (City of Toronto 2018, 28-32), and personally visits. The 22-storey model comprised various panels attached to the shell, individually (unitised curtain walls) or assembled like stick curtain walls and aluminium spandrel panels. The model included over 70% clear glazing assemblies, with some areas covered with opaque panels where daylighting was not a primary consideration. Further details on all the diverse options are provided below:

W1: Aluminium Spandrel Panels

The initial wall assembly discussed in this report is situated on the northwest side of the PSC Building. There are two varieties of aluminium spandrel panels, each measuring 1.8m x 0.6m, with an estimated total of 2468 panels. These assemblies comprise four layers (from outer to inner): dark, grey-coated aluminium panels, thermal insulation, and A-W-V barriers, and are supported by gypsum sheathing.

W2: Aluminium Curtain Walls 1

There are 276 vertically installed aluminium curtain walls running parallel to W1. These components, sized at 3.0m x 0.6m, are coated in yellow or white and are layered with glass screens and double-sided glass, supported by aluminium frames with an air-vapor barrier.

W3: Aluminium Curtain Walls 2

There are 100 curtain walls measuring 4.5m x 1.2m. These walls are framed with aluminium extrusions and incorporate two sections of double-sided glass, with one part consisting of opaque light grey-coloured glass screens. The design of these wall assemblies' balances visibility requirements and solar shading.

W4: Aluminium Curtain Walls 3

There are 495 W4 curtain walls, each measuring 4.5m x 1.2m, with a similar design to W3, including double-sided glass and opaque light grey glass screens. These wall assemblies also feature double-coated triangle-shaped aluminium louvers, providing solar shading and enhancing the aesthetic appeal.

W5: Aluminium Curtain Walls 4

The unitised curtain wall W5 is the most prevalent type, with 953 members. These 4.5m x 1.2m wall assemblies consist of aluminium frames for support, double-sided glass for daylighting, and opaque dark grey screens running in horizontal bands to conceal structural members and HVAC equipment.

W6: Aluminium Curtain Walls 5

The final wall assembly, W6, consists of a stick curtain wall situated on the double-height first floor. These 3.6m x 1.2m walls offer transparency between the building's interiors and the street and are constructed with aluminium extrusions, featuring double-sided glass or light grey glass screens with thermal insulation at the back.

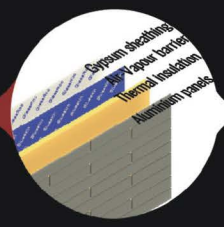
ii. LCA: Life Cycle Assessment & Building Circularity

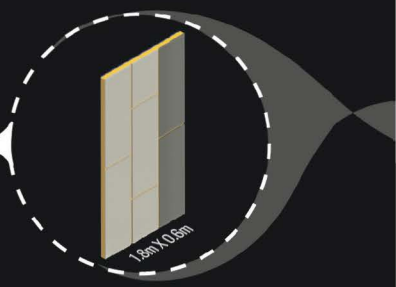
When evaluating the Patient Support Centre, the same approach as for the McMaster Building was used. This involved conducting a Life Cycle Assessment (LCA) and providing Building Circularity data that details the materials and quantities used in recent years. The latest available Environmental Product Declaration (EPD) reports from North America or nearby areas were considered to ensure that the materials with the best environmental impact were used.

Upon inputting all the necessary data, the tree map (Illustration 14) revealed that materials such as aluminium and glass again played a significant role, contributing a much higher total embodied carbon in the building, equivalent to 97.62% or 11715941kgCO_2e. This is comparable to the annual electricity consumption of about 15,000 average American homes! Further analysis of Building Circularity focused on examining better approaches to minimize waste and maximize the reuse and recycling of materials at the end of their lifecycle. The findings indicated that approximately 95.9% of the materials used in building construction were virgin, with 4.1% being recycled materials. In the future, after around 30 years, during the demolition of the envelope, it is estimated that up to 96.8% of the materials could be recycled, with only 3.2% being disposed of. This could lead to missed opportunities for significant savings.

SickKids : Forensic Analysis : P.S.C

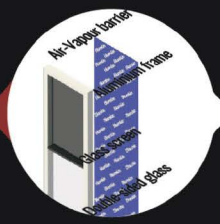
W1
Aluminium panels
2468

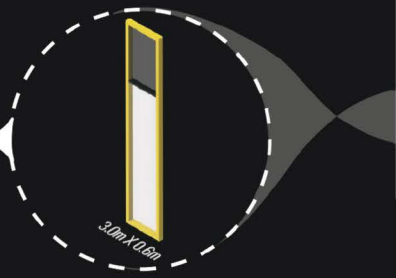




+

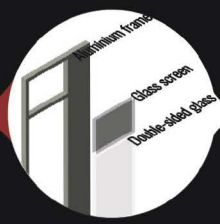
W2
Alu. Curtain wall 1
276

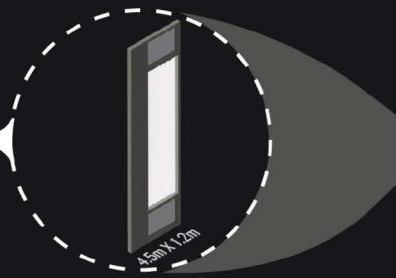




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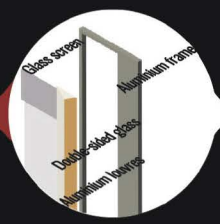
W3
Alu. Curtain wall 2
100

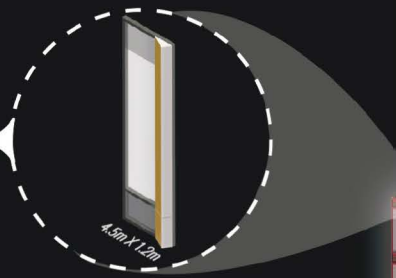




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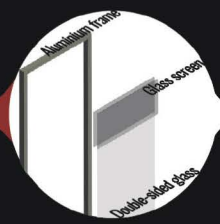
W4
Alu. Curtain wall 3
495

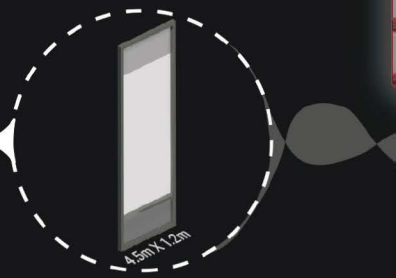




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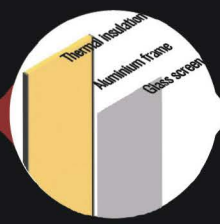
W5
Alu. Curtain wall 4
953

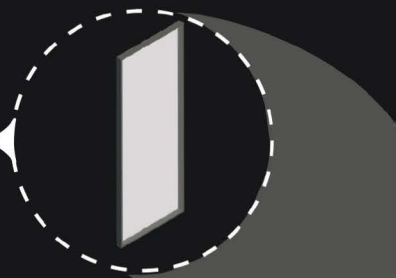




+

W6
Alu. Curtain wall 5
260





=

4552 units

"-1": CLARITY

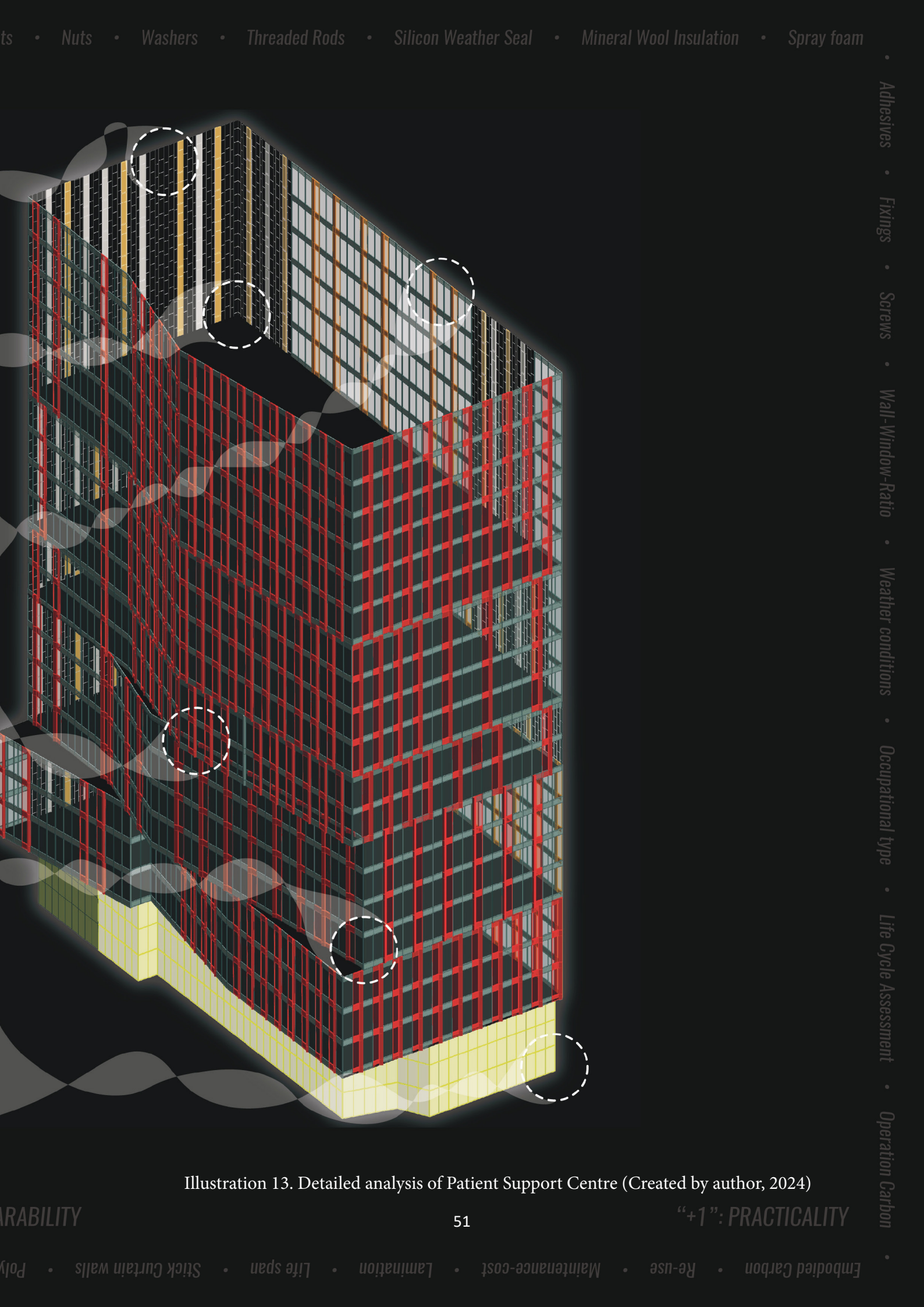
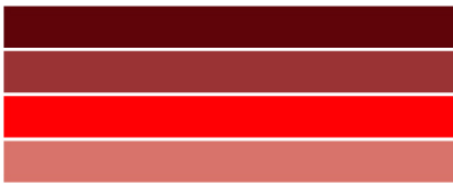


Illustration 13. Detailed analysis of Patient Support Centre (Created by author, 2024)



Material covered 4.2%

Virgin	**95.9 %**
Renewable	**0 %**
Recycled	**4.1 %**
Reused	**0 %**



Material returned 96.8%

Reuse as material	**0 %**
Recycling	**96.8 %**
Downcycling	**0 %**
Use as energy	**0 %**
Disposal	**3.2 %**

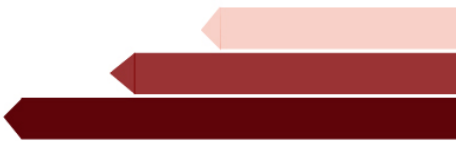
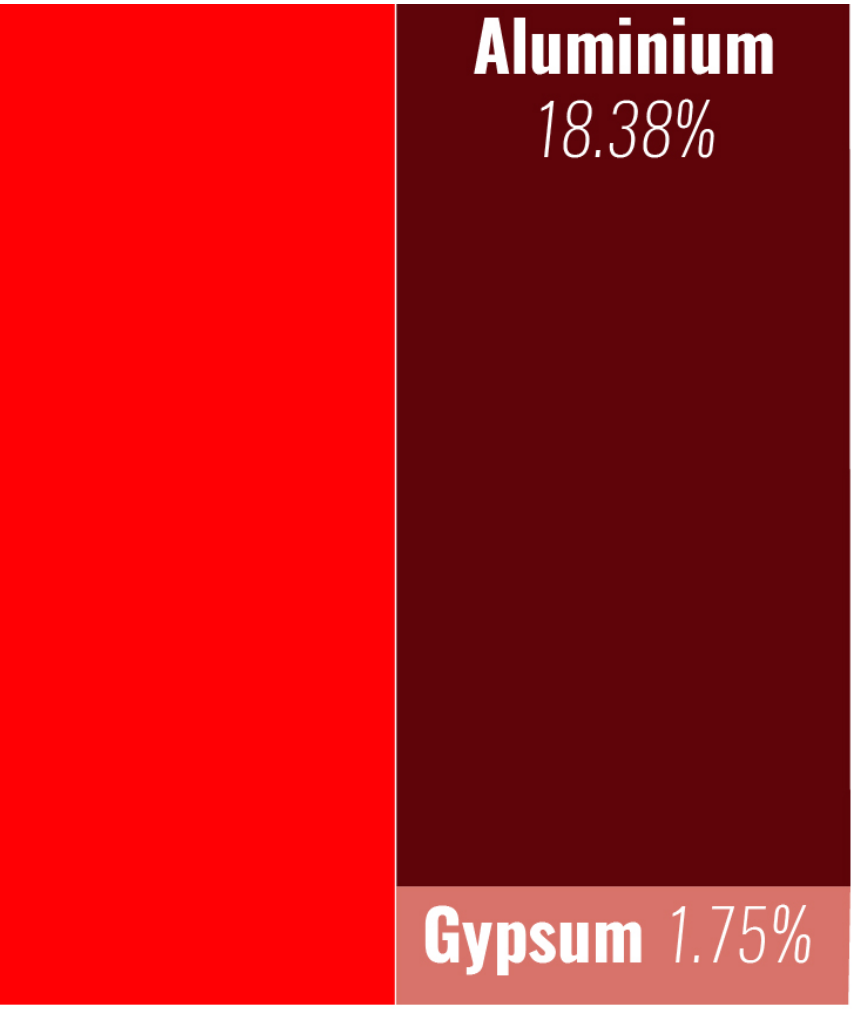


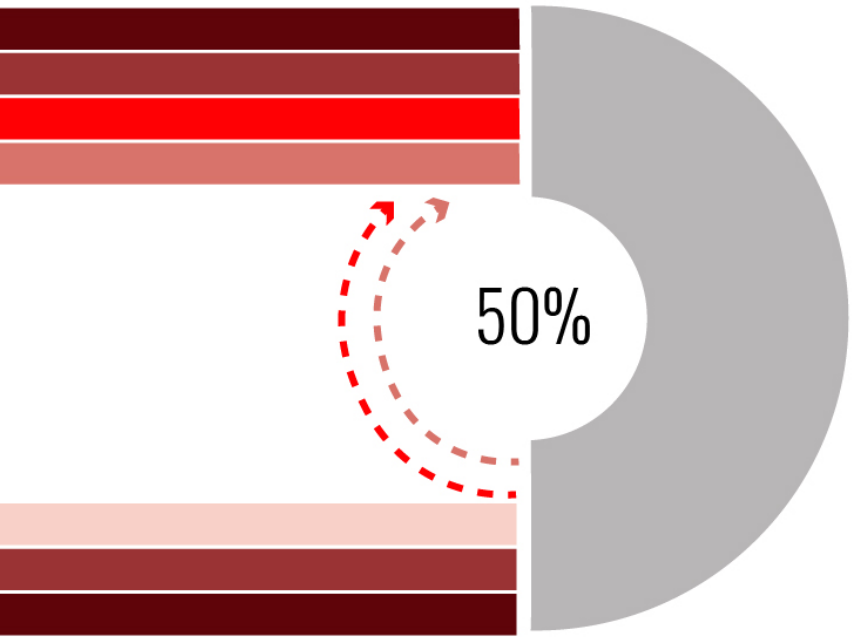
Illustration 14(left-to-right). Tree map depicting material's carbon



Aluminium
+
Glass

97.62%
of facade

1715941
CO_2e



58%
of circularity

0%
of Adaptive reusability

emissions; Building circularity diagram (Created by author, 2024)

2.4 Conclusions: *Learnings*

The lack of adaptive reusability of materials, which contributes significantly to the carbon footprint during the initial phases A1-A5 and C1-C4(Illustration 15) through embodied carbon, has been a longstanding issue in the construction industry. This issue was evident 30-40 years ago with the McMaster Building and continues to persist, as observed with the PSC Centre. The disposal or downgrading of materials like aluminium and glass leads to environmental concerns, and the blame for this fall on outdated demolition practices technologies rather than solely blaming the materials themselves. These outdated practices necessitate innovation in demolition techniques and financial incentives for developers to prioritize deconstruction over traditional demolition, ensuring that material recovery is not only environmentally beneficial but also economically viable. Balancing embodied and operational carbon and promoting the reuse of older buildings in new construction projects can help achieve the current focus on reducing carbon emissions in the building industry. Embracing a shift from a 'wasteful' to a 'circular' mentality can further accelerate the transition to a circular economy.

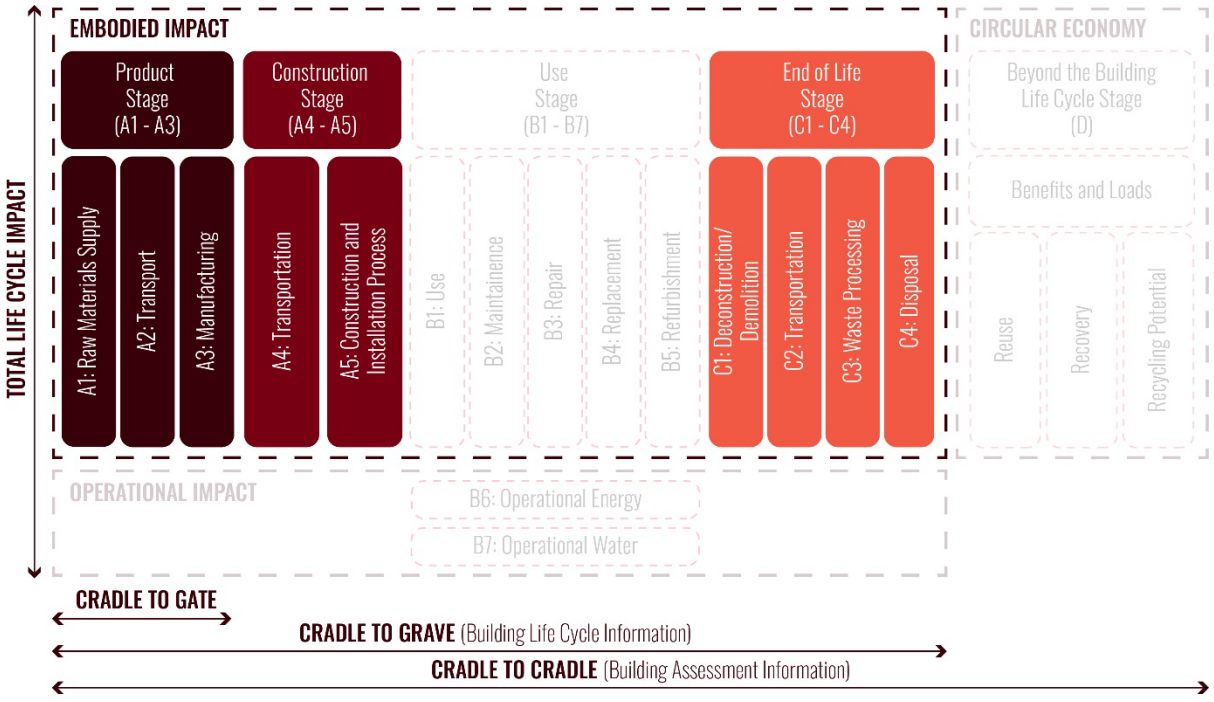
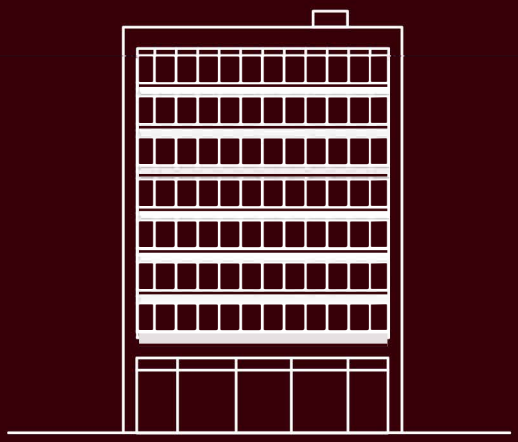


Illustration 15. Life cycle stages involved from Elizabeth McMaster Building to Patient Support Centre(Created by author, 2024)

3. Aluminium Curtain Walls



Basic glazing systems, encompassing window-walls, windows, storefronts, and curtain walls, represent integral building elements(Figure 30) that utilise glass to provide natural light, insulation, and aesthetic appeal. These systems also play a crucial role in maintaining structural integrity and enhancing energy efficiency through the use of periodically applied extrusions.

This chapter focuses on curtain walls, particularly Unitised Aluminium curtain walls, discussing their current design criteria, construction strategies, and sustainable practices. The analysis includes an in-depth examination of their material properties, lifespan, and carbon footprint. Furthermore, the chapter explores how unitised aluminium curtain walls can more effectively and efficiently contribute to the circular economy by emphasizing practices such as reuse, remanufacturing, and recycling.

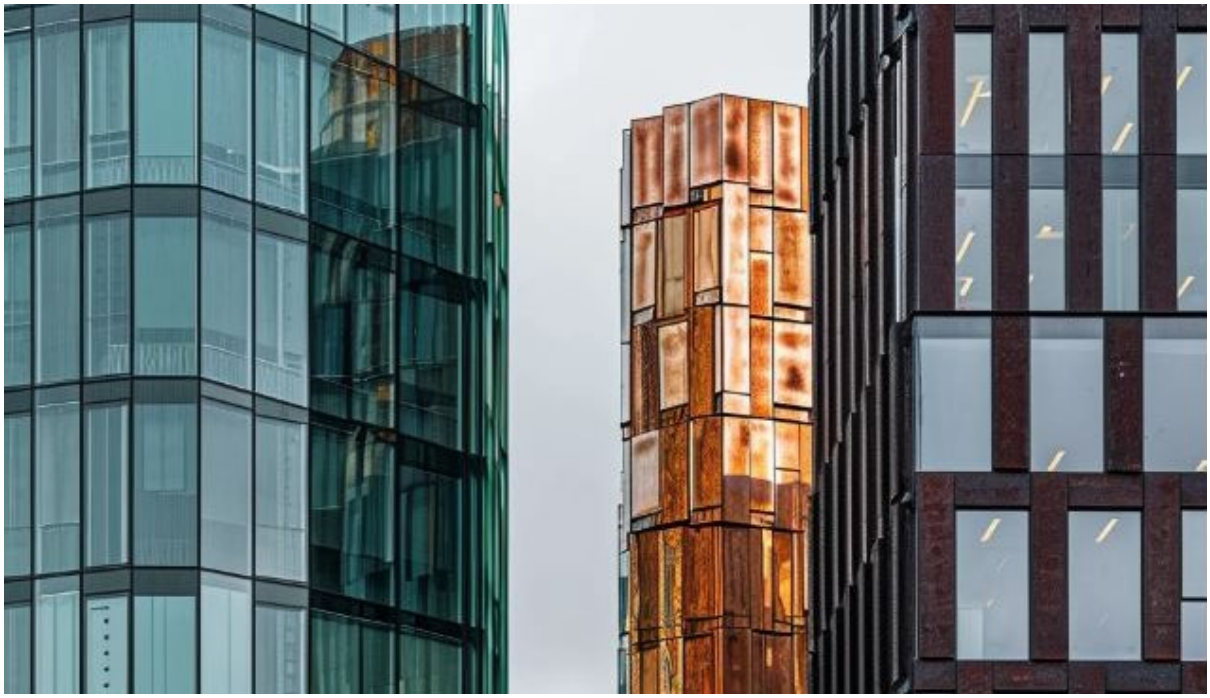


Figure 30. A render visualisation of varied facades for high-rise buildings(Created by author, 2024)

3.1 *Curtain* walls

3.1.1 What is a Curtain Wall System?

In the past, curtain walls were constructed using materials such as thick masonry, brick, terracotta, and wood, in addition to aluminum, steel, and glass. However, the advent of modern architecture revealed limitations of these traditional materials, particularly their heavy weight, and restrictions in height (Allana and Carter 2012, 99-100). These older types of curtain walls also restricted the amount of natural light that could penetrate buildings. The development and widespread use of structural steel and reinforced concrete enabled smaller columns to support large loads, allowing designers to create non-loadbearing, lighter, and more open exterior walls (Figure 31). This advancement led to the increased use of glass in exterior facades, culminating in the modern-day curtain wall (Allana and Carter 2012, 99-100). The evolution of curtain walls can be traced from the first glass curtain wall in the Boley Clothing Company (Figure 32), United States, designed by Louis S. Curtiss in 1909 (Allana and Carter 2012, 99-100), to the recent unitised curtain walls in the Patient Support Centre, Canada, completed by B+H Architects in 2023, as mentioned in the previous chapter.

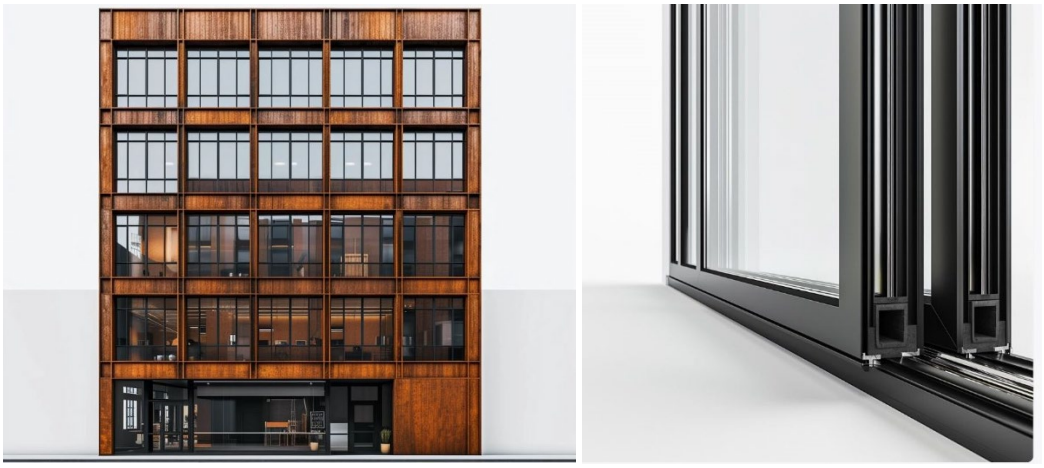


Figure 31(left-to-right). A render visualisation of: a. Curtain wall components on a facade; materials involved in these facade systems(Created by author, 2024)



Figure 32. Boley Clothing Company building, Kansas City (Allana, 2012)

A curtain wall is the exterior facade of a building that spans two or more floors in height and is non-structural, meaning it does not support any loads except for its gravity load while transferring wind and other loads to the building structure via connections to each floor, column, or roof (Allana and Carter 2012, 99-100). Thus, "curtain" implies that the wall is hung from the building's structural frame, generally at the edge of the slab. As shown in Figure 33, curtain walls necessitate meticulous design to provide several crucial advantages, as outlined by Kazmierczak (Kazmierczak n.d., 3):

- A *smaller wall footprint*, leading to a larger usable floor area.

- *Parallel scheduling*, facilitating expedited building construction.

- A *lighter structure*, decreasing the demand for materials and transportation.

- *Structural flexibility*, rendering them suitable for seismic areas.

- Improved *daylight access*, contributing to flexible layouts and indoor comfort.

- *Structural independence*, guaranteeing adaptable layouts without imposing additional loads on the main structure.

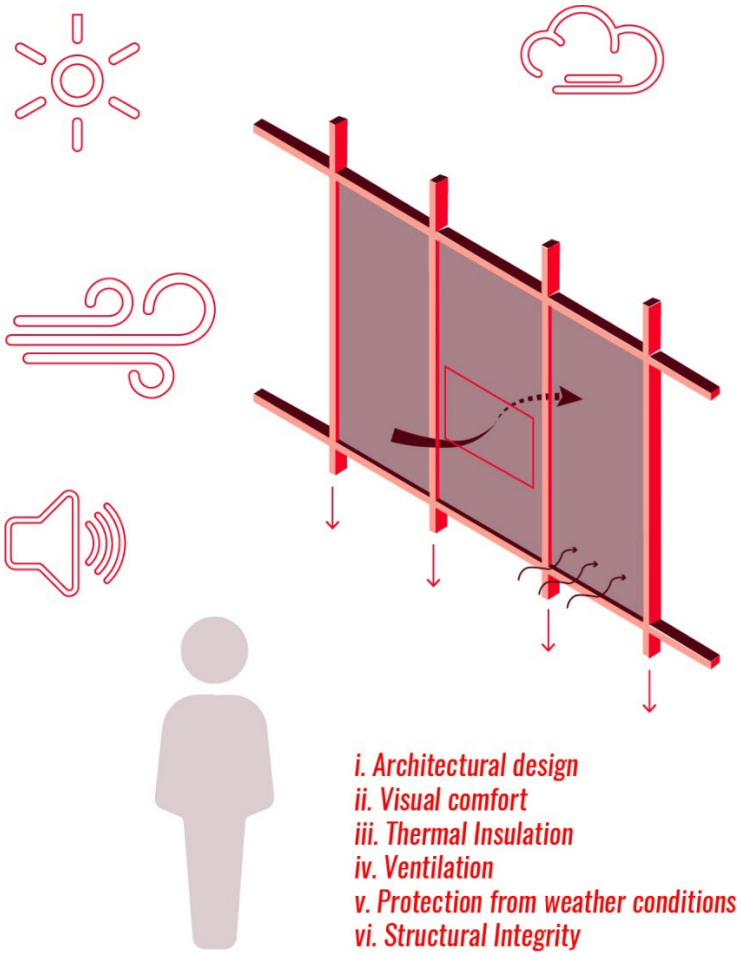


Figure 33. Curtain wall requirements (adapted from Knaack, Auer et al., 2014)

The curtain wall facade holds great importance, serving to protect interior spaces from external weather conditions while also shaping the building's outward appearance. Depending on the design's distinctiveness, the facade system may be classified as standard or custom. Standard components are typically more economical and provide limited customisation options, such as various glass types or mullion profiles, making them suitable for smaller-scale projects or those with budget constraints and no specific requirements. On the other hand, custom systems are uniquely designed for a particular building, offering greater technical and/or aesthetic performance at a higher cost(Figure 34).

These contemporary facade systems and materials have been highly complex and uniquely challenged the experts like architects, facade specialists, building physics consultants, and others, to upgrade their appearance, design, installation, maintenance, and repair. Consequently, a comprehensive approach has developed to identify, understand, and play with form, function, and typical materials used in curtain

wall systems, including aluminum extrusions, glass (vision and spandrel), and aluminum panels in sheet, plate, or aluminum composites (Allana and Carter 2012, 99-100). Curtain walls are available in various styles, all adhering to fundamental design principles by incorporating a mix of frames and panels. The stick and unitised systems are among the most favored types (Murray 2009, 11), as discussed in the following section.

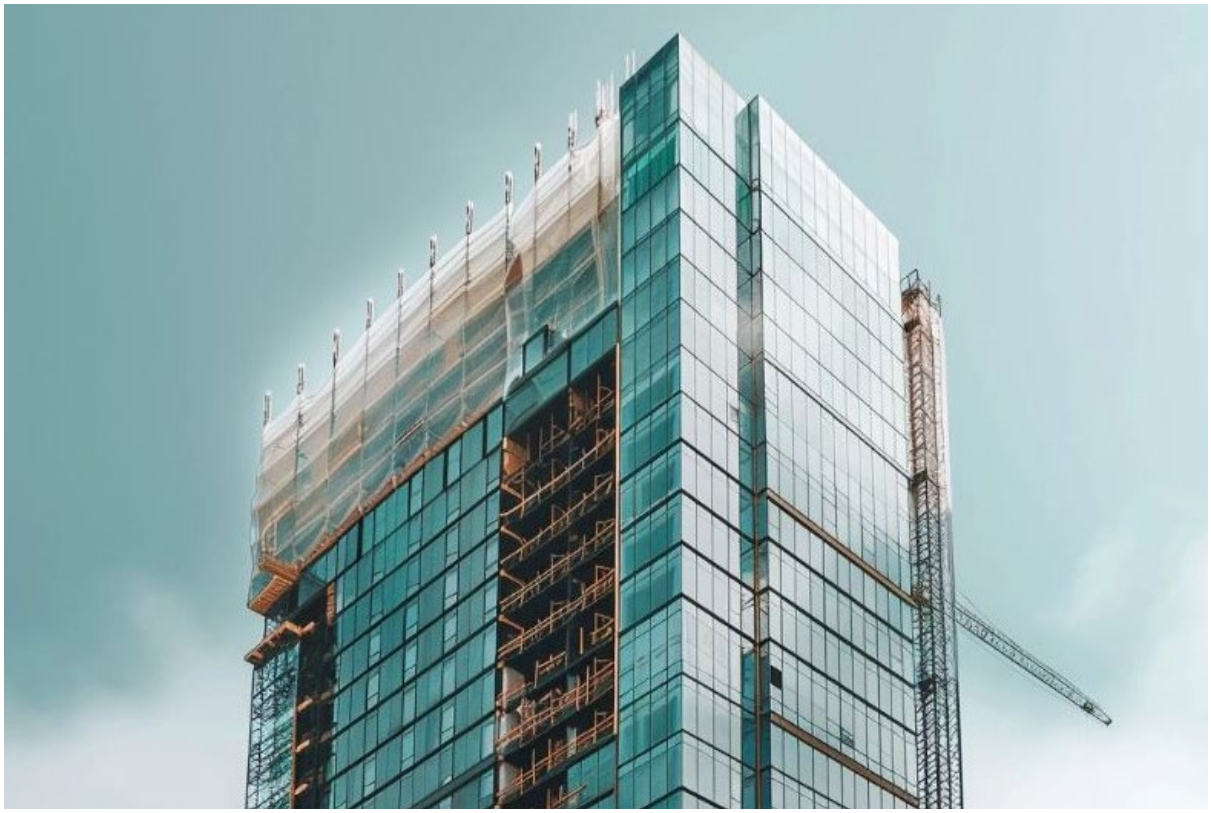


Figure 34. A render visualisation of under construction of Curtain walls on a mid-rise building(Created by author, 2024)

3.1.2 Stick v/s Unitised Curtain Wall systems.

The original structural framing for the glass curtain wall used hot-rolled steel sections, which were installed piece by piece in what is known as 'sticks'. Later on, in the 1970s, this transitioned to aluminium (Lsvm 2023). In designing these systems, the designer had to minimize the height of the tallest lite of glass, increase the mullion face dimensions, and specify all glass to be heat-strengthened or annealed. Additionally, laminated glass one face adhered to the frame (one face of each laminated lite in a double laminated insulated glass unit [IGU]) with a silicone sealant (Allana and Carter 2012, 101-104). For mounting and installation, stick-assembly curtain walls (Figure 35) typically used vertical mullions spanning two floors, anchored with steel or aluminium clip angles mounted on the face of the slab by welding to a hot-rolled screed angle or by expansion bolts/epoxy bolts into reinforced concrete. The dead load/wind load anchor had horizontal slots for adjusting the mullion cantilever in and out, while the wind-load-only anchor had vertical slots to bolt the mullion with slip pads to allow for thermal movement. Embedded “Halfen” channels or tubes cast into the slab replaced welding or field hammer drilling of the slab (Allana and Carter 2012, 101-104).

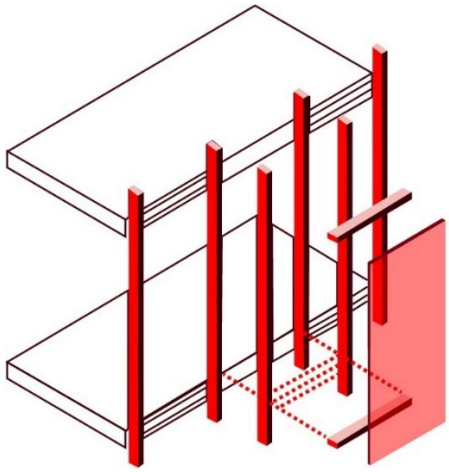


Figure 35. Stick curtain wall system (adapted from Murray, 2009)

In contrast, unitised curtain walls(Figure 36) are composed of large units being assembled and glazed in the factory, then shipped to the site and erected on the building. Unitised curtain walls offered more advantages such as speed, lower field installation costs, and enhanced quality control within an interior climate-controlled fabrication environment (Allana and Carter 2012, 101-104). Considerable economic benefits, including lower costs, were being realized on larger projects. For mounting and installation, unitised curtain walls typically connect to the top of a slab cast with a recessed pocket and half-embedded inserts. An extruded aluminium or formed steel angle plate is bolted to the insert and cantilevered off the slab, engaging with a mating anchor bolted to each side of the units. The mating frame-hook anchors contain jack bolts used to raise the units to the correct elevation. The bottom of each unit nests within the head of the lower unit and a lock bolt is used to ensure the units do not “walk” after installation (Allana and Carter 2012, 101-104).

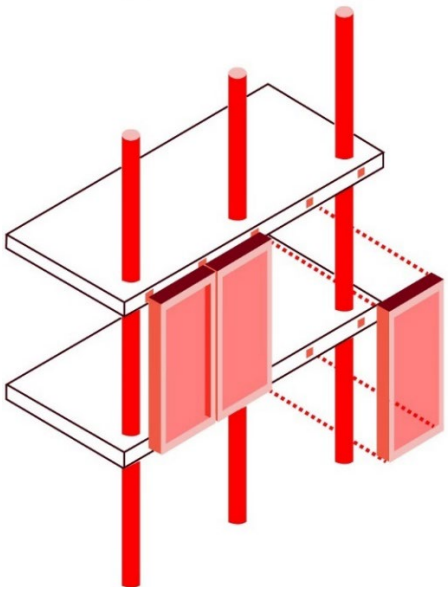


Figure 36. Unitised curtain wall system (adapted from Murray, 2009)

Considering these factors, unitised curtain walls have proven to be significantly better than stick systems. They not only enable faster installation, reduced labour costs, and improved quality control, making them the primary choice in modern curtain wall systems, but also major challenging changes such as the shift to thermally broken frames and the transition from single to double, and even triple, glazing.

3.2 *Unitised* Curtain wall systems

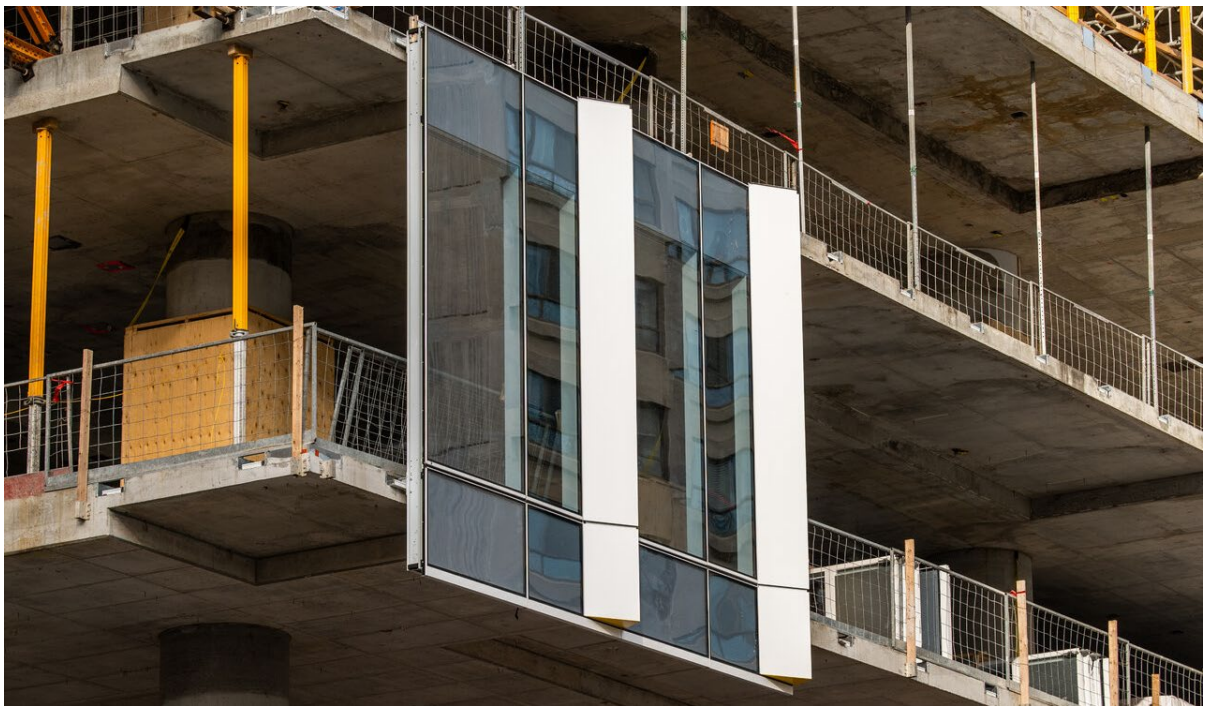


Figure 37. Unitised curtail wall components visible during installation on PSC building (Urban Toronto, 2021)

3.2.1 Elements, Sub-components, and Materials.

a. Elements and Sub-components

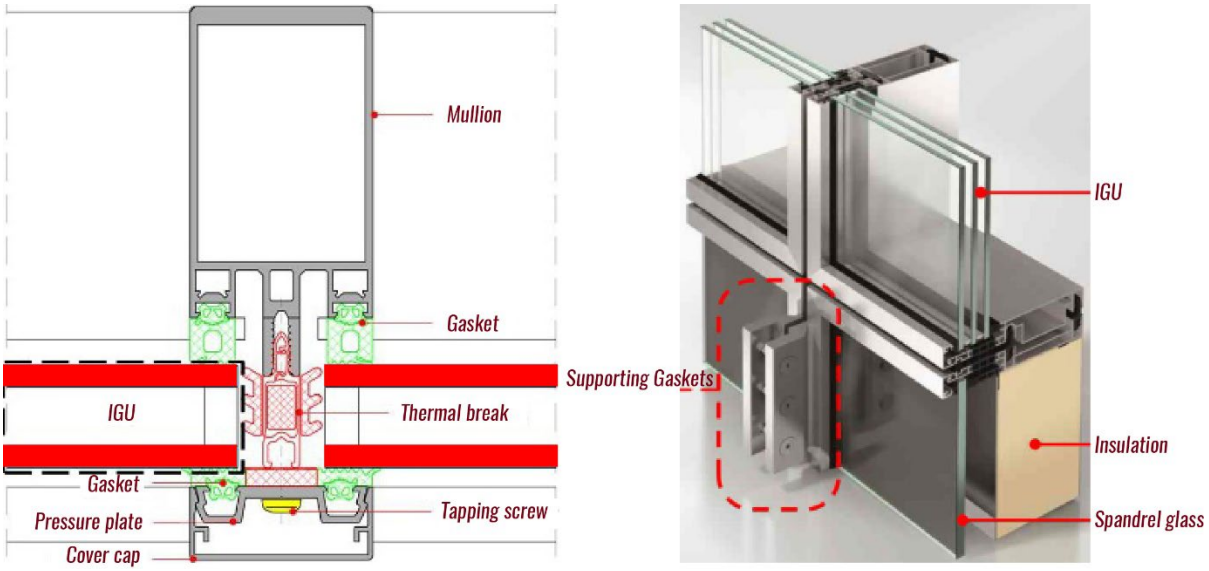


Figure 38. Details of elements involved in a curtain wall(Ntailianas, 2019)

To analyse the makeup of unitised curtain walls, it is crucial to scrutinize the specific details and components (Leising 2017, 50) involved in their construction. As shown in Figures 37 and 38, a curtain wall comprises several essential elements:

- ***Mullions and transoms***: Vertical and horizontal supports
- ***Glass panels and thermal breaks (isolators):*** Thermal insulation and Soundproofing elements.
- ***External gaskets:*** Weatherproofing seals
- ***Internal gaskets:*** Airtightness seals
- ***Pressure plates:*** Glass panel fasteners
- ***Tapping screws:*** Fastening hardware
- ***Cover caps:*** Standardised aesthetical covers for exposed components.

i. Mullions and Transoms

Mullions and transoms play a pivotal role in unitised curtain walls by transferring external forces, such as wind loads, to the primary structural components of the building. Mullions are the vertical primary elements, while transoms are the horizontal secondary elements (Ntailianas 2019, 85). As depicted in the Figure 39, these components support the facade module. Referring to the numbered diagram:

1: Main mullion.

2: Main transom.

3: Secondary mullion.

4: Secondary transom.

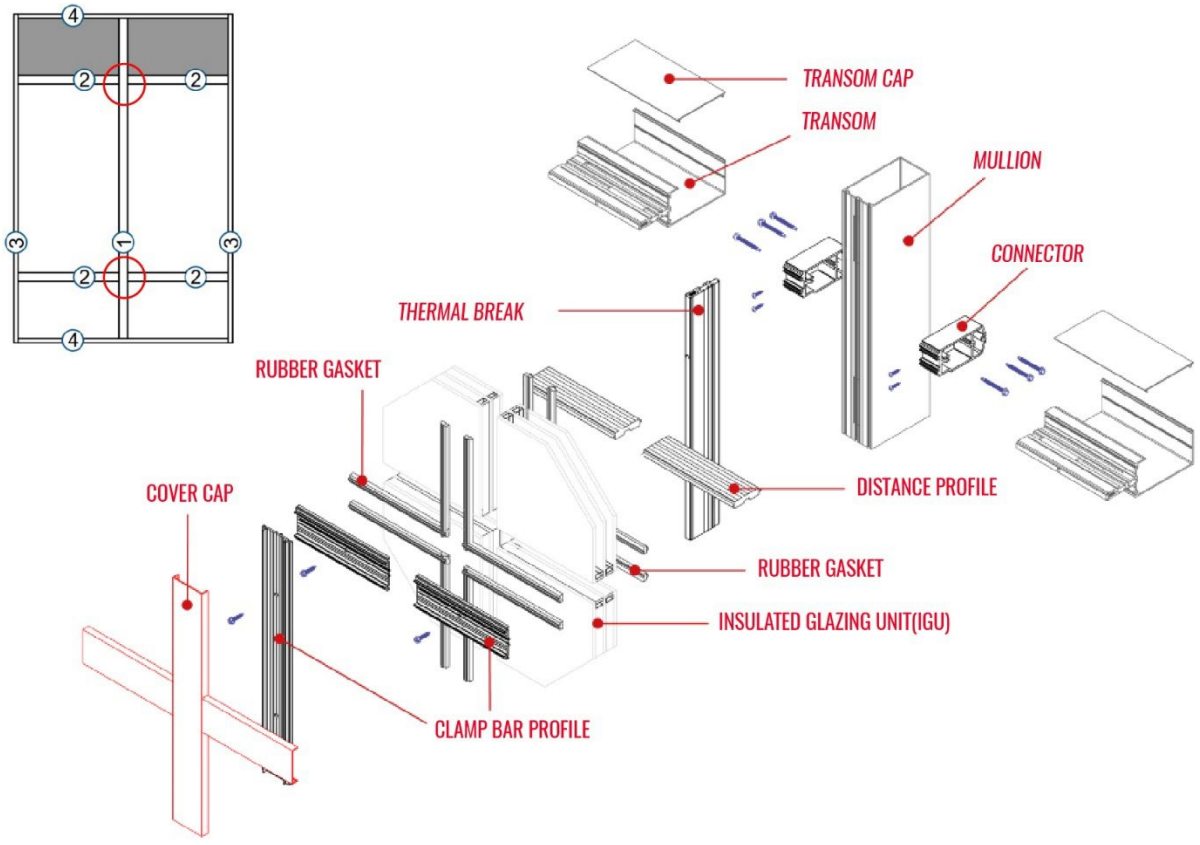


Figure 39. Exploded Isometric mullion-transom connection (Ntailianas, 2019)

ii. Anchors

Anchors play a critical role in connecting facade elements to the primary structure of a building. To achieve efficient installation without compromising safety, it is essential to utilise adjustable connections(Figure 40), typically employing slotted holes to allow for tolerance (Ntailianas 2019, 82).

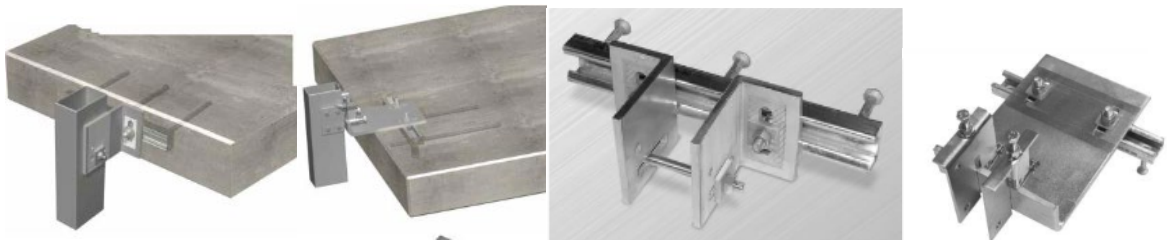


Figure 40. Varied materials used in anchors (Halfen, 2019)

Various types of anchors can be attached to concrete slabs or beams. Figures 41 depict anchors mounted on the side and top of concrete slabs, respectively. These anchors (Ntailianas 2019, 82) consist of:

a. Channels: These contain rebars anchored in the concrete slab.

b. Brackets: These link the channels to the mullions.

c. T-bolts: These provide secure attachments without the need for welding.

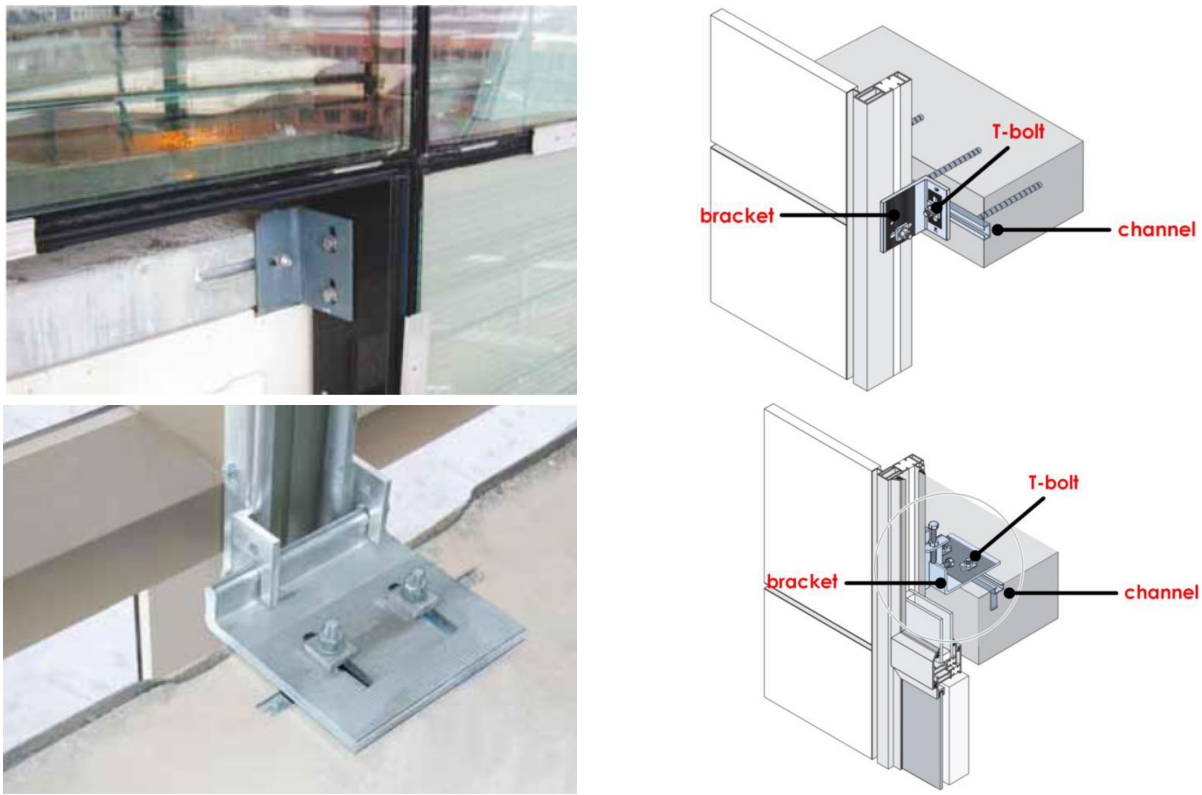


Figure 41(left-to-right). a. Anchors on the side of a concrete slab(on site); b.Visual representation of anchors on the side of a concrete slab; c. Anchors on the top of a concrete slab(on site); d.Visual representation of anchors on the top of a concrete slab(Halfen Ntailianas, 2019)

Selecting the appropriate connection method for layout fixation is crucial (Ntailianas 2019, 83). Anchoring can span one or two floors and may either hang from the top or bear from the bottom. Figure 42 illustrates the various layout fixations:

- One-level hanging (Layout 1G)
- Two-level hanging (Layout 2G)
- One-level bearing (Layout 1-0)
- Two-level bearing (Layout 2-0)

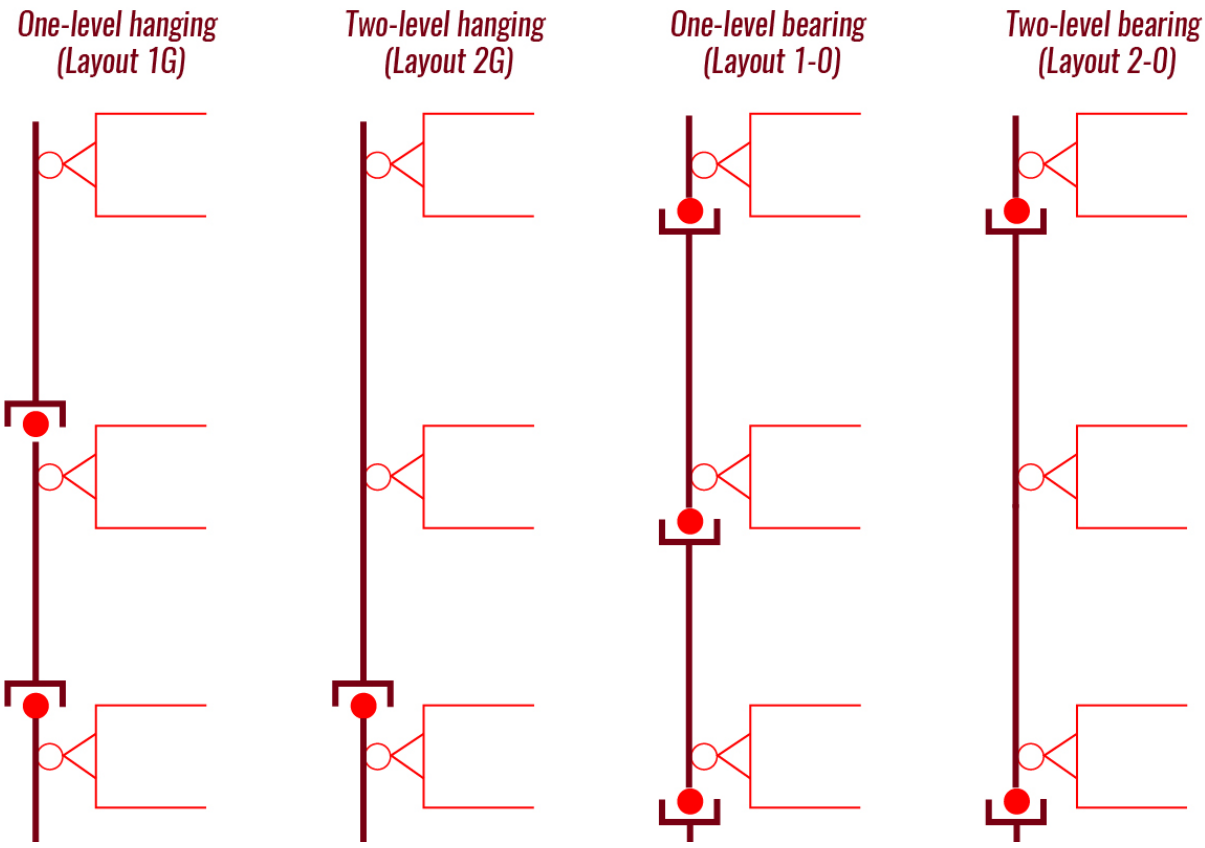


Figure 42. Main layouts of curtain wall fixation (Adapted from Ntailianas, 2019)

iii. Assembly Sequence

The assembly sequence emphasizes that anchor elements are not all installed simultaneously. Some channels are set before the concrete floor is poured, while brackets and T-bolts are added afterward. Unitised curtain wall modules are then transported to the site and installed. Each module is positioned with the assistance of a crane, and T-bolts are used to precisely secure the mullions.

b. Materials

ELEMENTS	Mullion/Transom	Pressure plate	Cover cap	Channel	Brackets	T-bolts	Tapping screws	Gaskets	Thermal breaks
MATERIALS	Aluminium	Aluminium	Aluminium	Steel	Steel	Steel	Steel	EPDM	Aesbestos sheets

Table 1. Varied materials used in curtain walls (Adapted from Ntailianas, 2019)

i. Aluminium

The global market for unitised curtain walls offers a variety of materials(Table 1), with aluminium standing out due to their high strength-to-weight ratios, technical performance, and aesthetic appeal. These materials have seen the introduction of newer options such as timber, glass fibre, and u-PVC, but aluminium (Kakolyri 2015, 58) remains the most used and higher-value material (Table 2), which will be the primary focus of this thesis and chapter.

PROPERTIES/MATERIALS	WEIGHT VALUE	ALUMINIUM	STEEL	TIMBER	u-PVC	GRP
Lightweight	3	6	1	3	6	7
Durability	5	7	7	2	6	7
High strength	2	6	7	5	1	7
Low maintainence	4	7	6	2	7	7
Easily cleaned	2	7	6	3	7	7
Low initial cost	3	6	2	3	7	1
Low life cost	3	6	6	3	7	7
Low thermal conductivity	2	1	2	7	5	7
Complex shapes	1	7	5	4	7	5
High life expectancy	5	6	6	4	5	7
Primary Embodied energy & CO_2 emissions	4	2	6	7	3	4
Recycling Embodied energy & CO_2 emissions	4	4	5	0	7	0
Recyclability / Reusability	5	7	7	2	7	2
Easily repaired	5	7	7	4	1	1
TOTALY VALUE OF MATERIAL		276	265	157	256	221

Where:
- **Weight value of properties' importance:**
1 - 2 - 3 - 4 - 5: Very Insignificant - Insignificant - Neutral - Significant - Very Significant

- **Materials' values:**
1 - 2 - 3 - 4 - 5 - 6 - 7: Very Unsatisfactory - Unsatisfactory - Slightly Unsatisfactory - Neutral - Slightly Satisfactory - Satisfactory - Very Satisfactory

Table 2. Comparison of properties between materials (Adapted from Kakolyri, 2015)

Aluminium, a primary material for curtain walls, is predominantly sourced from alumina, derived from bauxite ore found in countries such as Brazil, Suriname, and Venezuela (Kakolyri 2015, 51). The production of aluminium profiles involves extruding sections formed from prime or recycled aluminium, followed by finishing processes like anodizing or painting. This extrusion process allows for the creation of complex and highly detailed shapes, including recesses for weather-strip rubber seals, glazing, and thermal breaks. Despite the benefits of using aluminium profiles in facade design, such as lightweight, high strength, and durability, they have high thermal conductivity (Kakolyri 2015, 51), resulting in a high U-value for window units. This necessitates the design of thermal breaks to reduce (from 2.0 to 0.5 W/m^2K) heat transfer between the interior and exterior. By incorporating an inner and outer shell connected by a heat-insulating material, typically plastic, the U-value or energy efficiency can be significantly improved, albeit with increased costs. The following Table 3 outlines the advantages and disadvantages of aluminium profiles (Kakolyri 2015, 51), providing a comprehensive comparison to inform design decisions.

Advantages	Disadvantages
• Lightweight (20 g/cm3) • High strength and stiffness • Durability (>75 years) • Low maintenance • Water resistance • Corrosion resistance (naturally generates a protective oxide coating) • Ease in cleaning and low cost • Most secure (compared with other kinds of frames) • Recyclable and reusable (matter of design)	• Good thermal conductivity (thermal breaks are necessary) • Poor condensation resistance • High primary embodied energy

Table 3. Advantages and disadvantages of Aluminium profiles (Adapted from Fradelou, 2013)

ii. Insulating Glass Unit (IGU)

Insulated Glass Units (IGU) typically consist of two or three layers of glass, which may be coated to enhance performance (Ntailianas 2019, 93). The edges of an IGU consist of various elements (Figure 43):

i. ***Spacer:*** This component holds the glass panes together while maintaining a fixed gap. Made from silicone foam, the spacer also serves as a bed for the desiccant. Spacers are available in widths of 6mm, 12mm, or 15mm, depending on the required gap size.

ii. ***Desiccant:*** Acting as a drying agent, the desiccant absorbs humidity within the IGU. Common materials for desiccants include silica and zeolites.

iii. ***Sealants:*** These are crucial for sealing the space to prevent gas from escaping the cavity. The primary sealant, usually Butyl, creates an airtight seal between the spacer and the glass. The secondary sealant, made from silicone or polysulfide, provides structural integrity to the unit.

iv. ***Cavity:*** The cavity between the glass panes is filled with an insulating inert gas, such as argon or krypton, to reduce heat conduction. A vacuum is generally not used.

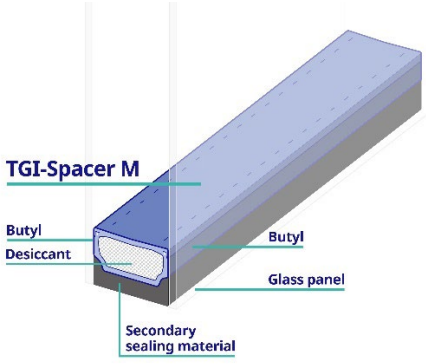


Figure 43. Various elements involved in an Insulated Glass Units (Technoform, 2024)

iii. Spandrel Glass

The spandrel glass serves to conceal elements of a building's structure, such as the area between the floor and the false ceiling (Ntailianas 2019, 93). As shown in Figure 44, it is commonly opaque and available in various colours for aesthetic purposes. To ensure its resistance to heat-induced breakage, it

is essential to treat the glass panels. When it is necessary to remove the panel, the process involves removing the cover caps, unscrewing the screws, taking out the pressure plate, and then extracting the spandrel glass along with the rubber gaskets.

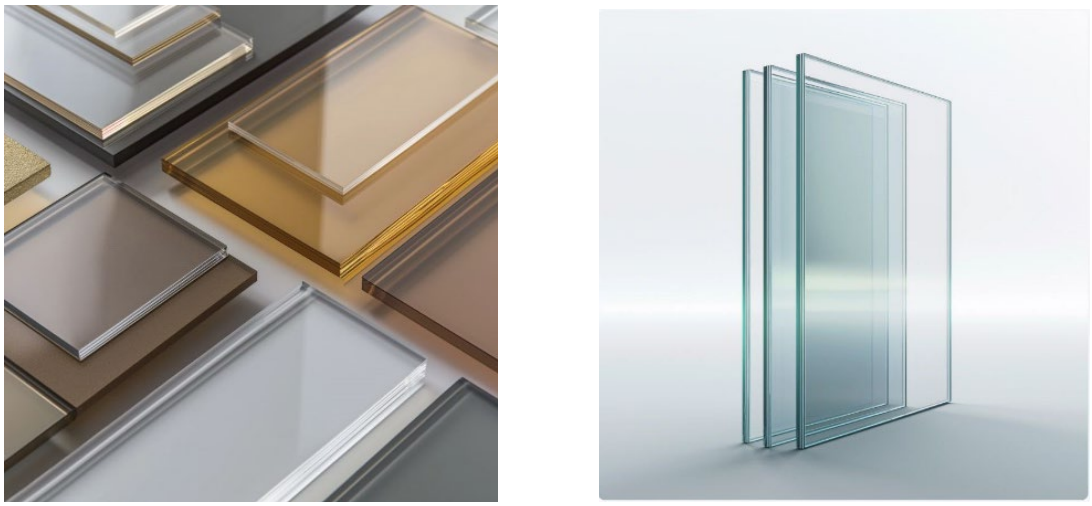


Figure 44. Varied types of spandrel glasses (INTOS, 2024)

iv. Insulation

Various types of insulation materials offer unique benefits for buildings, such as lower embodied carbon, higher R-value, and DfD ease, as shown in Table 4. For curtain wall design, sandwich panels are the preferred choice for insulation. Polyurethane (Grazieschi, Asdrubali and Thomas 2021), Polystyrene (Grazieschi, Asdrubali and Thomas 2021), Phenolic Foam (EWIPRO 2023), and Rockwool (ROCKWOOL n.d.) are among the commonly employed insulation materials for sandwich panels, as shown in Figure 45.

Material	Sustainability	Embodied Carbon	R-value/mm	DfD Ease
Polyurethane (PUR)	Lower	High	High	Difficult
Polystyrene (EPS/XPS)	Limited	Moderate	Good	Moderate
Phenolic Foam	Good	Low	High	Difficult
Rockwool	High	Low	Good	Easy

Table 4. Comparison of insulating materials (Created by author, 2024)

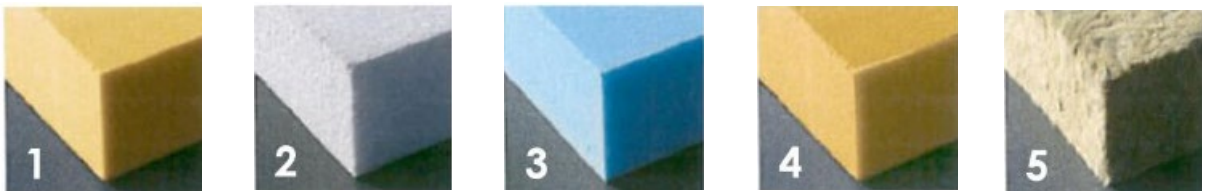


Figure 45(left-to-right). Most common insulation materials used in sandwich panels: a. PUR / PIR (Polyurethane); b. EPS (Expanded Polystyrene); c. XPS (Extruded Polystyrene), d. Phenolic; e. Rockwool (Assan Panel, 2019)

3.2.2 Life span

The lifespan of an aluminium unitised curtain wall system is not uniform across its constituent components. While the manufacturer typically guarantees the system for up to 10 years (Teeuwen 2023, 25), covering material and workmanship defects, the actual lifespan of individual components can vary considerably. Components with the shortest lifespan (Illustration 16), such as EPDM gaskets, sealants, and insulated glazing units (IGUs), typically last approximately 30 years. In contrast, steel anchors, extruded aluminium frames, and their overcaps can endure for over 70 years (Alcoa 2015). Notably, silicone structural sealants require replacement every decade to maintain optimal water tightness and thermal insulation.

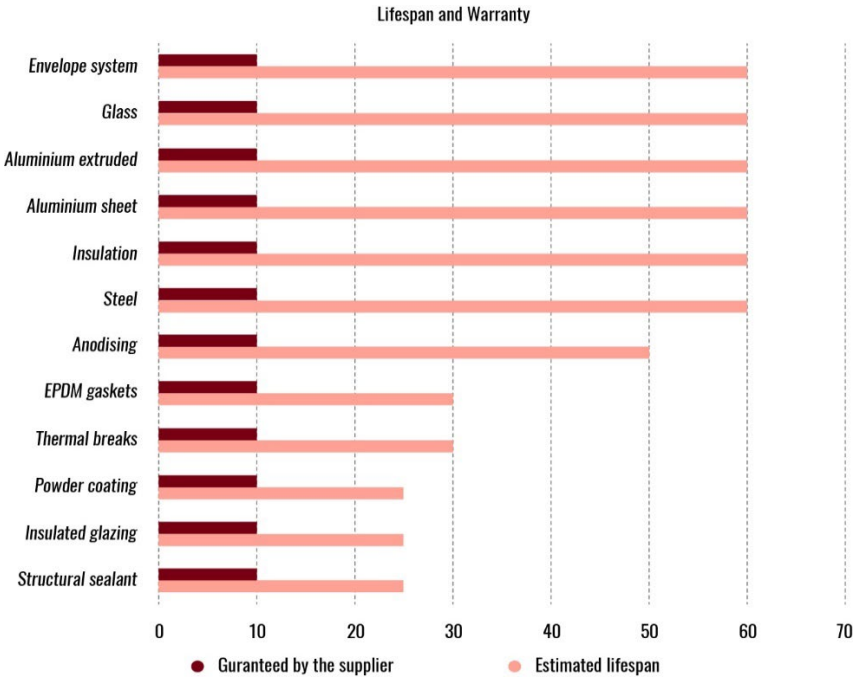


Illustration 16. Guaranteed and Estimated lifespan(adapted from Teeuwen, 2023)

This disparity in lifespan necessitates a nuanced approach to maintenance and replacement. Often, replaced materials may still have a remaining lifespan, highlighting the need for a strategic replacement plan that prioritizes components nearing the end of their service life. As shown in Illustration 17, the aluminium frames and anchors may remain viable for decades, whereas proactive maintenance of gaskets, sealants, and thermal breaks is crucial to ensure the curtain wall's continued performance and longevity (Arup and Saint-Gobain Glass n.d., 63).

Replacement needs across the life span of the building. Considered follows:-

Element	Replacement Frequency
Glass	30 years
Accessible gaskets & sealants	30 years
Framing	60 years
Sealants and Gaskets which are concealed within the system, and which cannot be inspected and replaced without dismantling the envelope system.	60 years
Insulation	60 years
Blinds- material	20 years
Blinds- motor	15 years

Illustration 17. Replacement frequency of elements in curtain walls(Adapted from ARUP, 2024)

In conclusion, the analysis of Illustration 16 and 17 shows the critical role gaskets and sealants play in the lifecycle management of aluminium unitised curtain wall systems. Illustration 16 highlights their relatively short lifespan (10-15 years for EPDM gaskets), requiring frequent inspection and timely replacement to maintain system integrity and prevent water infiltration. The Illustration 17 supports this by demonstrating that while shorter-lived components like gaskets might initially be more cost-effective, their frequent replacement increases environmental impact and overall lifecycle costs due to material waste and labour (Kakolyri 2015, 47). The illustration further emphasizes the importance of design choices that facilitate easy access for maintenance and replacement of gaskets, as their exposure asks for regular attention. Different curtain wall designs can impact the ease and cost of gasket replacement, with systems featuring exposed silicone joints potentially offering easier access compared to older systems with aluminium cover caps. Investing in high-quality gaskets with longer lifespans, coupled with designs that facilitate easy replacement, can contribute to a more sustainable and cost-effective approach to curtain wall maintenance(Figure 46).

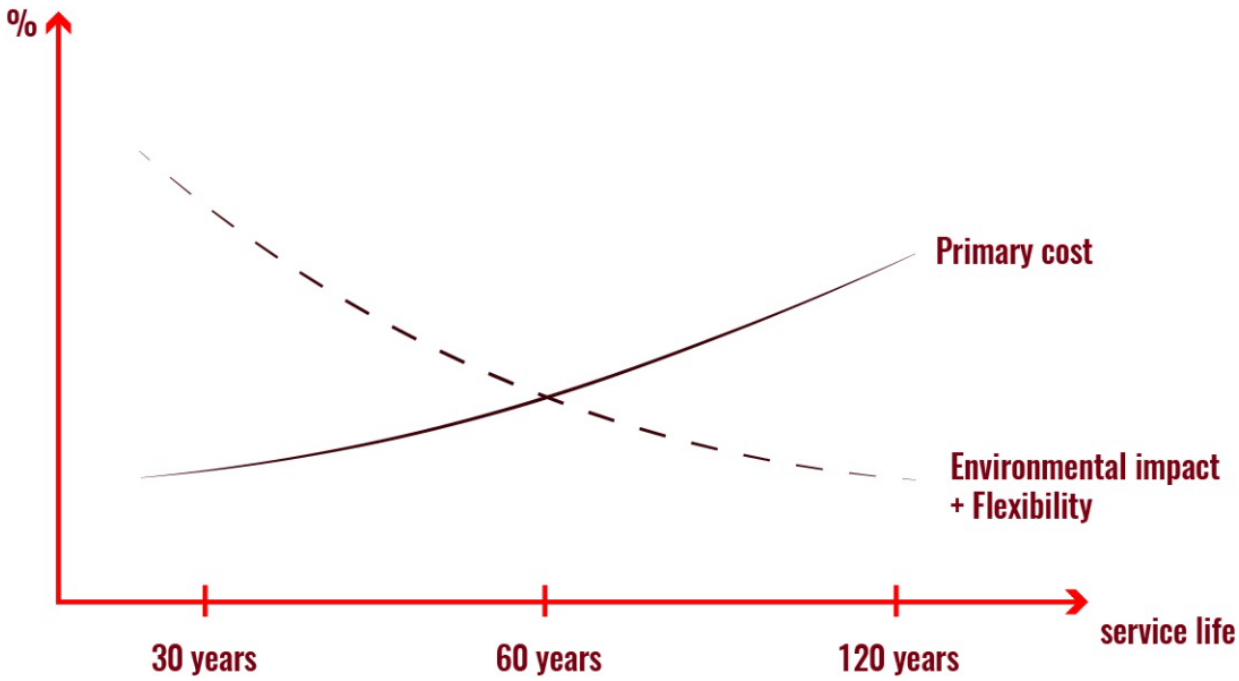


Figure 46. Facade's service life(adapted from Kakolyri, 2015)

3.3 Carbon Footprint

3.3.1 Embodied carbon: A Holistic Assessment of Building Impacts

In assessing the embodied carbon footprint of the six previously mentioned projects, focusing on the A1-A5 phases, a significant trend emerged. Figure 47 illustrates that aluminium constituted a substantial 43% of the total upfront carbon, a considerable contribution. Glazing and steel further compound this impact, accounting for 22% and 11%, respectively (Teeuwen 2023, 23). This analysis underscored the substantial environmental burden associated with these materials in the early stages of construction.

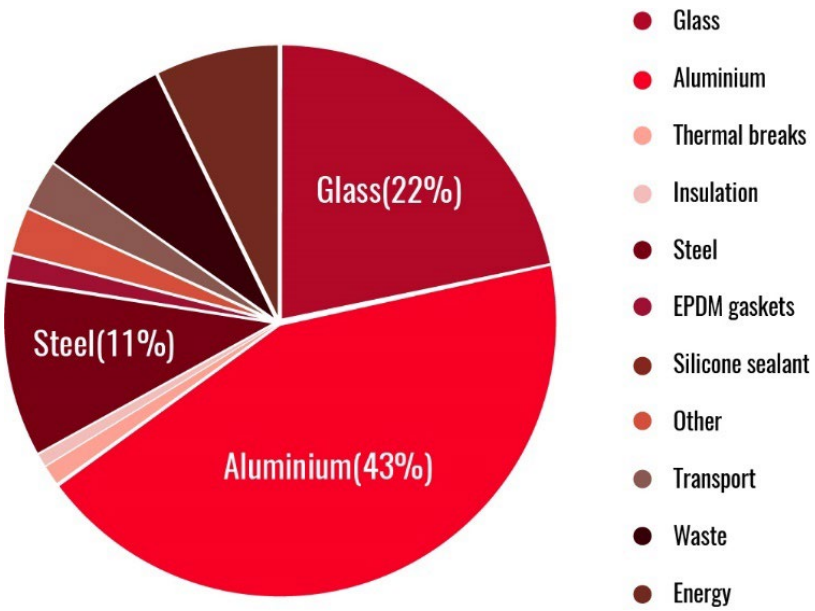


Figure 47. Upfront carbon emissions(adapted from Teeuwen, 2023)

Further examination revealed that aluminium, glazing, and steel also emerged as the primary culprits in terms of waste and energy generation within the average facade. Delving deeper into the aluminium component, Figure 48 demonstrates that aluminium extrusions (33%) and aluminium sheeting (24%) included most of the average carbon impact attributable to this material. The cumulative analysis of six projects (Teeuwen 2023, 23) , thus elucidated that aluminium, glazing, and steel significantly contribute to the carbon emissions associated with both curtain wall construction and the broader building process. This finding underscored the need for concerted efforts to mitigate the environmental impact of these materials in the pursuit of sustainable construction practices.

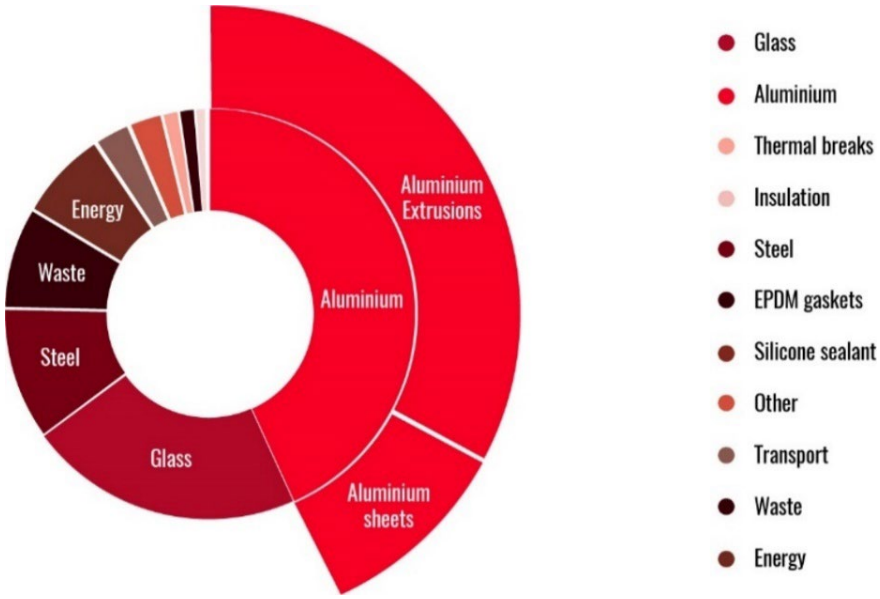


Figure 48. Carbon distribution for aluminium material, in comparison to others(adapted from Teeuwen, 2023)

3.3.2 Embodied carbon: A Detail Assessment of Unitised Curtain Walls

As shown in Figure 49, leading companies like Saint Gobain and Arup (Arup and Saint-Gobain Glass n.d., 9) have already made commitments to achieve net-zero emissions and are integrating whole-life carbon assessments into their projects.

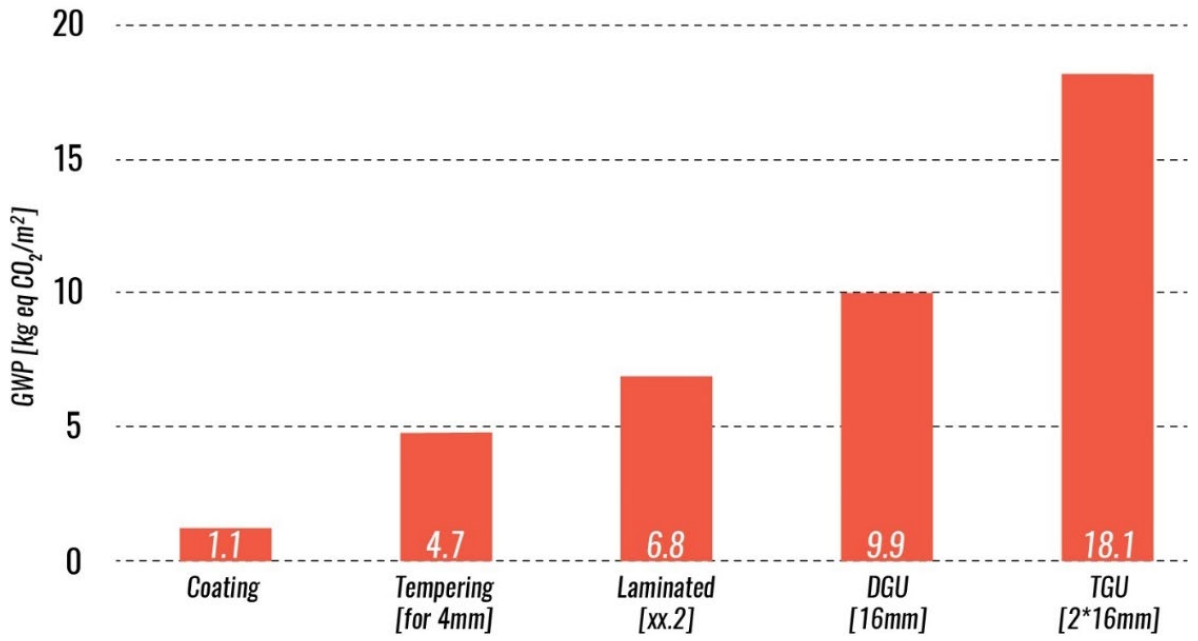


Figure 49. Embodied Carbon with glass products (Adapted from ARUP, 2024)

This collaborative study between Saint Gobain and Arup untangled some complexities of low-carbon design and manufacturing solutions for facades, particularly unitised curtain walls. The study identified potential avenues to minimize whole-life carbon emissions by comprehending their components' distinct contributions to the overall carbon footprint. The study extensively examined diverse facade systems (Illustration 18), representative of the current UK and EU markets (as well as similar markets in North America). The aim was to dissect the embodied carbon contribution of various materials, such as aluminium, glass, and steel, within each facade system. This thorough analysis (Arup and Saint-Gobain Glass n.d., 17) involved developing detailed designs for each system, enabling accurate calculations of material quantities per square meter of facade.

While the study encompasses a wide range of facade typologies, including unitised curtain wall systems, stick curtain wall systems, handset systems, deep and narrow cavity double skin systems, and rain-screen systems, the primary focus of this thesis is specifically on unitised curtain walls, which includes WT-01 to WT-06(Illustrations 19, 20, and 21). These six systems share similar performance characteristics in terms of thermal insulation, solar control, daylighting, acoustic performance, safety, and aesthetics (Arup and Saint-Gobain Glass n.d., 44-49). By concentrating on these specific systems, a deeper understanding of their material compositions and opportunities for reducing embodied carbon without compromising performance can be gained. This targeted approach will provide valuable insights for designers and manufacturers seeking to develop more sustainable facade solutions.

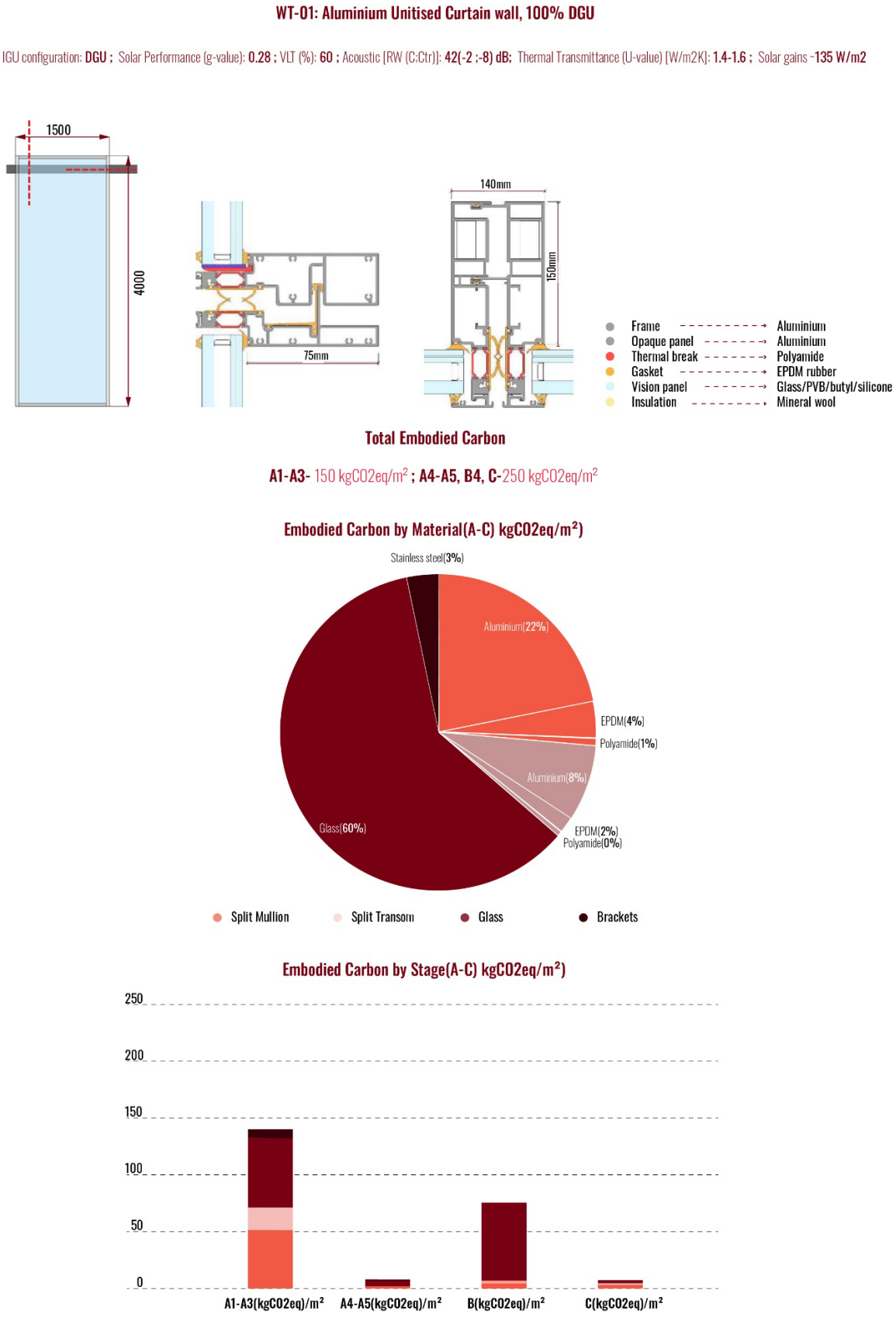
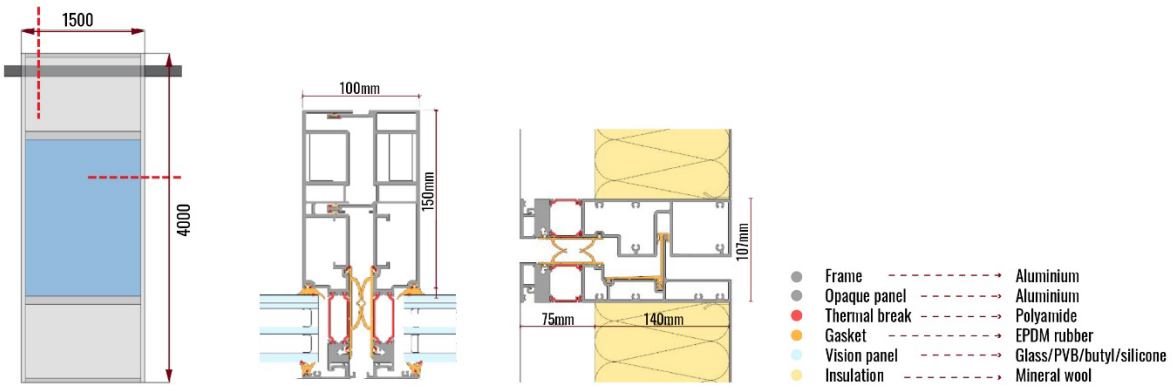


Illustration 19(top-to-bottom). WT-01: Technicalities, Embodied Carbon(EC) generated, and EC by stage(Adapted from ARUP, 2024)

WT-02: Aluminium Unitised Curtain Wall, Aluminium Cladding, 50% DGU

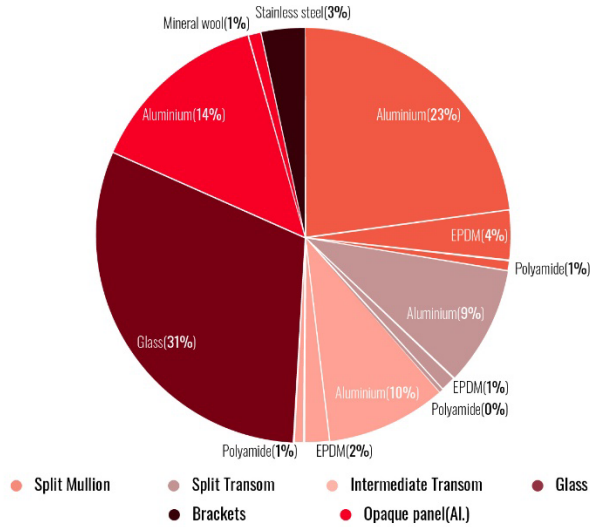
IGU configuration: **DGU** ; Solar Performance (g-value): **0.28** VLT (%): **60** ; Acoustic [RW (C;Ctr)]: **41(-3 ;-7) dB**; Thermal Transmittance (U-value) [W/m2K]: **1.3-1.5** ; Solar gains ~**75 W/m2**



Total Embodied Carbon

A1-A3- 180 kgCO2eq/m² ; **A4-A5, B4, C-**240 kgCO2eq/m²

Embodied Carbon by Material(A-C) kgCO2eq/m²)



Embodied Carbon by Stage(A-C) kgCO2eq/m²)

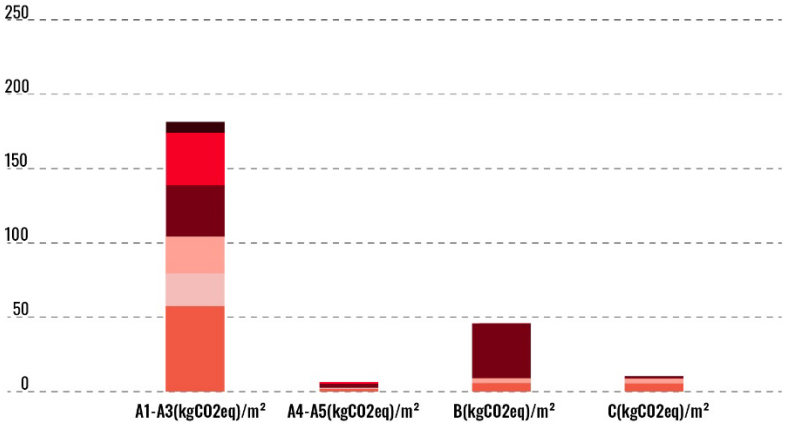


Illustration 20(top-to-bottom). WT-02: Technicalities, Embodied Carbon(EC) generated, and EC by stage (Adapted from ARUP, 2024)

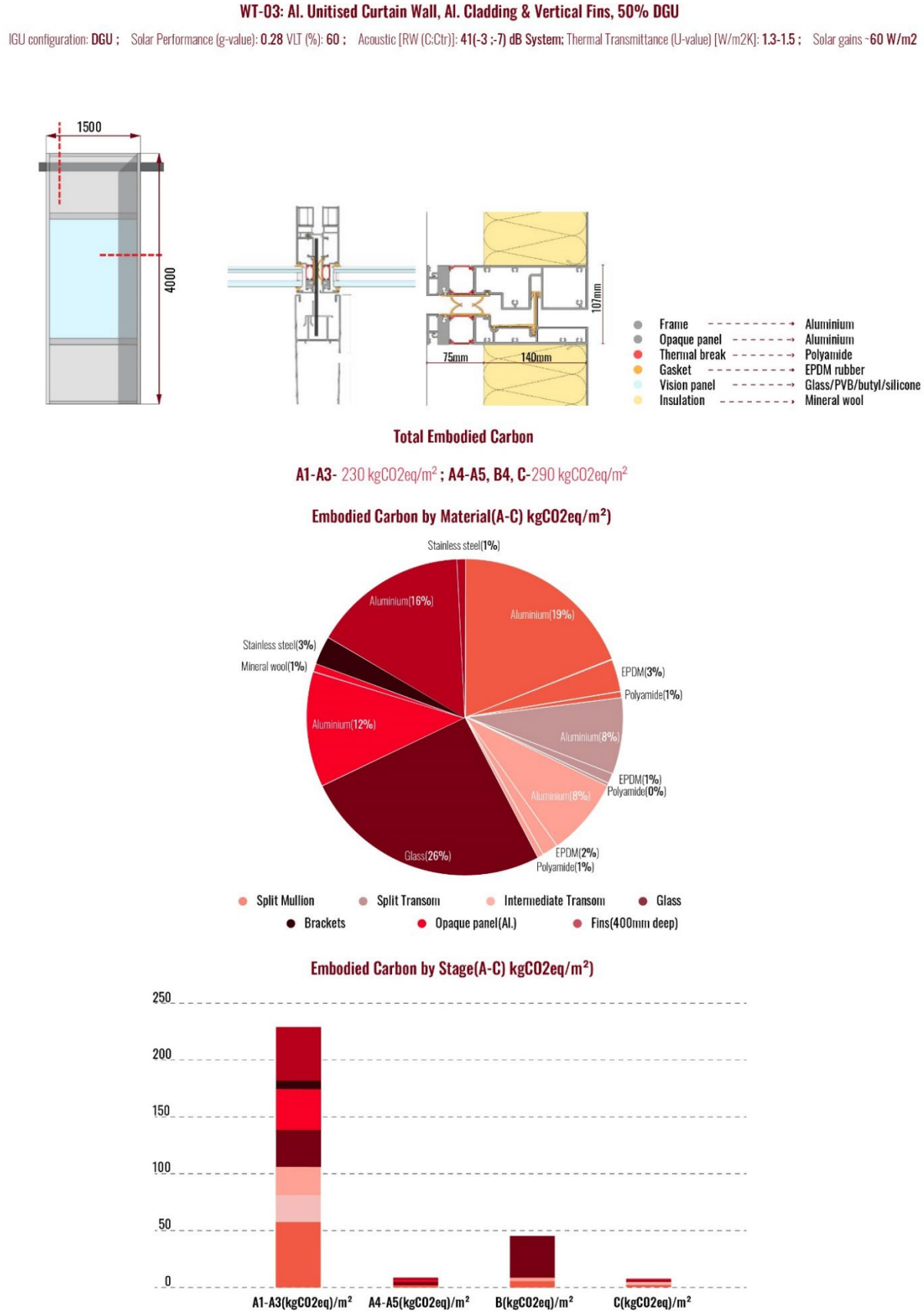
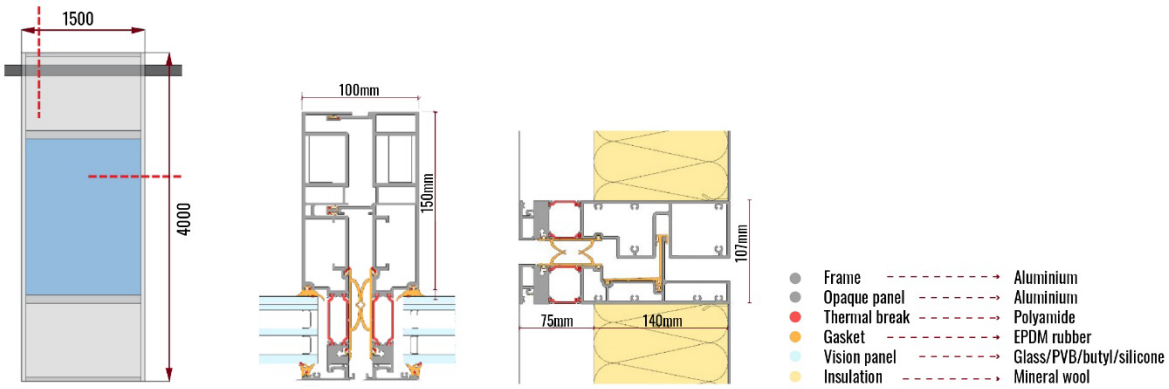


Illustration 21(top-to-bottom). WT-03: Technicalities, Embodied Carbon(EC) generated, and EC by stage(Adapted from ARUP, 2024)

WT-04: Aluminium Unitised Curtain Wall, Aluminium Cladding, 50% TGU

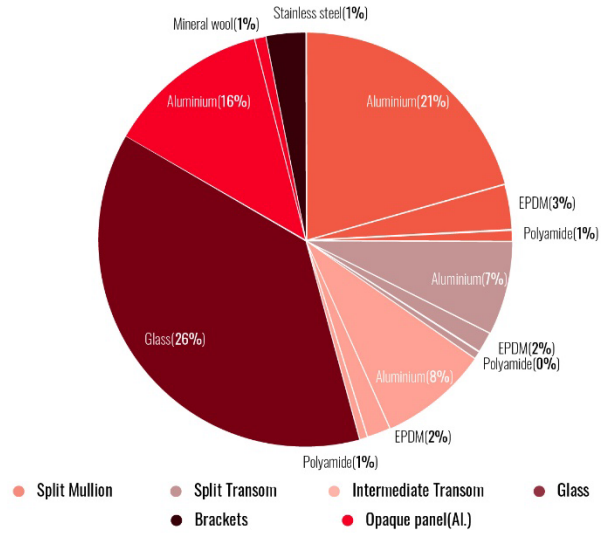
IGU configuration: **TGU ;** Solar Performance (g-value): **0.28** VLT (%): **60 ;** Acoustic [RW (C;Ctr)]: **41(-1 ;-5) dB System** Thermal Transmittance (U-value) [W/m2K]: **0.9-1.1 ;** Solar gains ~**75 W/m2**



Total Embodied Carbon

A1-A3- 190 kgCO2eq/m² **; A4-A5, B4, C-**270 kgCO2eq/m²

Embodied Carbon by Material(A-C) kgCO2eq/m²)



Embodied Carbon by Stage(A-C) kgCO2eq/m²)

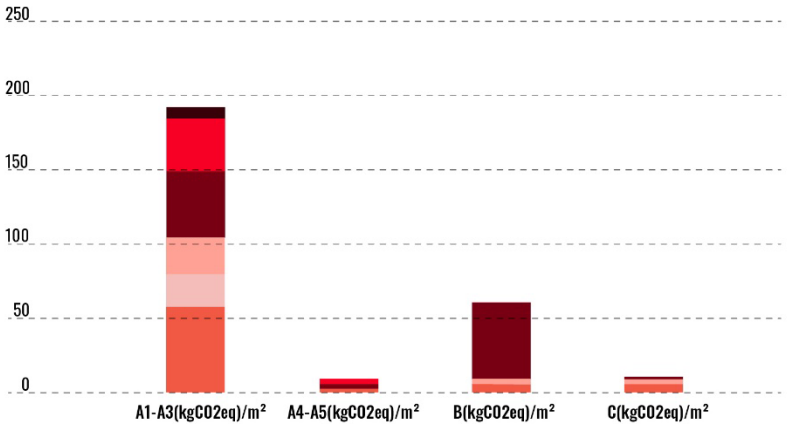
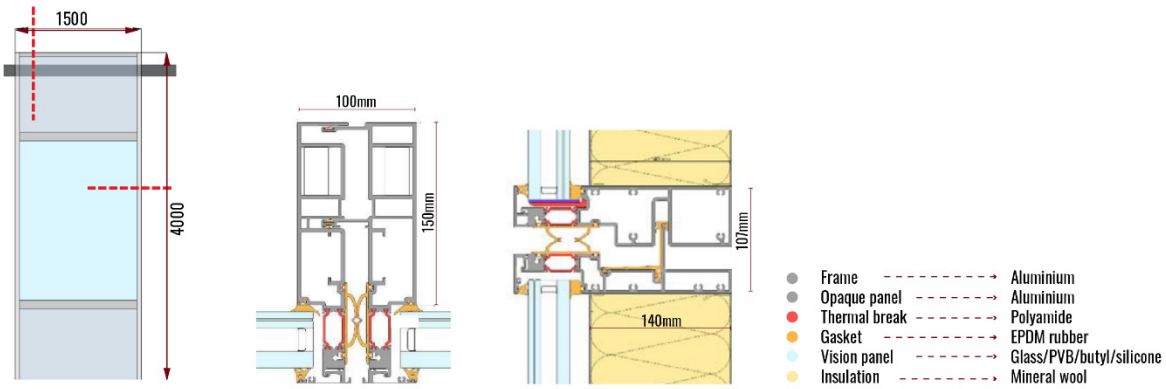


Illustration 22(top-to-bottom). WT-04: Technicalities, Embodied Carbon(EC) generated, and EC by stage (Adapted from ARUP, 2024)

WT-05: Aluminium Unitised Curtain Wall, Insulated Shadow Box, 50% DGU

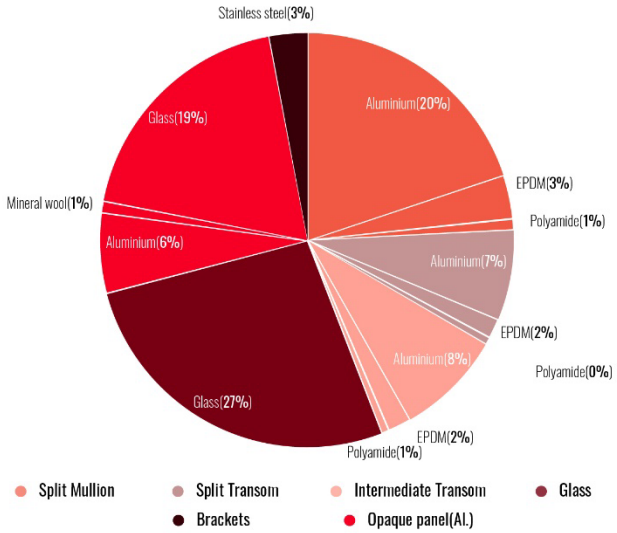
IGU configuration: **DGU ;** Solar Performance (g-value): **0.28** VLT (%): **60 ;** Acoustic [RW (C;Ctr)]: **41(-3 ;-7) dB System;** Thermal Transmittance (U-value) [W/m2K]: **1.3-1.5 ;** Solar gains ~**75 W/m2**



Total Embodied Carbon

A1-A3- 190 kgCO2eq/m² **; A4-A5, B4, C-**280 kgCO2eq/m²

Embodied Carbon by Material(A-C) kgCO2eq/m²)



Embodied Carbon by Stage(A-C) kgCO2eq/m²)

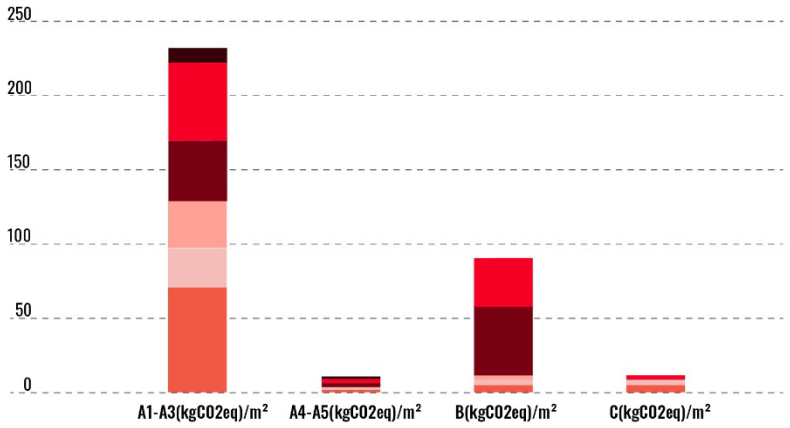


Illustration 23(top-to-bottom). WT-05: Technicalities, Embodied Carbon(EC) generated, and EC by stage; ; (Adapted from ARUP, 2024)

WT-06: Aluminium Unitised Curtain Wall, GRC Cladding, 50% DGU

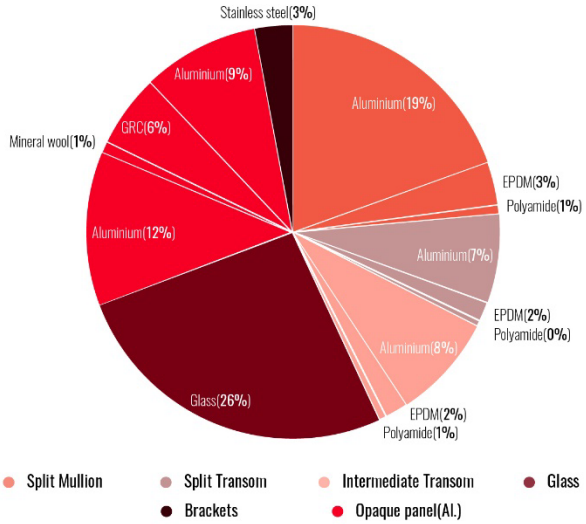
IGU configuration: **DGU** ; Solar Performance (g-value): **0.28**; VLT (%): **60** ; Acoustic [RW (C;Ctr)]: **41(-1 ;-7) dB System**; Thermal Transmittance (U-value) [W/m2K]: **1.3-1.5** ; Solar gains ~**75 W/m2**



Total Embodied Carbon

A1-A3- 220 kgCO2eq/m² ; **A4-A5, B4, C-**280 kgCO2eq/m²

Embodied Carbon by Material(A-C) kgCO2eq/m²)



Embodied Carbon by Stage(A-C) kgCO2eq/m²)

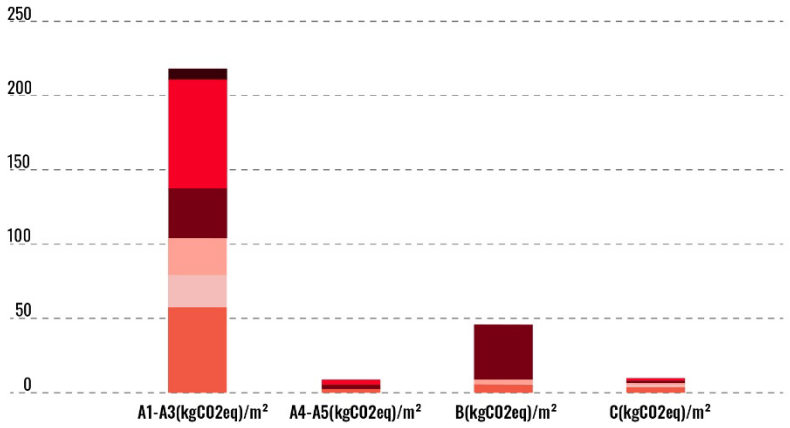


Illustration 24(top-to-bottom) WT-06: Technicalities, Embodied Carbon(EC) generated, and EC by stage (Adapted from ARUP, 2024)

Upon analysing six unitised curtain wall assemblies, the research zeroed in on three pivotal aspects: facade comparisons, material contribution, and component contribution.

A. Facade Comparisons

In Illustration 22, a comprehensive assessment of the six facades could be notices, which reveals a wide range of embodied carbon over a 60-year lifecycle, spanning from 150 to 290 kgCO2e/m2 (Arup and Saint-Gobain Glass n.d., 18-20). Notably, WT-06 exceeded 230 kgCO2e/m2. The cradle-to-gate stages (A1-A3) emerged as the primary contributors to embodied carbon, followed by stage B4, representing the replacement of glazing after 30 years. Among the unitised curtain walls, WT-01 (Aluminium Unitised Curtain Wall, 100% DGU) ranked third in overall embodied carbon, trailing behind the double skin facades WT-10 and WT-11.

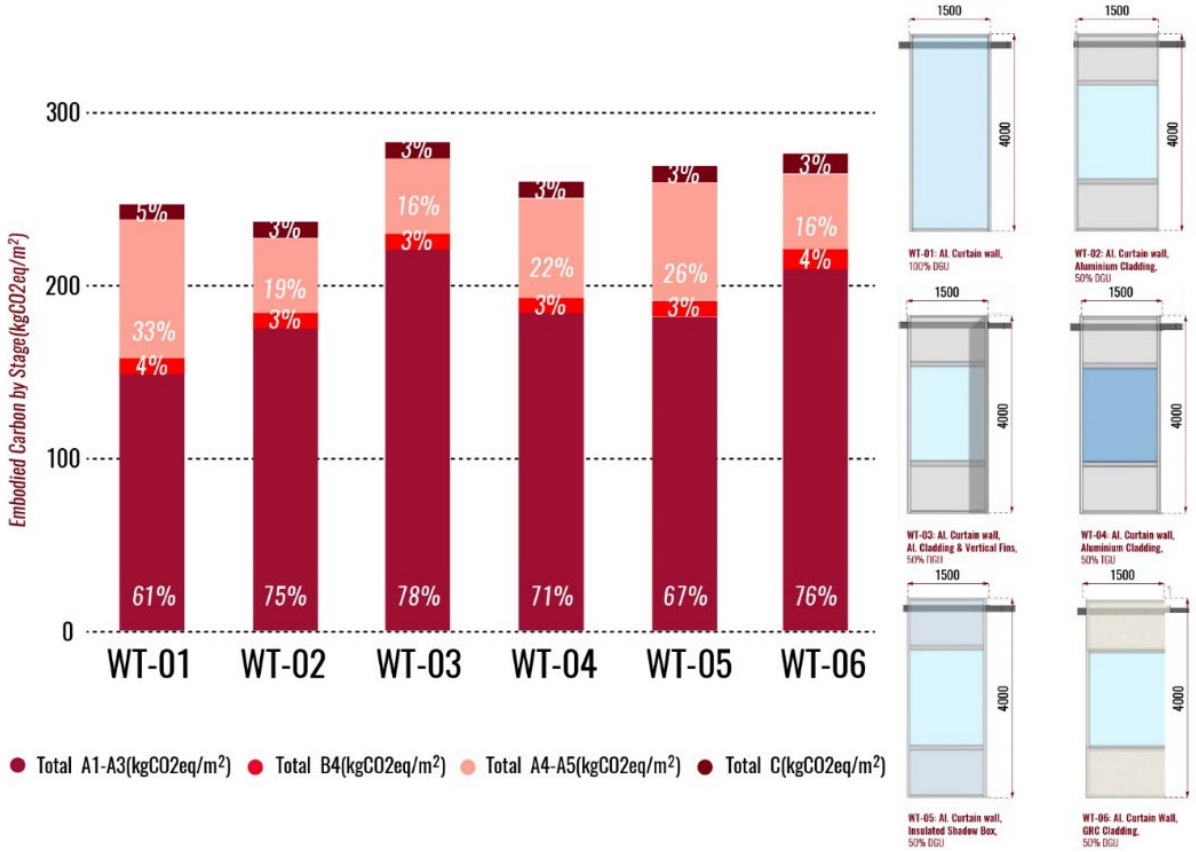


Illustration 25. Total Embodied carbon, between WT-01 to WT-06, over 60 years lifetime(Adapted from ARUP, 2024)

B. Material Contribution

In Illustration 23, the analysis of embodied carbon by material indicates that aluminium framing accounts for most of the embodied carbon in 50% DGU aluminium unitised curtain wall systems (WT-02 to WT-06), while glass contributes up to 60% for WT-01(Arup and Saint-Gobain Glass n.d., 18-20). This explains that glass can potentially have a higher embodied carbon footprint than aluminium. However, implementing techniques such as reducing the WWR to 0.4 instead of the selected 0.5 for the wall assemblies considered above, using smaller class sizes, and opting for less carbon-intensive materials for spandrel panels(Timber mullions or Cellulose insulation) can increase the R-value for the wall. This method can lead to a mutually beneficial situation for unitised curtain walls compared to the ones mentioned above. It not only saves materials, costs, labour, and other resources but also allows the reduction of the environmental impact by lowering the embodied carbon. Especially in hospitals, sustainable strategies can be more beneficial compared to other office buildings. The reason is due to the different uses of interior spaces, leading to fewer material requirements and higher carbon savings.

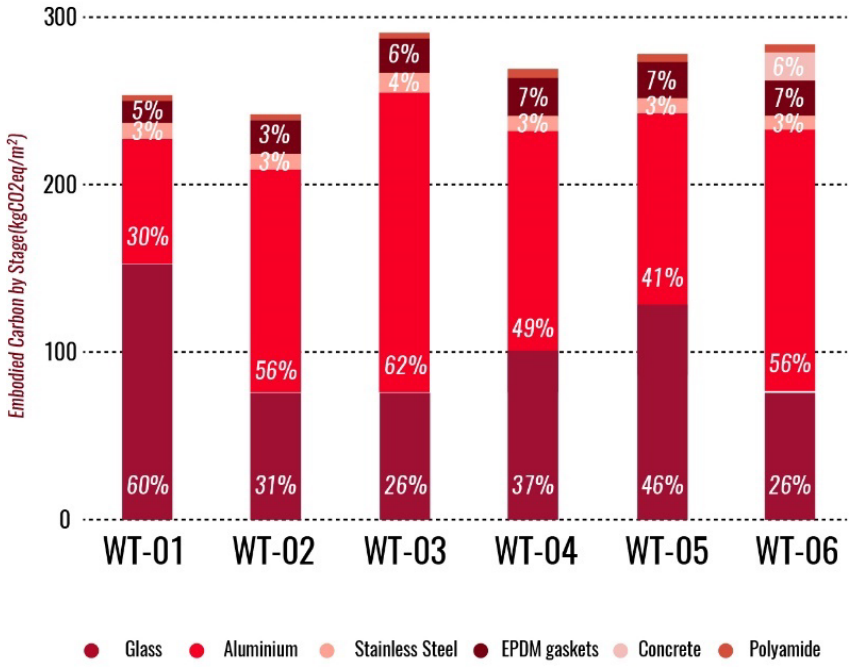


Illustration 26. Embodied carbon by material, between WT-01 to WT-06, over 60 years lifetime(Adapted from ARUP, 2024)

C. Component Contribution

Delving deeper into the individual components of each facade system, as seen in Illustration 24, glass emerged as the largest contributor to embodied carbon in most cases. However, in WT-05 (Aluminium Unitised Curtain Wall, Shadow Box, 50% DGU), the opaque panel, consisting of an insulated shadow box with a glass spandrel, surpassed glass in terms of embodied carbon. This comprehensive analysis (Arup and Saint-Gobain Glass n.d., 18-20) not only illuminates the carbon footprint of various facade systems but also emphasizes the intricate interplay between materials, components, and design choices.

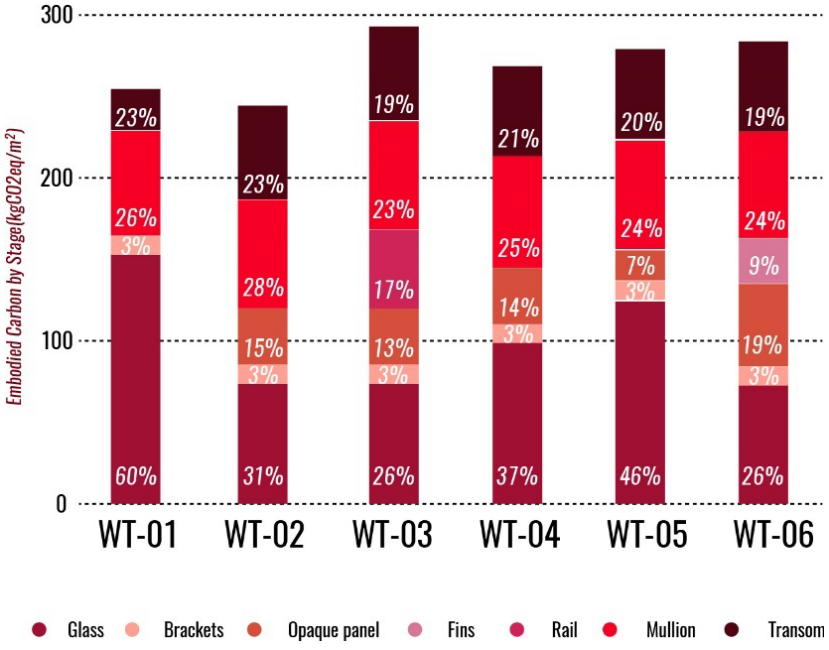


Illustration 27. Embodied carbon by component, between WT-01 to WT-06, over 60 years lifetime(Adapted from ARUP, 2024)

3.4 Conclusions: *Learnings*

The in-depth analysis of facade systems done by Saint Gobain and ARUP illuminated five key outcomes to reduce embodied carbon in buildings, which are: -

1. The lifespan of Insulated Glazing Units (IGUs) significantly affects the overall embodied carbon of facades. The assumption of a 30-year lifespan for IGUs means they need replacement within the facade's lifetime, contributing significantly to embodied carbon. However, in commercial buildings, entire facades are often replaced instead of just the glazing, resulting in unnecessary waste.

   To address these issues, there is a need to promote a shift in industry standards and practices. By using curtain wall systems with thermally broken frames and longer lifespans, there could be a focus on replacing only the IGU when necessary. Achieving this will require education and awareness campaigns highlighting the environmental benefits and cost-effectiveness. Additionally, developing standardised design and installation practices that allow for easier IGU replacement within existing frames is crucial.

2. Replacing Insulated Glass Units (IGUs) shows a big challenge due to the need for exterior access, with building height and accessibility being of top importance. Although window washing tracks provide an existing access point, their practicality for IGU replacement varies depending on the context. Concerns such as building height and the load-bearing capacity of the tracks are crucial, as the tracks may not support the additional loads and safety requirements associated with workers and materials at considerable heights. Also, the size and weight of the windows, associated with strict safety rules for working at heights, require thorough checks. Utilising window washing tracks for IGU replacement demands specialised expertise and may not be possible in all cases, potentially calling for alternative methods such as swing stages, rope access, or mobile elevated work platforms based on the specific building and project requirements.

3. Glass is crucial for daylighting and plays a significant role in reducing embodied carbon. As other industries work on reducing carbon emissions, the contribution of glass to the overall embodied carbon of facades may increase. This study found that glass accounted for 26-60% of the embodied carbon, underscoring the need for the glass industry to actively support designers in creating lower-carbon projects.

   Similarly, aluminium framing also contributes, explaining the importance of making thoughtful material choices that consider both material efficiency and the potential to optimize daylighting. For instance, determining an optimal window-to-wall ratio (WWR) can balance daylighting benefits with the embodied carbon impact of glass. Strategic placement of windows and daylighting technologies can reduce the amount of glazing needed while still providing sufficient natural light, ensuring occupant comfort while minimizing the environmental footprint of the façade
   .
4. It's important to base decisions on data when choosing materials and designing responsibly. Embracing circular economy principles and prioritizing low-carbon materials from the start is crucial. This is where Environmental Product Declarations (EPDs) play a vital role, as they provide thorough data on the environmental impacts of products throughout their lifecycle. Suppliers should provide these EPDs, allowing designers to make well-informed choices. Many design factors affect operational performance and embodied carbon, often leading to trade-offs. Understanding these interdependencies and the "carbon payback period" of design choices is vital for optimizing carbon outcomes.

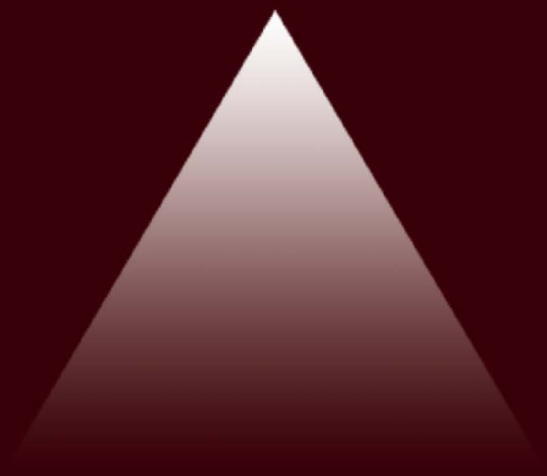
These findings are relevant to North America, given the prevalence of similar curtain wall systems in the region. This leads to the question(Figure 50):

How can these insights be applied to further reduce the embodied carbon footprint of facades in North America?



Figure 50. Demolition of curtain wall for Amsterdam Centrum(Created by Universiteit van Amsterdam HuisvestingsOntwikkeling, 2011)

4. Circular Loop



This chapter delves into the concept of the Circular Economy (CE), also known as the Circular Loop. It starts with defining CE and then progresses to explore its principles, categories, business models, and strategies. It also covers methods for calculating embodied carbon and concludes with insights applicable to industries worldwide. The chapter serves as a foundational resource for rethinking current practices on a global scale.

4.1 What is a *Circular Loop*?

The theory of the Circular Economy (CE) was primarily discussed by scholars like Pearce and Turner, in 1996. The research which majorly focused on closed loop system, skyrocketed in the conversation in the coming two decades. For instance, in 2013, Ellen MacArthur Foundation (EMF) adopted this research and defined the concept of Circular Loop (Ellen MacArthur Foundation n.d.) as,

"An industrial economy that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems and, within this, business models".

In 2014, EMF (Ellen MacArthur Foundation n.d.) integrated some more important information was added on circular loops, such as:

"A circular economy is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value always, distinguishing between technical and biological cycles. This new economic model seeks to ultimately decouple global economic development from finite resource consumption".

From the definitions mentioned above, McArthur aimed that both economic and ecological value shall be preserved, through the continuous reuse of materials and products. It involves closed loops that enable materials and components to be reintegrated into various cycles for reuse. Many scholars (Damen 2012) other than EMF, studying the Circular Economy (CE), offered varied interpretations rather than a single definition. However, they commonly emphasized the importance of closing material loops Another frequent point is the need for systemic change and adopting a system thinking approach (Kok., Wurpel and Wolde 2013). However, the most famous and recent one by Metabolic (Kubbinga et al. 2018, 11) in 2019, who aim in transitioning towards CE (Figure 51). They quote,

"A building that is developed, used and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation. It is constructed in an economically responsible way and contributes to the well-being of people and the biosphere. Here and there, now and later. Technical elements are demount-able and reusable, and biological elements can also be brought back into the biological cycle."

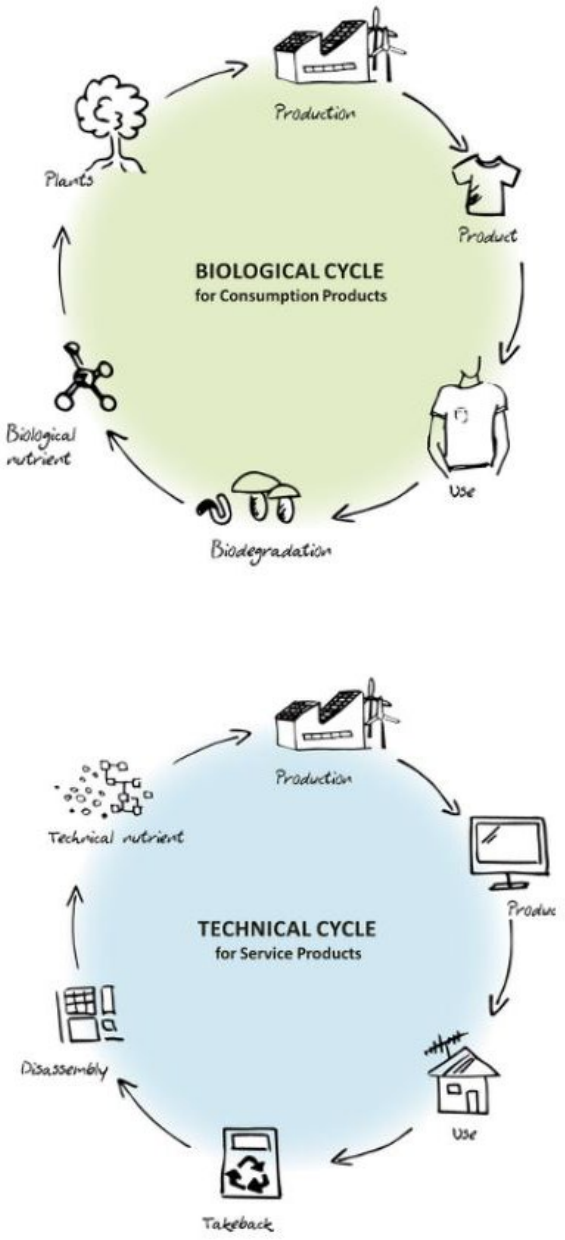


Figure 51. Biological Cycle vs Technical Cycle (Created by Leising, 2016)

Concluding this, Circular Loop strives not only to shift our current linear production and consumption model towards a circular one but also to maximize product and raw material reusability while minimizing value reduction. The introduction of Circular Loop delineates two fundamental dichotomies: Linear Economy versus Circular Economy, and the biological versus technical sphere. The former highlights the contrast between the 'Take-Make-Dispose' approach and the more sustainable 'Reuse-Remanufacture-Recycle' culture. The latter, as emphasized by the Ellen MacArthur Foundation (EMF), distinguishes between two material cycles within Circular Loop. In the Biological cycle, residuals naturally return to the biosphere, enriching natural capital. In contrast, the Technical cycle encompasses materials like fossil fuels, plastics, and metals, which are finite. These branches are further detailed in further topics (4.2 and 4.3).

4.2 *Principles* of Circular Loop

4.2.1 Principles and the Butterfly Diagram

This chapter elucidates the concept and operations of the Circular Loop, depicted through the Butterfly Diagram developed by the Ellen MacArthur Foundation (EMF). The diagram visually represents the concept of a Circular Economy, emphasizing the need for careful management of material flows to rebuild capital, as illustrated by the various loops. The concept revolves around two material cycles: a biological cycle where residues return to the biosphere safely to rebuild natural capital (green cycle), and a technological cycle where materials are designed to circulate at high quality without entering the biosphere (blue cycle). The Butterfly Diagram (Ellen MacArthur Foundation 2019) in Circular Loop emphasizes material loops but neglects to include energy input, highlighting the importance of energy in adding ecological and economic value, and the significance of saving energy by preserving value. Additionally, EMF (2013) also represents five main principles (Leising 2016, 16) that operationalize a Circular Economy:

1. **Design out of waste:** Products should be designed for remarketing, remanufacturing, disassembly, or repurposing, viewing components as nutrients for material cycles. Technical nutrients should be designed to be recoverable, refreshable, and upgradable, minimizing energy input and maximizing value retention.

2. **Build resilience through diversity:** Modularity, versatility, and adaptivity should be prioritized in production systems to thrive in an uncertain and fast-evolving world. Systems should be flexible to use various inputs.

3. **Shift to renewable energy sources:** Systems should aim to run on renewable energy, facilitated by reduced energy thresholds required by a restorative, circular economy.

4. **Think in systems:** It is crucial to understand how parts influence one another within a whole and their relation to the environment and society. Elements should be considered in their environmental and social contexts.

5. **Think in cascades:** For biological materials, value creation lies in extracting additional value by cascading products and materials through other operations.

The principles and Butterfly diagram(Illustration 25) underscore the importance of designing materials and products to stay as close to the top (representing higher value) as possible. This approach minimizes the "falling speed" of value loss through the circles, ultimately increasing overall value. The theories for the technological cycle, as outlined by EMF (2013), Bakker et al. (2014), and de Pauw (2015), emphasize the significance (Leising 2016, 16) of this design strategy by:-

i. **Maintenance** - Regular upkeep tasks to preserve a product's functionality and extend its lifespan, often conducted on a schedule.

ii. **Repair** - Restoring a product or component to a usable state after wear, decay, or damage.

iii. **Refurbishment** - Repairing or replacing major components nearing failure, combining aspects of maintenance and repair.

iv. **Reuse/Redistribution** - Reusing a product or component without any modifications, capturing its value by finding new users with varying needs. This process often involves platforms like online marketplaces, second-hand shops, or physical markets.

v. **Upgrade** - Enhancing product quality, value, or performance by replacing parts or components.

vi. **Remanufacture** - Restoring used products to original or better-than-original performance, typically with a warranty.

vii. **Recycling** - Separating materials from products for reuse in the same or new products.

viii. **Energy Recovery** - Reclaiming some or all of the energy embodied in a used product before disposal.

ix. **Disposal** - The final step in material flow, with efforts in a Circular Economy aimed at finding value in all other steps before disposal.

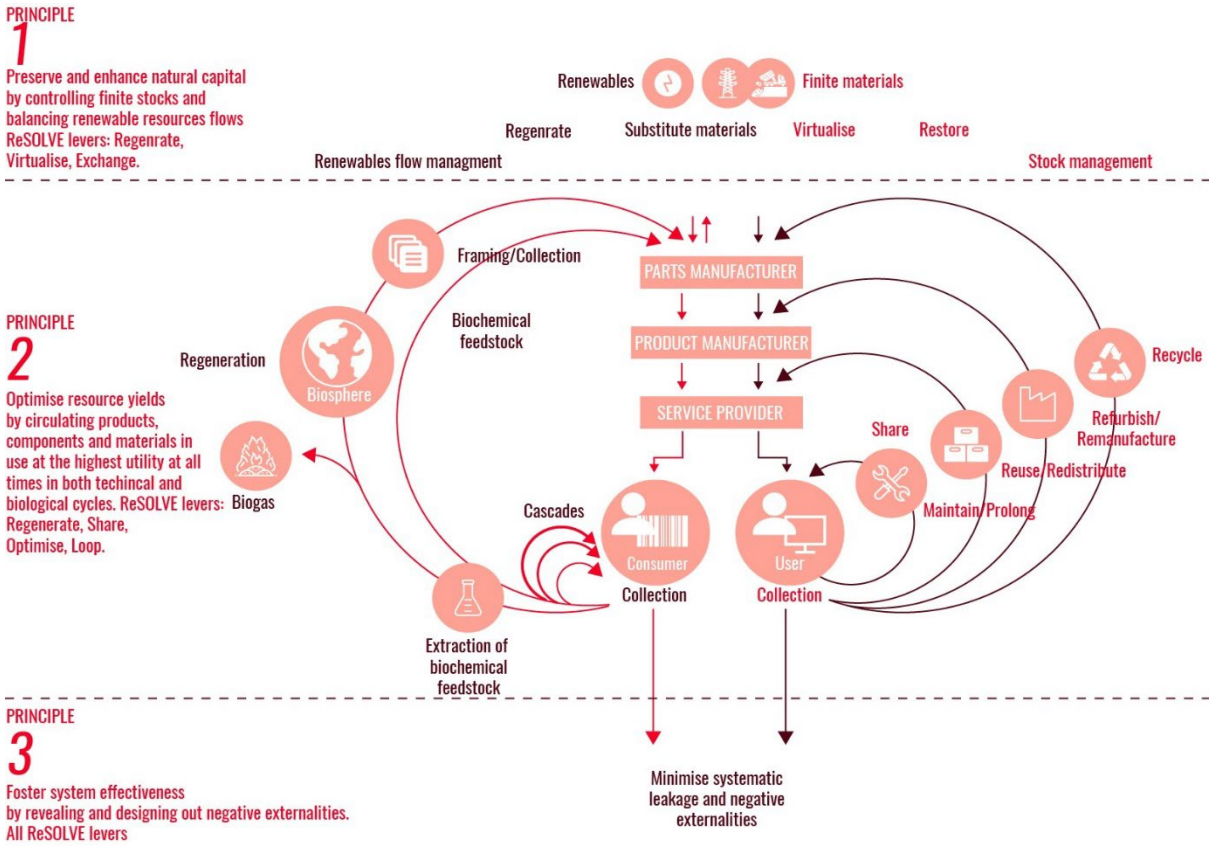


Illustration 28. The Butterfly Diagram (Adapted from EMF, 2013)

4.2.2 Foundations of Circular Loop

The EMF (2013) has formulated the core principles of Circular Economy (CE) based on various fields like business, economy, and design. While these fields (Table 5) have different areas of focus, they share a common foundation. These foundations strive to create more value from waste, transition to system-based innovation, and establish a sustainable framework (Leising 2016, 14), such as:-

Foundations	Key principles
Performance Economy (Stahel & Reday-Mulvey, 1981)	Stahel envisioned an economy based on product-life extension, durable goods, and activities like reconditioning to create circular loops in the economy. In this model, consumers pay for the performance of a product rather than owning it outright, leading to more efficient resource use and controlled waste production.
Industrial Ecology (Graedel, 1994)	Industrial Ecology takes a holistic approach to human problems, integrating technical, environmental, and social aspects. Its goal is to minimize energy use, material consumption, and environmental impacts across the lifecycle of products and services.
Regenerative Design (Lyle, 1996)	Regenerative Design, pioneered by John T. Lyle, emphasizes that all processes within systems should renew or regenerate their energy and material sources. It aimed to satisfy society's needs while respecting nature's limits.
Biomimicry (Benyus, 1997)	Biomimicry, developed by Janine Benyus, looks to nature's designs for solutions. It views nature as a model, measure, and mentor, offering insights into solving human challenges in society, economy, and the environment.
Blue Economy (Pauli, 2010)	Blue Economy, an economic philosophy by Gunter Pauli, draws inspiration from natural systems in terms of production and consumption. It follows a cascading principle where one's output becomes another's input, mimicking the efficient cycles found in nature.
Cradle to Cradle® (McDonough &Braungart, 2002)	Cradle to Cradle® proposes a model where materials are viewed as nutrients in both industrial and commercial cycles. This approach considers the entire lifecycle of products and their materials, starting from the design phase.

Table 5. Key principles of fields of study, combined in the concept of CE (Created by Leising, 2016)

4.2.3 Relatable Principles for Circular Loop

As mentioned in diagram below, there are two Product Life Extension (PLE) or fundamental strategies that increase the durability of products and therefore enable to use products longer (Leising 2016, 16). These include:

i. **Slowing Resource Loops-** By designing durable goods and implementing product-life extension strategies (such as repair and remanufacturing), it can prolong the use of products. This approach slows down the depletion of resources by intensifying and extending the utilization period of products.

ii. **Closing Resource Loops-** Recycling materials enable us to close the loop between post-use and production, creating a circular flow of resources. This process of closing resource loops through recycling and reuse is crucial for sustainable resource management.

4.3 Cradle-to-*Grave* vs Cradle-to-*Cradle*.

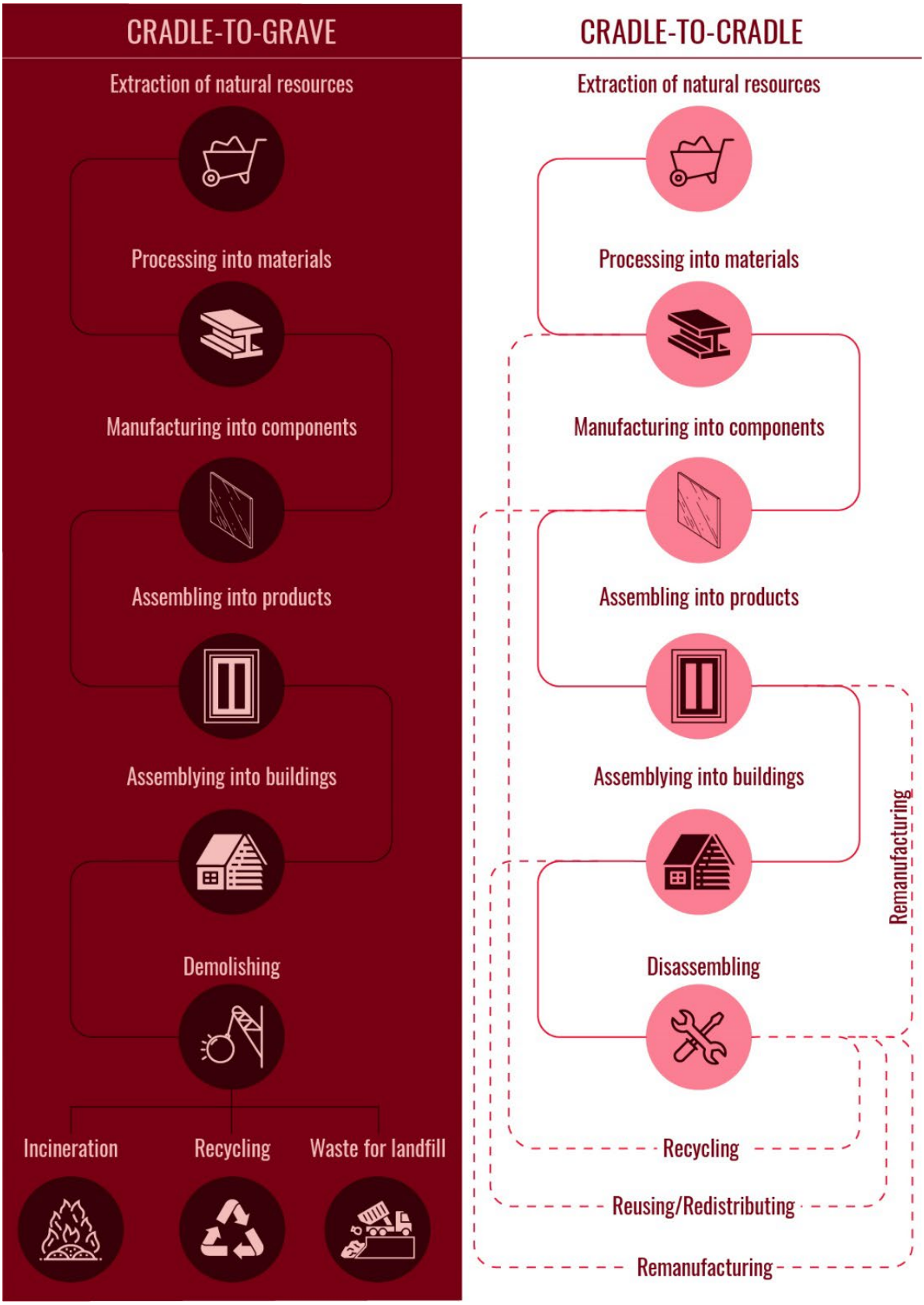


Illustration 29. Cradle-to-Grave vs Cradle-to-Cradle(Adapted from Michael, 2016)

4.3.1 Cradle-to-Grave!

With more than 100 billion tons (U.S.) of raw materials used globally, two-thirds of it ultimately find their way into the environment as non-recoverable "waste" or pollution- ending up in landfills, oceans filled with plastics, and the atmosphere burdened with carbon dioxide, a by-product of burning fossil fuels (Michael 2016, 13-15). This practice might not be new, as it's been going on for centuries. The typical lifecycle of a building, from its inception to its end, has been likened to a 'Cradle-to-Grave' journey(Illustration 26). Philip Crowther (Crowther, 2005) described this process as "single use and disposal.".

This linear "take-make-waste" economy, characterized by resource extraction, transformation into usable products, and eventual disposal, often referred to as a building's lifecycle, is not as circular as one might think. In today's time even with the best-case scenarios where a significant portion of the waste is recycled, it doesn't guarantee that the secondary materials will return to the construction industry. While incineration is a better alternative to landfilling, it comes with its challenges, including high energy and cost requirements, not to mention the release of pollutants.

4.3.2 Cradle-to-Cradle!

Cradle-to-Cradle (Illustration 26) or Circular Economy, on the contrary, prioritizes minimizing waste and energy consumption by empowering users to reclaim components or materials used in construction. In this "Circular Loop" system, materials can be reused, remanufactured, or recycled multiple times, regardless of their initial quality (Beck 2021, 5).

Ultimately, this approach extends the lifespan of materials and reduces environmental impact. As discussed above in the Butterfly diagram, a few of its elements (Illustration 27) are also reflected over here, this includes: -

1. **Maintenance:** Regular upkeep, such as cleaning or tuning, to extend a component's lifespan, typically outlined in the product manual.

2. **Reuse/Redistribute:** Reusing a component in good condition in the same or another building with minimal maintenance and cleaning.

3. **Refurbishment:** Restoring a product to good working condition by replacing or repairing major components and making cosmetic changes.

4. **Remanufacture:** Disassembling and recovering reusable parts at the sub-assembly or component level, including quality assurance and potential enhancements.

5. **Recycling:** Recovering materials from a product that is no longer usable for use in the original or other purposes, returning them as crude feedstock into the process.

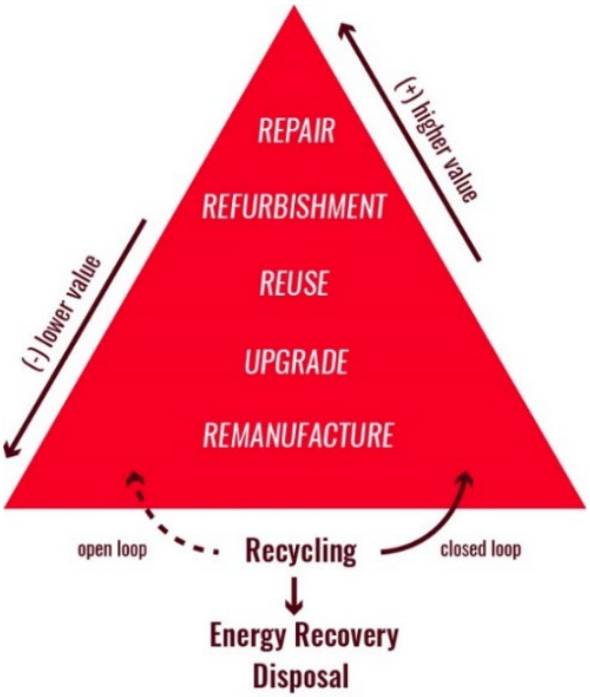


Illustration 30. The Inertia Principle(Adapted from Michael, 2016)

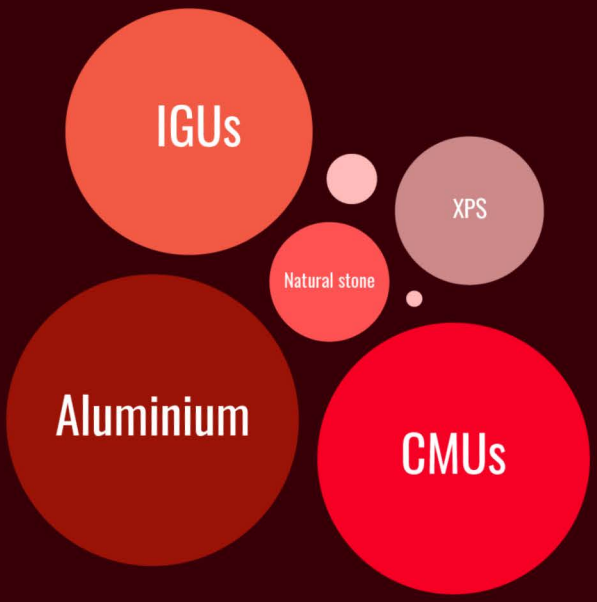
4.4 Conclusion: *Learnings*

In conclusion, this chapter delved into the intricacies of the Circular Loop, covering principles, strategies, foundations, and typologies. It began by highlighting the flaws of the linear economy model, characterized by "extract-produce-use dump," as highly unsustainable. The solution presented by Circular Economy (CE) treats everything in the economy as a valuable resource, emphasizing the reuse of products and raw materials while minimizing resource consumption and environmental impact in the 21st century. MacArthur and EMF proposed CE as the best approach to extend the life of products and components, aiming to treat all materials and components as valuable resources to minimize waste. This restorative and regenerative model, in simpler terms, maximizes the retention of Energy, Labour, and Materials.

The EMF framework forms the core of this research, complemented by studies in similar fields that provide strategic guidelines on the concept. The chapter also outlined the five principles that underpin the circular economy's functionality: designing out of waste, building resilience through diversity, shifting to renewable energy sources, thinking in systems, and thinking in cascades. Additionally, the butterfly diagram, which distinguishes between the biological and technical cycles, was analysed. The concept's operation is based on these two material cycles: the biological cycle, where residues return to the biosphere to rebuild natural capital, and the technological cycle, where materials, components, and products circulate at high quality without entering the biosphere.

Eight different processes were explained, including maintenance, repair, refurbishment, reuse, upgrade, remanufacture, recycling, energy recovery, and disposal. These processes can be classified into two types of loops in a Circular Economy: slowing resource loops (reuse) and closing resource loops (recycle). Furthermore, six key approaches and principles were briefly explained from the foundations of the Circular Loop: Performance Economy, Industrial Ecology, Regenerative Design, Biomimicry, Blue Economy, and Cradle-to-Cradle. These approaches serve as initial examples where resource efficiency, waste reduction, and closed loops are fundamental principles. Lastly, the chapter compared Cradle-to-Grave, supporting Linear Economy, and Cradle-to-Cradle, supporting Circular Economy, initiating a new discussion on the Circular Loop in the Built Environment for the next chapter.

5. Circular Loop *Practice*


IGUs
XPS
Natural stone
Aluminium
CMUs

Addressing climate change through energy-efficient buildings is a top priority in today's environment. To tackle this, there's been a recent push in material ecology, where the concern is not just to consider operational energy use but to think about embodied carbon count as well. Therefore, this chapter takes a further step towards Circular Loop, where the main conversation is decreasing the total greenhouse gas emissions over a product's life cycle. To understand this, a detailed analysis of present circular market trends, their challenges, and opportunities in varied industries will be discussed.

5.1 Circular Loop in *Other* Industries

Prior to delving into the circularity of the construction industry, it is important to understand how the circular loop operates on a macro level in other industries. In Paul Polman's book "Net Positive," it is discussed that many companies are committed to a culture of reuse, reduction, and remanufacturing. Some examples (Polman and Winston 2021, 100) of this commitment from such other industries are outlined below:

Patagonia:

An outdoor clothing brand has a program called "Worn Wear" that aims to reduce waste and promote reuse. Their focus on sustainability is evident in their use of recycled materials in their products and their motto, ***"We're here to save our home planet."*** Patagonia is committed to ethical and sustainable practices in the fashion industry.

Unilever:

A renowned company that produces consumer goods, has set goals to reduce waste and increase the use of recycled materials in its packaging. They also prioritize using sustainable sourcing practices for their raw materials, which is part of their ***"Unilever Sustainability Living Plan."***

IKEA:

The Swedish furniture company has made sustainability a core part of its business strategy to become ***"Plant positive"*** by 2030. Their focus is on reducing waste, promoting circularity in their products, and using renewable materials in their production processes. Additionally, IKEA has taken steps to encourage customers to recycle and repurpose their products.

Amid the aims and objectives of large-scale companies, there's more! Two of them have mentioned their plan and process below.

A. CISCO: A technology company

Cisco's "Refresh program"(CISCO 2023) is a circular economy initiative that refurbishes and resells used networking equipment. The program reduces waste and offers cost-effective solutions for customers who do not require the latest technology. The process starts by collecting equipment from customer trade-ins, lease returns, and excess inventory. The equipment undergoes a rigorous inspection and testing process to ensure its functionality and condition. As shown in Figure 52, Cisco ensures that the refurbished equipment meets the same quality standards as new products through thorough testing and certification. Certified refurbished equipment from the Refresh program is made available for sale to customers, complete with a warranty. The lower price point of these refurbished products compared to new equipment makes them an attractive and cost-effective option for customers seeking to reduce their environmental impact. By extending the lifespan of networking equipment, Cisco's Refresh program contributes to reducing electronic waste and promoting sustainability in the technology industry.

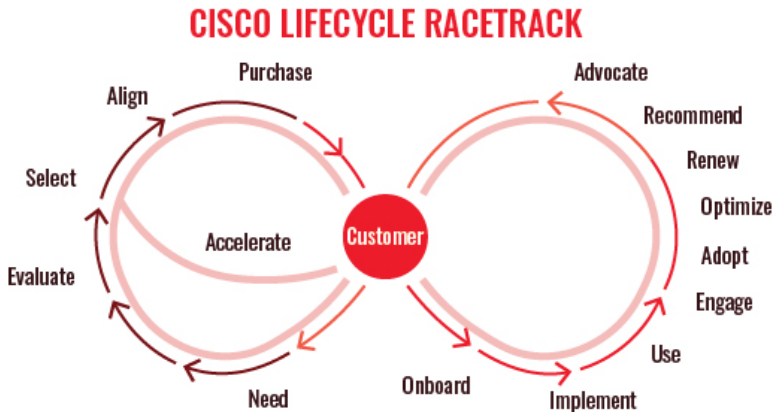


Figure 52. CISCO Lifecycle Racetrack(CISCO, 2020)

B. Philips: A healthcare industry

Philips stands out as a company that has fully embraced circular economy principles in the healthcare industry. Their product design (Figure 53) focuses on durability, repairability, and recyclability, to ensure that all products launched after 2020 are designed for circularity. The company also targets (Philips 2023) a 25% recycled content in their products by 2025, and a 30% reduction in CO2 emissions by 2025 compared to 2015 levels. Philips is also committed to making all of their packaging materials 100% recyclable or reusable by 2025. One of their products, the Azurion image-guided therapy platform, employs a modular design that allows for easy disassembly and repair, and it can be upgraded without needing to replace the entire system. Philips selects materials that are both recyclable and environmentally friendly and conducts lifecycle assessments to minimize their environmental impact. They have also implemented a reverse logistics system that enables them to collect and refurbish used equipment, thereby extending its life and reducing the need for new materials. Philips works with recycling partners to ensure proper recycling of materials, demonstrating their commitment to sustainability.

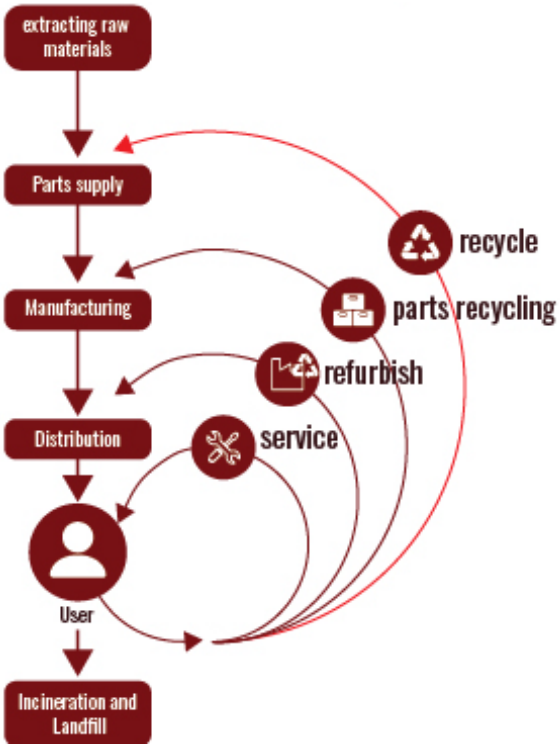


Figure 53. Philips Circular-Economy-Diagram (Philips, 2022)

Circular strategies have been successfully implemented across various industries, including healthcare, construction, and fashion. The initial stigma and misunderstanding surrounding circular materials in some industries have decreased due to the influence of reputable brands and increasing customer demand for sustainable products. By adopting various fitting strategies, companies have enhanced their impact and demonstrated that customer concerns can be addressed with the right approach. Additionally, a circular approach in the fashion and healthcare technology industry has been developed through collaborative efforts within the supply chain, where all aspects of the technology and garment's lifecycle contribute to the goal of circularity. Consumers are provided with options to manage their clothing sustainably, ensuring items are reused, donated, or recycled. In the upcoming section, a deeper look into the circularity of the construction industry, draws parallels with other sectors.

5.2 Circular Loop in *Construction* industry

5.2.1 Introduction

5.2.1.1 Business model and Frameworks

The Business model and Frameworks are like a roadmap, and at their core are three key concepts that form the foundation of the circular loop, a well-known principle in our construction industry. First up is the business model called Value Hill, a versatile approach used across various industries. Then, a quick tour of the different levels in a Circular Built Environment (CBE). And at last, delving into the ongoing challenges within the layers of a building, uncovering the complexities of changing layers that shape our built environment.

a. Value Hill

To initiate a conversation about Circular Economy (CE) in the construction sector, introducing the concept of the "Value Hill" can be quite effective. As shown in Figure 54, this business model, popularized by Metabolic (Metabolic 2021, 15), a sustainability-focused consulting firm, represents a shift from a Linear to a Circular Loop. It emphasizes quality over quantity, promoting the circular use of materials and highlighting their value preservation. This concept is particularly relevant to the construction industry due to the strategies mentioned below:

1. **Base of the Hill:** At the bottom of the Value Hill lies the traditional linear economy, where resources are extracted, transformed into products, used, and ultimately discarded as waste.

2. **Peak of the Hill:** At the peak of the Value Hill lies the pinnacle of a circular economy. Here, products and materials are crafted for reuse, repair, or recycling, forming a closed-loop system that minimizes waste and maximizes resource use.

3. **Value Creation:** As companies move up the Value Hill, they transition from linear to circular practices, which can result in various forms of value creation:
   a) *Cost Reduction:* Circular practices save costs through efficient resource use, reduced waste disposal, and lower production costs.
   b) *Brand Reputation:* Embracing sustainability enhances brand image, attracting eco-conscious consumers and investors.
   c) *Risk Reduction:* Diversifying supply chains and reducing reliance on finite resources mitigates risks from scarcity and price fluctuations.

d) *Innovation:* Circular approaches drive innovation in product design, materials, and business models, creating new market opportunities.

4. **Transitioning Up the Hill:** Moving up the Value Hill requires companies to adopt circular economy principles, such as designing products for durability and recyclability, implementing reverse logistics for product take-back and recycling, and collaborating with stakeholders across the value chain to close the loop.

As a whole, the idea of 'Value Hill' not only supports Circular Loop by reducing the amount of waste generated but also creates new forms of value benefits to businesses and the environment.

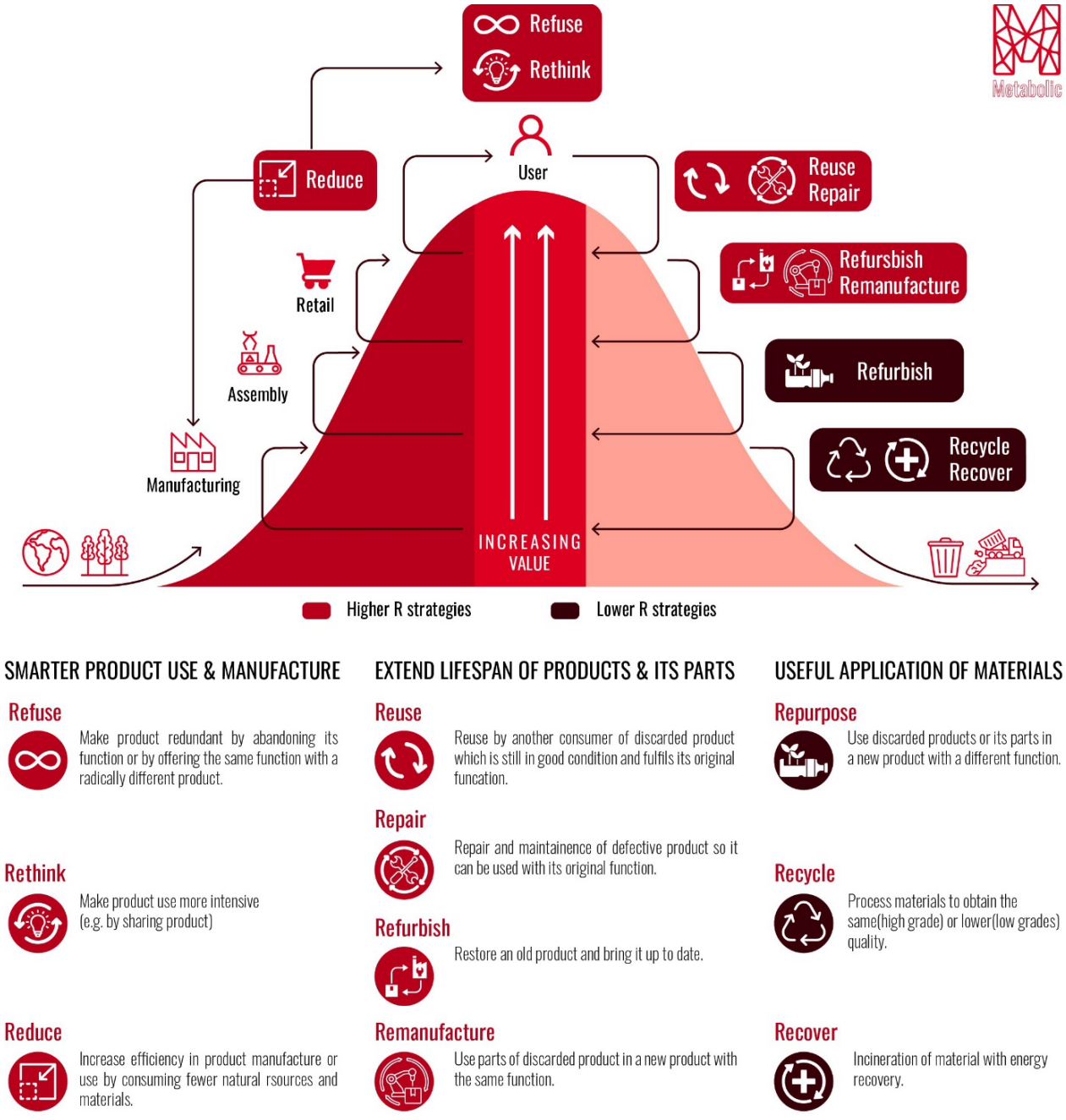


Figure 54. Value Hill (Created by Metabolic, 2023)

b. Circular Built Environment

Circularity, or the Circular Built Environment (CBE), is a holistic and interdisciplinary approach (Figure 55) that considers various scales, from the city down to individual buildings, components, and materials. This approach emphasizes the importance of social, technological, environmental, and economic factors, along with stakeholders, processes, and design considerations, as highlighted by TU Delft (TU Delft n.d.).

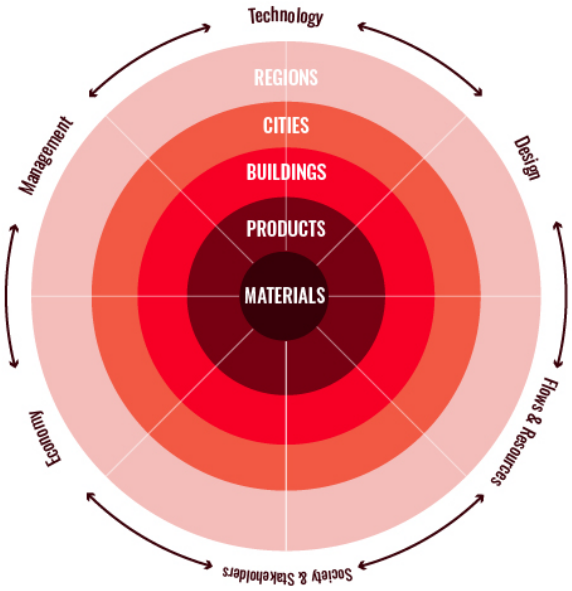


Figure 55. Circular Economy for a Sustainable Built Environment (Adapted from Klein, 2013)

c. Layers of Change

In the built environment, buildings are often designed as static structures, but they should be able to adapt to changing needs and environmental conditions over time. This idea, coined by Beurskens and Bakx (2015, 21), suggests that a building should be seen as a series of different buildings over its lifespan. As shown Figure 56, Stewart Brand (1994) introduced the concept of "layers of change" in buildings (Brand 1994, 12), which outlines different aspects that can be modified over time:

i. **Site and Landscape:** These changes are considered eternal and involve landscaping and outdoor infrastructure.
ii. **Envelope:** Upgrades to walls, windows, and roofs occur approximately every 20 years to enhance energy efficiency and aesthetics.
iii. **Structure:** Changes to the structural system, such as walls or beams, are made every 30-300 years to accommodate new layouts or support needs.
iv. **Interiors:** Alterations to interior partitions, finishes, and fixtures are made every 3-30 years to adapt to new uses or aesthetics.
v. **Mechanical Systems:** Upgrades to heating, ventilation, air conditioning, plumbing, and electrical systems are typically done every 7-15 years to improve efficiency and comfort.
vi. **Smart Systems:** Integration of smart technologies is done intermittently to enhance building performance and user experience.

This framework allows for a flexible approach to building design, ensuring that structures can adapt to changing needs and environmental conditions over time.

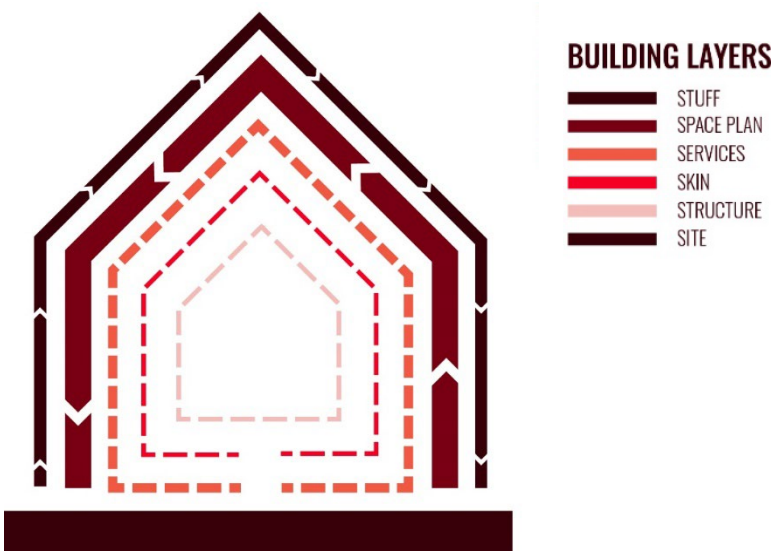


Figure 56. Shearing layers of change (Adapted from Brand, 1994)

d. Calculating Circular Loop

To gain a better understanding of circular theories, it's vital to consider each stage of the defined life cycle before conducting a forensic analysis of embodied carbon. If any stage is overlooked, transparency can be compromised in the calculation part. It's crucial to evaluate circularity at every step since each component affects the environment.

Therefore, Life Cycle Stages help to break down into modules and make us understand each process, its significance, and parameters. For instance, in the construction industry, buildings go through various stages from planning to demolition, and these stages are guided by specific standards that can be incorporated into Life Cycle Assessments (LCAs). Examples of such standards include “EN 15978” and “EN 15804”. To illustrate these stages, refer to the categorised diagram in Figure 57.

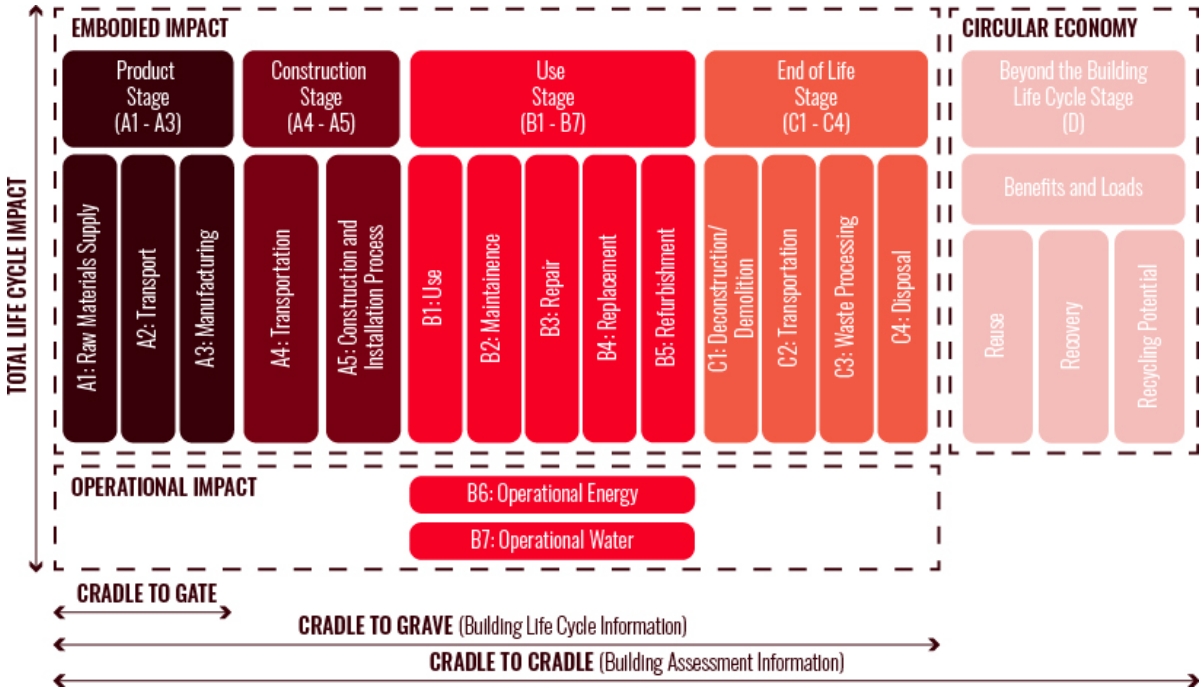


Figure 57. Life-cycle stages according to the EN standard (Adapted from OneClick LCA, 2023)

The Life-cycle stages shown above that are adopted by OneClick LCA (Masson 2023) and followed accordingly by the EN standards, includes: -

1) **Product stage(A1-3):** Module A1, A2, and A3 can be considered as a collective stage, encompassing the extraction and processing of raw materials, secondary material input processing, transportation to the manufacturer, and the manufacturing process itself. Each stage includes the provision of all necessary materials, products, and energy, as well as waste processing until the end-of-waste state or the disposal of final residues during the product stage. Please note that the assessment only considers the building and its parts, excluding furniture and appliances.

2) **Construction process stage(A4-5):** Stages "A4 and A5" involve the transportation and installation of the product, including all impacts and aspects related to any losses during the construction process stage, such as production, transport, waste processing, and disposal of lost products and materials.

3) **Use stage(B1-7):** During stages "B1 to B7", the product is used or applied, maintained, repaired, replaced, refurbished, and operated for energy and water use, including all related material, product, energy, and water provisions, waste processing until the end-of-waste state, or disposal of final residues.

4) **End-of-life stage(C1-4):** Stages "C1 to C4" cover the de-construction, demolition, transportation to waste processing, and waste processing for reuse, recovery, and/or recycling. Each stage includes the provision and transportation of all necessary materials, products, and related energy and water use.

5) **Beyond life cycle stage(D):** Lastly, "D" represents the potential for reuse, recovery, and/or recycling, expressed as net impacts and benefits. There is an optional module (Module D) available for the assessment, which can include additional information beyond the building lifecycle. With Module D, it is possible to consider the supplementary benefits and burdens of disposal after demolition, especially for construction products. This approach is aligned with the cradle-to-cradle philosophy.

5.2.1.2 Hierarchies in building levels

Following the previously outlined hierarchy, but in contrast to traditional building structures, disassemblable structures should be viewed as a hierarchy of building levels. This means that at any level of detail, the building can be described: at the highest level (building level) as a complete assembly of systems, at an intermediate level (system level) as a composition of components, and the lowest level (component level) as an assembly of elements or materials. This approach (Durmisevic 2006, 142–43) allows for a more flexible and adaptable understanding of building structures, where each part can be understood both as a whole and as part of a larger system. Considering that a structure is essentially a functional assembly, the hierarchical levels of building composition can be defined as follows:

1. **Building Level:** This represents the assembly of systems that perform the main building functions, such as load bearing, enclosure, partitioning, and servicing.

2. **System Level:** This represents the composition of components that carry out the functions of the system, such as bearing, finishing, insulation, reflecting, and distributing.

3. **Component Level:** This represents the layered or framed assembly of component functions, which are allocated through the elements and materials at the lowest level of building assembly.

This approach offers a more dynamic and adaptable understanding of building structures, where each level is interconnected and contributes to the overall functionality of the building.

5.2.1.3 Hierarchies in building products

This framework (Figure 58) allows for a flexible approach to building design, ensuring that structures can adapt to changing needs and environmental conditions over time. The hierarchical structure of building products, as developed by (Klein 2013, 100) and applied to the facade discipline, is based on the concept of "product levels." These levels represent different stages of product complexity and integration. Here's a simplified explanation of each level:

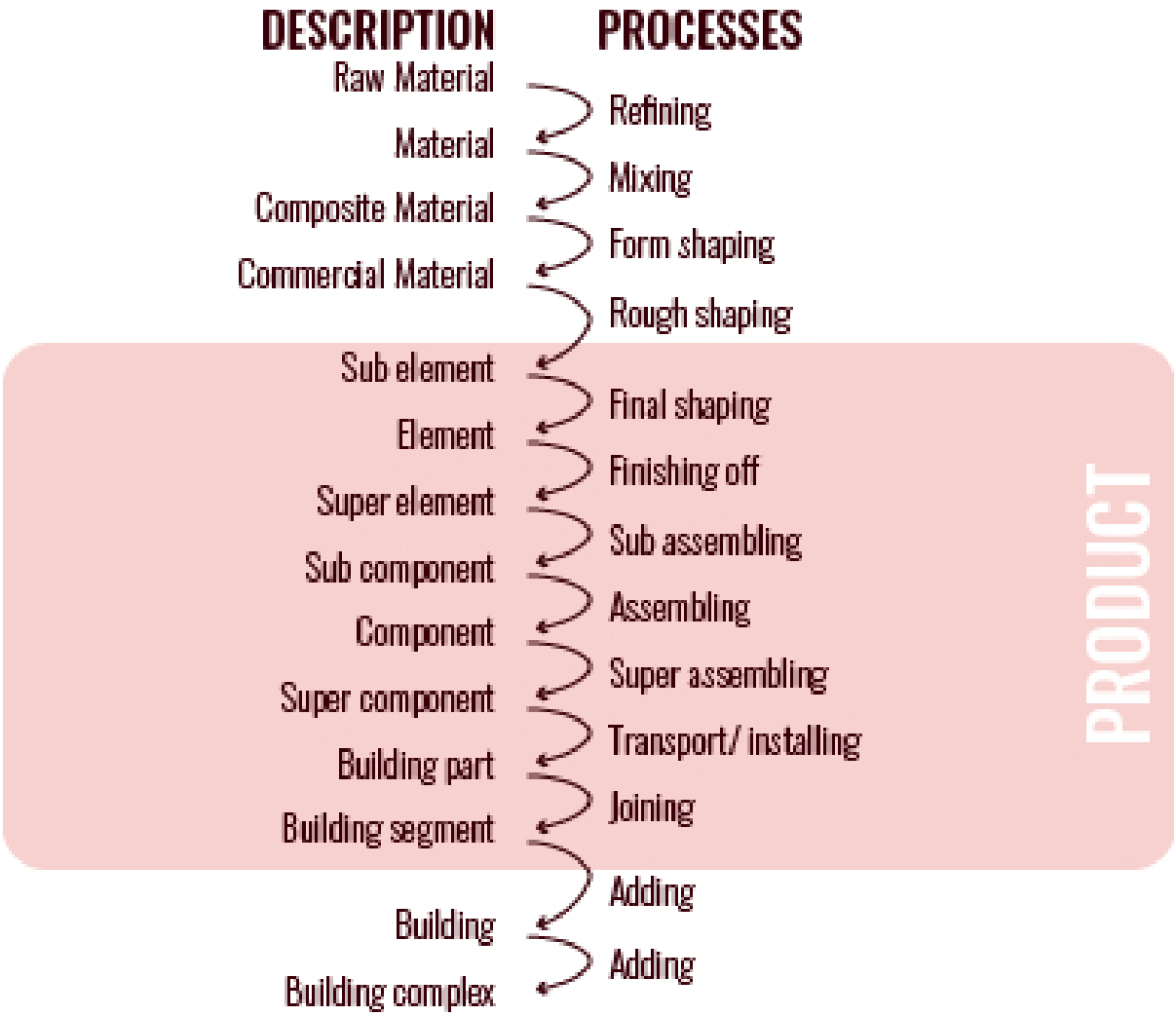


Figure 58. Hierarchical range of building products (Adapted from Eekhout, 2008)

1. **Materials:** These are the basic ingredients used in construction, such as glass or steel, including composite materials.

2. **Standard Materials:** Intermediate goods available in standardised forms, like I-beams, tubes, coils, and bricks.

3. **Commercial Materials:** These are shaped for specific products or projects, like extruded aluminium profiles for window frames or rubber gaskets for specialized purposes.

4. **Elements:** Assemblies made from different commercial materials, such as insulated glass units made of glass panes, aluminium spacers, and silicone.

5. **Sub-components:** Closed assemblies of elements with a single functional purpose, like window frames or sun-shading devices.

6. **Components:** These are independent, functioning building units made up of several composing elements. They are assembled off-site and then transported to the site. For example, a unitised facade part.

7. **Building Parts:** Collections of elements and components with identical technical main functions, such as a curtain wall or the primary load-bearing structure of a building

8. **Building:** This refers to the complete structure and needs no further explanation.

These levels help categorize building products based on their complexity, integration, and functional purpose within the built environment.

5.2.1.4 Circular building levels & its principles

The concept of circular building product levels introduces a structured approach to designing buildings with circular economy principles. It contrasts(as shown in Figure 59) traditional building structures by focusing on subassemblies rather than elements. This approach, influenced by the works of Brand (1994, 12), Eekhout (1997), and Durmisevic (2006, 37-38), aims to create a more specified hierarchy for designing circular buildings. The circular building product levels consist of six levels: building level, building system level, sub-system level, component level, element level, and material level. Each level represents a different level of abstraction, from the overall building assembly to the individual materials used.

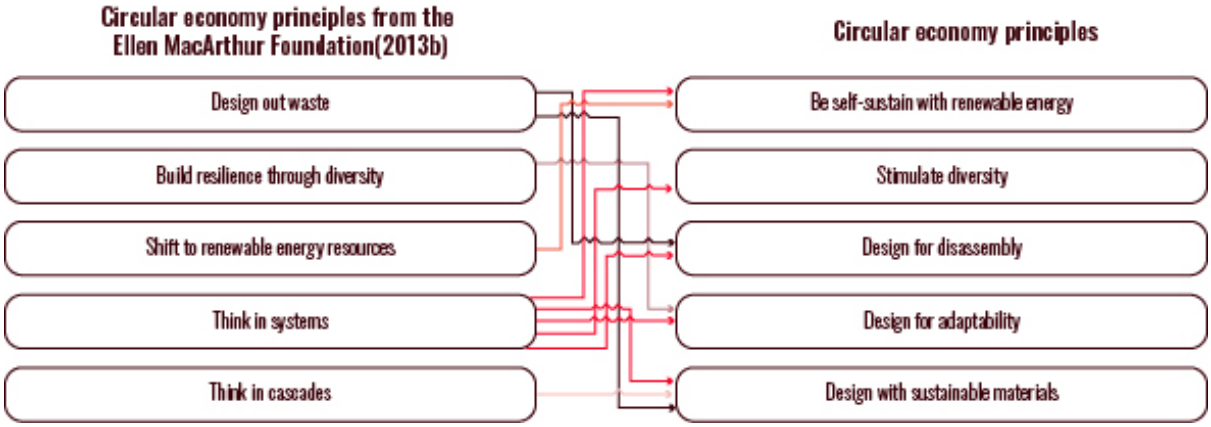


Figure 59. Linking model: Circular Economy principles by EMF(Adapted from EMF, 2013b)

This approach emphasizes the importance of thinking in systems, aligning with the principles of the circular economy. By providing a systematic approach to building design, the circular building product levels help designers create buildings that are adaptable, sustainable, and in line with circular economy principles. The five Circular Building Design principles (Gupta 2021, 30) are: -

a) Be self-sustaining with renewable energy.

b) Stimulate Diversity.

c) Design for Disassembly.

d) Design for Adaptability.

e) Design with Sustainable materials.

As this thesis explores last three principles of circular design (Leising 2017, 42-45), therefore they will be explained and visualised(Figure 60) in detail below.

i. Design for Disassembly

Design for Disassembly(DfD) is a critical concept often overlooked in construction. While the industry focuses on improving assembly techniques, little attention is paid to simplifying the disassembly process. This oversight results in many buildings being demolished and generating significant waste. To address this, it is essential to consider disassembly during the design stage. By doing so, building components can have multiple lives, significantly extending their life cycle. Incorporating the circular building principle of Design for Disassembly allows for various re-life options from the circular economy model.

In general, disassembly should be non-destructive to reuse components or elements without losing their embodied value or requiring energy to melt down as, in recycling, such as embodied energy and labour. Historic examples like London's Crystal Palace demonstrate successful disassembly, relocation, and reassembly after its useful life. However, Design for Disassembly is not yet standardised in building practice, necessitating more guidance on its implementation. This principle aligns with the circular economy's aim to 'design out waste.'

ii. Design for Adaptability

Designing for Adaptability(DfA) is crucial in an era where change is constant. Buildings should be as flexible as living systems, able to respond to evolving needs and conditions. Factors like high vacancy rates, economic fluctuations, and a growing focus on sustainability have heightened the importance of adaptable design. To achieve this, architects can adopt the circular building principle of 'design for adaptability.' This approach allows buildings to adjust to changing demands and user requirements.

However, despite being a longstanding topic in the construction sector, implementing adaptable design strategies remains challenging. There is a need for more guidance on how to effectively incorporate 'design for adaptability' into building designs. This principle aligns with the circular economy concept of 'build resilience through diversity' and encourages thinking in systems. By embracing adaptability, buildings can better withstand future uncertainties and serve the needs of their users and the environment.

iii. Design with Sustainable materials.

Designing with Sustainable Materials (DSM) is crucial for the future of construction. As resources become more costly and limited, the availability of materials will significantly impact building practices (Gorgolewski & Ergun, 2013). Currently, the construction industry has a low recycling rate for construction and demolition waste (Mulders, 2013). Transitioning to more sustainable practices, such as reusing materials, can reduce resource consumption and waste generation.

Incorporating the principle of designing with sustainable materials is essential for creating a more resource-efficient construction approach. This principle focuses on using materials that align with the circular economy, promoting the reusability and recyclability of building materials. Embracing this principle can lead to develop construction methods that are less reliant on new materials and more environmentally friendly.

5.2.2 Market Developments & Stakeholders

The construction sector has a significant embodied carbon footprint due to its continuous need for extraction, transportation, and manufacturing of new building materials from virgin resources. As proved in a report (Beck 2021, 9-10) by U.N. Global Compact and Accenture in 2012, almost half of all extracted raw resources are used to make construction materials. Additionally, up to 40% of urban solid waste constitutes construction and demolition waste, and 11% of global energy-related GHG emissions are attributed to the construction industry. It is expected that by 2025, 2.2 billion tonnes of construction waste will be generated around the world, which is nearly double the amount of waste generated in 2018. With such pressure, the construction industry is trying to balance its legs in two boats. According to the World Economic Forum and Boston Consulting Group (Beck 2021, 9-10), on one side, the governments are pledging towards net-zero building and low-carbon retrofit pathways in the coming decades, whereas, on the other, global demand for resources and materials is still there due to rapid urbanization.

As studied in the previous Introduction, many of the challenges faced by the construction and real estate sectors, including climate action, innovation, and broader sustainability are resolved by the principles of Circular Economy (CE). This includes building waste reduction, adaptive reusability, and increased focus on end-of-life treatment for materials, which leads to the development seen in the market, that integrates design for disassembly and adaptability thinking, modular construction, durability, and deconstruction. The emergence of digital and disruptive technologies is driving significant advancements in productivity, efficiency, process improvements, and enhanced collaboration within the construction industry. As a result, products such as mass timber and those with increasing amounts of recycled content, such as concrete and aluminium, are becoming more favourable.

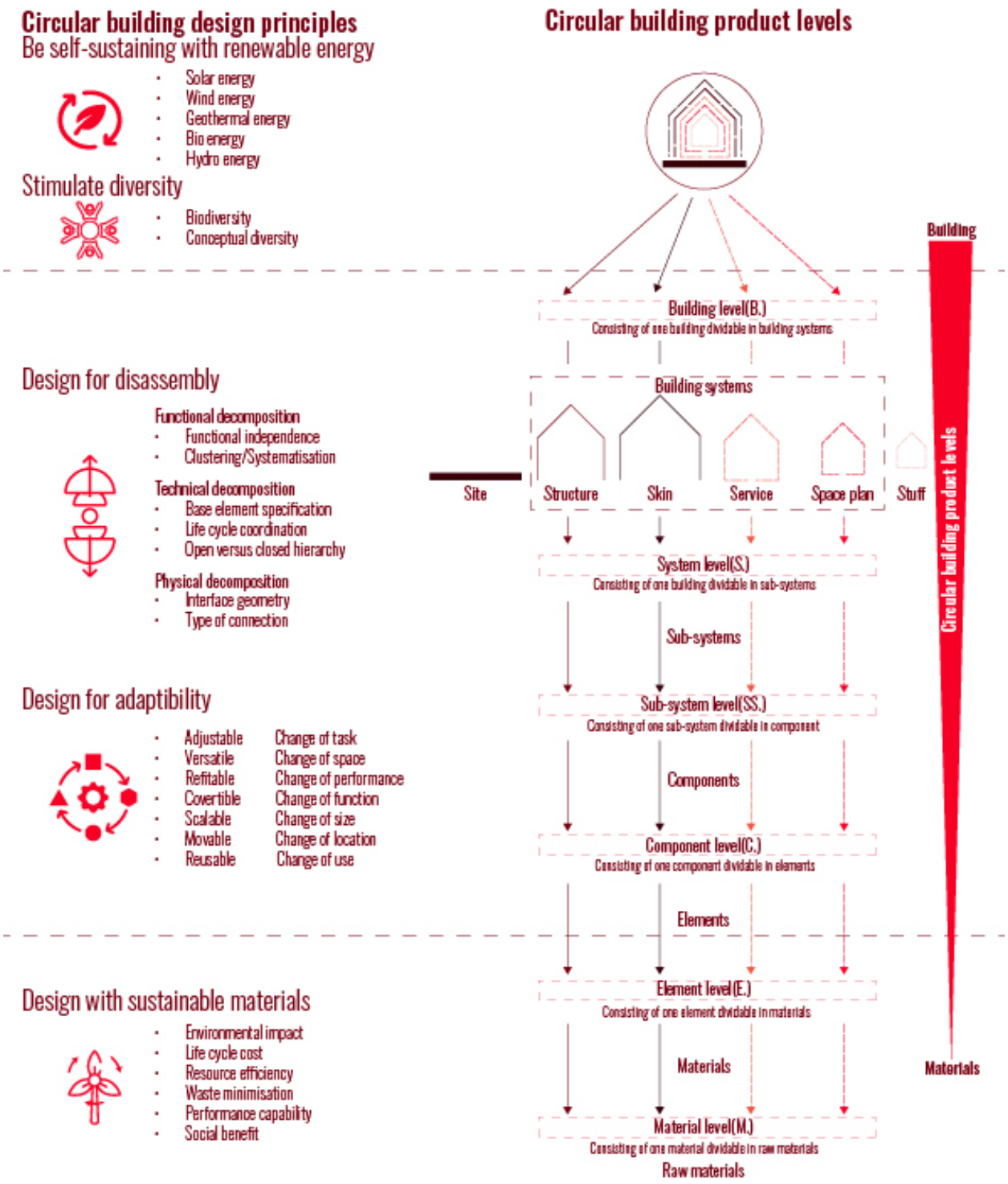


Figure 60. Design domain - Circular building design principles in relation to the circular building product levels (Adapted from Beurskens and Bakx, 2015)

The construction sector is increasingly adopting a circular economy approach, particularly focusing on the upstream components of the building life cycle. Europe, in particular, has been at the forefront, using the circular economy model to enhance economic competitiveness, improve resource efficiency, and realise environmental and greenhouse gas benefits. The EU's Circular Economy Action Plan, part of the European Green Deal, targets the construction and built environment sectors. Initiatives like the Building as Material Banks (BAMB) program and material passports are gaining traction, recognizing the value of materials in buildings (BAMB 2020).

Similarly, in Canada, the Green Building Council sees the circular economy as a key trend for the sector's future but acknowledges that its success hinges on industry innovation, addressing political trade-offs, and overcoming societal challenges, including behaviour change. Canada's built environment sector has been actively embracing circular economy practices (Beck 2021, 12), with the CSA Group developing key standards and guidelines since 1995. These include:

i. ***CSA S478:*** for Durability in Buildings, updated in 2019 and referenced in LEED Canada for Durable Building Credit.

ii. ***Z782-06***: Guideline for Design for Disassembly and Adaptability in Buildings; and

iii. ***Z783-12 (R2016)***: for the Deconstruction of Buildings and their Related Parts.

These initiatives underscore Canada's commitment to durability, design for disassembly, and adaptability, alongside sustainable deconstruction practices in provinces like British Columbia, Quebec, and Ontario. They reflect a growing realization among construction industry leaders, who through their principles (mentioned in Chapter 5.2.3) are integrating circular practices right from the start of a building's life cycle.

However, significant systemic barriers and inertia persist due to the complexities involving all stakeholders. In Chapter 5.3, the discussion will delve into the challenges and opportunities associated with stakeholders. However, an overview of the various stakeholder groups(Figure 61) and their affiliated organizations includes: -

1. Architects, designers, and engineers
2. Builders and trades
3. Product manufacturers and suppliers
4. Property owners and developers
5. Deconstruction firms
6. Waste haulers and recyclers.

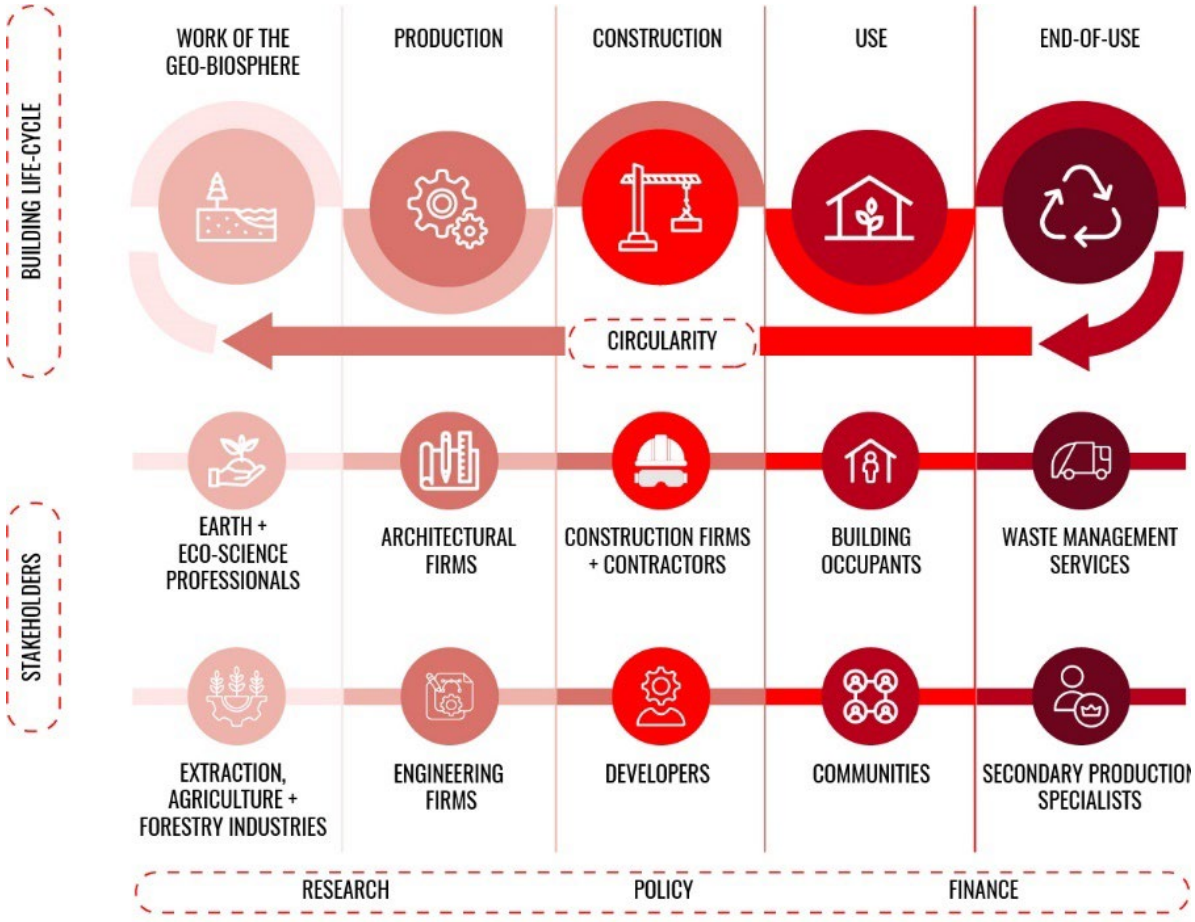


Figure 61. Key stakeholders' participation for decarbonising of buildings(Adapted from UNEP, 2024)

5.2.3 Circular building construction model

This sub-section introduces the "Circularity building construction model," developed by Beurskens and Bakx (2015, 29). The model outlines six key principles that not only motivate industry leaders to adopt circular practices from the outset of a building's life cycle but also challenge for reconsidering where improvements are needed. These principles (Beurskens and Bakx 2015, 26) serve as a guiding framework for rethinking the way the construction industry approaches building practices, emphasizing sustainability and resource efficiency.

i. **Use Phase:**
The circular building construction model simplifies the distinction between 'consumables' and 'durables' by incorporating a unified '(re)use' concept. This emphasizes the importance of designing buildings with materials that can be reused, adapted, or recycled, taking into account the varying rates at which different building systems change over time.

ii. **Building Systems:**
Building systems such as structure, skin, service, and space plan are identified as key components in the circular building construction model. These systems undergo processes directed at the building industry, ensuring that each system is considered for its potential reuse or recycling.

iii. **Processes & Participants:**
The model introduces the '(re)assembler' step, indicating the construction process in a circular economy where building products are assembled and disassembled. This step emphasizes the need for a systematic approach to reusing and repurposing building materials. Additionally, the model simplifies the biological cycle processes, focusing on cascades and biosphere, and replaces the term 'maintain' with 'service' to encompass all actions aimed at keeping building products in operable condition and improving their performance.

iv. **Reconfiguration:**
A new process step, 'reconfiguration,' is added to illustrate how buildings can be adapted and rearranged to maximize the use of circular building products. This step emphasizes the flexibility and adaptability of building designs in a circular economy.

v. **Disassembly:**
Disassembly is highlighted as a crucial process in the circular building construction model, allowing for the reclaiming of embodied value in building products. This step ensures that materials can be reused or recycled at high quality, promoting a more sustainable approach to building construction.

vi. **Redistribution:**
The model replaces 'reuse/redistribute' with 'redistribution' to avoid ambiguity. This step involves moving circular building products from one location to another for reuse in other buildings, emphasizing the circular flow of materials in the built environment.

5.2.4 Circular Loop Obstacles

The building industry and its components are unique when compared to other huge industries. Such uniqueness of the built environment not only makes to think about circularity more deeply, differently, and aggressively but also work on the obstacles that are presently stepping back. The obstacles due to an informal culture, project-based approach, or even a wide variety of organizational structures and management techniques have made the building industry focus least on standardisation, repetition, and compatibility of products.

For instance, in the building industry, a key management challenge stems from the industry's project-centric focus (Vrijhoef 2011), coupled with its inherently informal culture and fragmented structure. This poses a significant hurdle, especially in the production domain, where coordination and efficiency are paramount, as shown in Table 6.

	BUILDING SECTOR	INDUSTRIAL SECTORS	NON-INDUSTRIAL SECTORS
CULTURE	Informal	Formal	Dynamic
STRUCTURE	Diversified	Consolidated	Integrated
MANAGEMENT	Project-driven	Process-driven	Customer-driven

Table 6. Characteristics between Building, Industrial, and Non-Industrial sectors (Adapted by Noordhuis & Vrijhoef, 2011)

If the focus is narrowed in on the challenges faced in circular built environments, particularly from a North American perspective, several obstacles can be addressed to encourage improvement. Specifically, within the Canadian construction industry, there are significant opportunities for growth in five key areas (Leising 2017, 30-33): Economical, Social, Technical, Organizational, and Structural barriers. These barriers (Table 7) are described in more detail below.

Categories	Obstacles of Circular Economy in building industry
ECONOMICAL	- Market is not willing to invest upfront - Short-term goals: pack back times - High costs of demounting/recycling - Focus of current BM limits recycling
SOCIAL	- Limited awareness and sense of urgency
TECHNICAL	- Inefficient demolition- current recycling is downcycling - Separating waste streams is labour intensive. - Limited attention to end-of-life phase - Linear technologies are deeply rooted - Current building components are not fit for circularity.
ORGANIZATIONAL	- Lack of transparency and information exchange - Complexity circular projects and extra process time - Lack of trust, passion, and shared interests - Issues concerning responsibilities, liabilities, and ownership
STRUCTURAL	- Coherence is lacking between policies - Certifications are administrative difficulty - Lack of supporting circularity in the built environment

Table 7. Overview of obstacles for implementing CE industry (Adapted from Leising, 2016)

i. Economical

The linear system in today's construction industry doesn't bother much with the true cost of consumption, which not only creates a silent dystopia of everything good in society but shifts problematically the circular business models to the requirement of substantial upfront investment costs. Even after proven by EMF(Ellen MacArthur Foundation, 2013) that circularity vows to offer material savings worth billions a major challenge by decision-makers is sadly still intact, that is to base the costs of circular measures on their understanding of the avoided risks, opportunities, and risks of change, projected on the current business situation(Kok et al., 2013). An instance of this can be observed among stakeholders such as developers, design communities, and construction firms, who neglect to assume accountability for the disposal of their buildings and associated materials after their life cycle. This disregard discourages them from considering the environmental impact of their actions.

ii. Social

There is a significant lack of awareness and comprehension of the circular economy in the built environment in our society, which explains why it is not a political priority. Although some areas show some circularity, they are mostly focused on waste management and recycling and do not take full advantage of the value of design, material, and process innovation, and new circular strategies. Additionally, the absence of standardised definitions, information, and data such as on material flows makes it difficult for local, regional, and cross-border collaborations. This creates challenges for the development of new policies, and powerful stakeholders with vested interests use this to their advantage and hinder the transition.

iii. Technical

The current state of product design often ignores the end-of-life phase, delaying the effective reuse and recycling of products and materials. For example, many electronic devices are glued or welded together, making it difficult to separate valuable components for reuse or recycling. The lack of understanding and implementation of circular design and strategies further compounds this issue, making it difficult to recycle materials. Often, current recycling technologies result in downcycling due to products and systems not being designed for disassembly. To overcome these challenges, improved collection systems and improved product and system designs are needed. Another significant obstacle encountered is the widespread use of linear technologies in society. Dependence on fossil fuels, for example, presents a challenge to transitioning towards renewable energy sources. This challenge stems from past decisions influencing our ability to make future choices, which is known as path dependence. This path-dependence hinders progress towards a circular economy, as society persists in following the same trajectory.

iv. Organizational

The current policies, legal frameworks, and incentives governing the design and development of buildings do not fully reflect the principles of the circular economy. This is due to the fact that different jurisdictions have different policy frameworks in place, which poses challenges for businesses and investments. The lack of integration of circularity in innovation policies and competition legislation also hinders cooperation between companies. Cities, on the other hand, face regulatory challenges as they have little control over much of the construction waste stream. The access to capital for commercializing and scaling up circular economy solutions is also limited. Although chain and cross-chain collaboration is necessary for circular product design and reverse logistics, competitiveness often prevents it. Moreover, conflicting market signals often arise, with short-term investors' interests misaligned with the long-term investment required for a circular economy transition. Investors are often not concerned with the full life cycle of a building or its end-of-life management.

v. Structural

Achieving a circular economy in the structural construction supply industry is a complex challenge due to geographical differences that make it difficult to exchange information and materials. The main concern is ensuring the quality, reliability, and affordability of feedstocks and materials within circular supply chains, which can result in legal and intellectual property issues. Additionally, the market for recycled materials is often restricted to specific regions, making transportation across borders difficult and subject to jurisdictional control. This challenge is further complicated by existing trade policies and frameworks. Moreover, there is a lack of investment in new infrastructure and activities such as material marketplaces and reverse logistics due to limited demand for reclaimed materials in Canada. The current value chains are not designed for a circular economy, and therefore cost-efficient and user-friendly reverse collection systems with infrastructure that supports high-quality products are needed.

5.2.5 Circular Loop Strategies

5.2.5.1 Strategy 1.0: Holistic approach

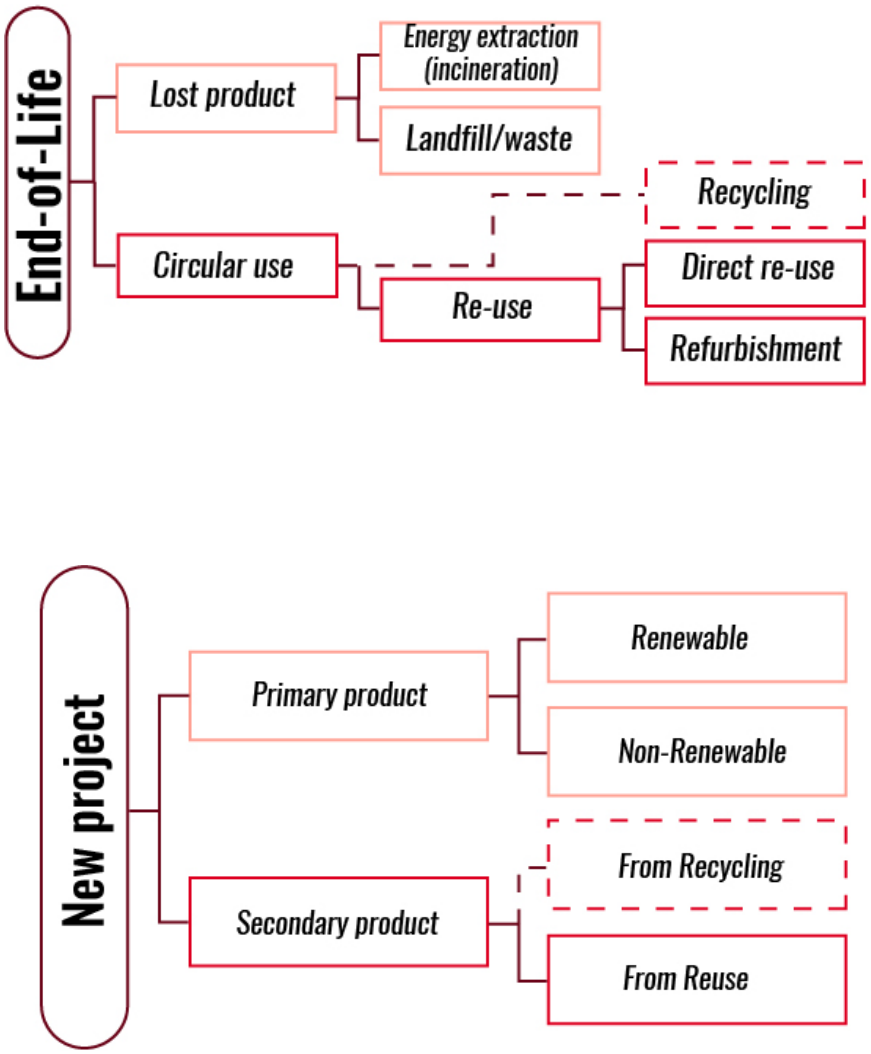


Figure 62. Choice distribution (Adapted from by Teeuwen, 2023)

As shown in Figure 62, to embrace the circular economy in the construction industry, holistic strategies are essential. These strategies (Table 8) encompass various aspects, from project inception to the end of a building's life cycle. The following strategies highlight key approaches.

Holistic strategies	Details
1. Phases for adopting Circularity.	Applying circular loop practice requires an approach that views the entire lifecycle of a project, from the initial design phases to the end-of-life scenarios of its components. This calculative move from traditional linear models offers meaningful opportunities for sustainable construction, particularly in the curtain wall industry. To promote adoption, emphasizing the financial benefits of circularity is important. For instance, executing a take-back program for aluminium curtain wall framing not only reduces material costs for future projects but greatly minimizes waste sent to landfills, showing the economic advantages of resource recovery. Furthermore, promoting circularity as a motivation for innovation, brand enhancement, and risk mitigation can further incentivise stakeholders. Companies that embrace circular design principles, such as designing for disassembly and utilising recyclable materials, can differentiate themselves in the market and mitigate risks associated with resource scarcity and price volatility. In essence, the successful integration of circularity in the construction industry connects on bold strategies that consider the entire lifecycle of building components while showcasing the tangible benefits for all stakeholders involved.
2. Education for Awareness.	The key to unlocking Circular Economy practices in the construction industry starts with upgrading Education and Awareness. Such a shift within stakeholders' mindsets (Developers/Clients, Architects, Contractors, Material processors, and others connected in the supply chain) can push more towards flexible and adaptive use and reuse. Flexibility in design, an idea of the Cradle-to-Cradle (C2C) principles, requires an entire lifecycle. From ensuring optimal performance throughout its service life to planning for efficient disassembly and the recovery of parts for reintegration into the value chain, C2C principles guide a holistic approach. This contains careful selection of materials, design for disassembly strategies, and thinking for end-of-life scenarios. To enable this transformation, targeted education and awareness initiatives are important. Workshops and seminars can educate stakeholders about the principles of circular economy, the advantages of material reuse, and the importance of DfD. Evolving industry policies and standards that promote sustainable materials and design for disassembly can further incentivise change. Showcasing successful circular economy projects through projects can inspire and provide practical examples for the industry. Collaboration among stakeholders, research institutions, and government agencies is crucial to developing and executing effective circular economy solutions. A tangible example of this shift can be in the difference between Donor-Receiver and non-Donor mentalities at the end-of-life stage of building. With a Donor mentality, stakeholders have the knowledge and awareness to actively participate in gathering, dismantling, and preparing materials for refurbishment. On the other hand, a non-Donor mentality, lacking education and awareness, would probably lead to downcycling or disposal of valuable resources. This contrast explains clearly the importance of education and awareness in driving the adoption of circular practices in the construction industry.
3. Collaboration for growth.	Collaboration across the value chain is essential for the success of circular economy initiatives. To do such, raising understanding among stakeholders about the benefits of circularity and the possible value of salvaged materials is crucial. It can be achieved through targeted education and engagement programs, emphasising successful case studies like Habitat for Humanity's ReStore (Habitat for Humanity Canada n.d.), which shows the feasibility of

	reusing and reselling salvaged materials. Additionally, developing supportive policies and regulations, such as tax incentives for using recycled materials or extended producer responsibility programs, can create a favourable environment for cooperation. Constructing infrastructure and networks, like online marketplaces, especially for salvaged curtain wall components or industry-specific platforms focused on reusing aluminium and glass, can also encourage partnerships and the exchange of resources. For example, a medium connecting building owners aiming to replace their curtain walls with contractors of deconstruction and material salvage can simplify the process and create a market for these valuable resources. Moreover, sponsoring research and innovation to develop advanced deconstruction and sorting technologies can improve the quality and quantity of reusable aluminium framing and glass panels, making them more appealing to potential buyers. Such a multi-faceted strategy can incentivise stakeholders across the value chain to vigorously participate in circular economy initiatives, encouraging resource conservation and waste reduction.
4. Legislative Frameworks	Present Green Building Systems, such as LEED (U.S. Green Building Council n.d.), have established the industry's ability to react to material challenges. However, their volunteer nature restricts their impact. By such legislation, policies, and regulations, governments can drive the shift toward sustainable curtain wall construction. This could involve requiring the recycled content in aluminium framing, incentivising the design of curtain walls for disassembly and reuse, or specifying norms to recover and recycle curtain wall materials at the end of their life. Such actions can promote invention and provide sustainability as a core consideration in curtain wall design and construction.
5. Incentives for Sustainable Outcomes	Financial incentives show the profitability of circular curtain wall approaches to overall adoption. The incentives can involve highlighting the cost savings related to reusing curtain wall components. Further, the possibility for new income streams through the refurbishment and resale of salvaged curtain wall components can appeal to companies. Governments can additionally incentivise these practices through fiscal policies, such as tax breaks for companies that reuse materials or by supporting research and development of innovative curtain wall recycling technologies. By emphasizing the economic benefits of circularity in the curtain wall industry, stakeholders can be motivated to adopt sustainable practices that benefit the environment and add to their financial interests.
6. Innovative Responses	Technological advancements are vital in the construction industry, just as in any other sector. These inventions can help address cost differences and improve productivity. Digital solutions and technology can also improve information sharing and tracking of resource and material flows, creating a more transparent and efficient market for recovered curtain wall materials. For example, a digital platform could link building owners seeking to replace their curtain walls with those looking for typical types of recovered aluminium framing or glass panels, simplifying the process and creating financial incentives for reuse. This strategy can also help reduce the percentage recovery rate for aluminium curtain walls and address the challenges with recycling polluted glass panels. Additionally, technical advances in deconstruction and material assessment can also improve the value and appeal of salvaged components, making reuse a more promising opportunity for all stakeholders involved.

Table 8. Holistic strategies that can be applied in facade industry (Created by author, 2024)

5.2.5.2 Strategy 2.0: Detail-oriented approach

As outlined in section 4.2.3, the meticulous circular strategies can be categorized based on the principles of circular loops, namely Slowing Resource Loops and Closing Resource Loops. Given current challenges in the industry, there is a need for greater development of circular products and industries. Slowing resource loops can facilitate the complete recycling of building products, while closing resource loops can enable easy reusability, promoting circular loop practices in the construction sector. Drawing inspiration from Figure 63, the Table 9 presents these strategies in detail.

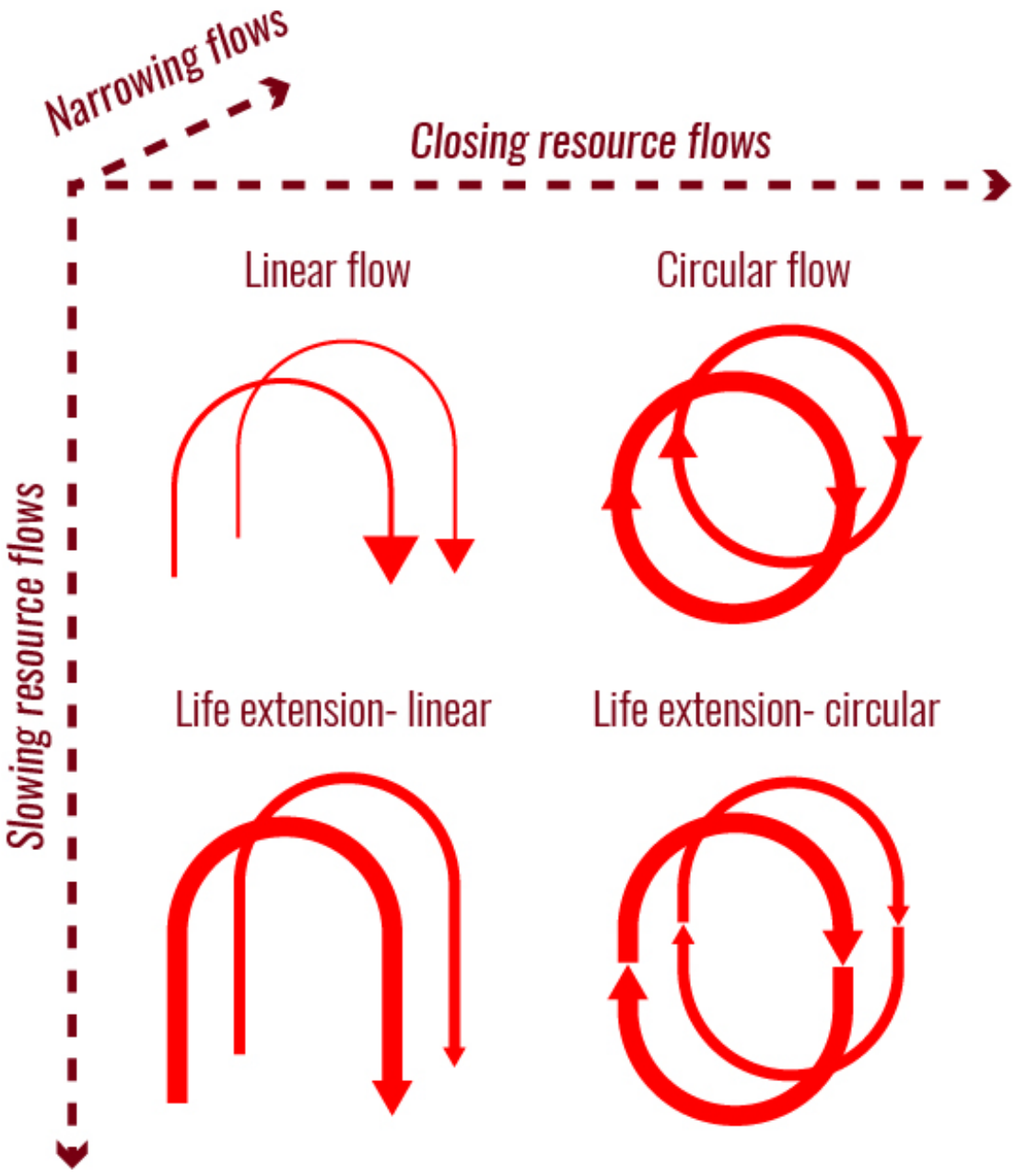


Figure 63. Categorisation of linear and circular approaches for reducing resource use. Based on, and expanded from (Adapted from Stahel(1994), Braungart et al.(2008))

a. Slowing Resource Loops

Strategies	Details
Designing Durable Products for Longevity	A long-lasting facade can aim by prioritising durability from the initial design phase. The selection of materials like aluminium alloys or specialised coatings, capable of withstanding environmental changes, can be important for extending the curtain walls' life span. Also, the "emotional durability" consideration of a facade by visually appealing designs that remain timeless helps to maintain the prematurity replacements due to changes in trends.
Highlighting Durability and Strategic Overengineering	Longevity in Design involves more than choosing the materials. Whereas Strategic Overengineering usually involves slight excess capacity during designing, which adjusts future changes in building use or environmental conditions, eventually developing the facade's lifespan (Moss 1985). This aggressive strategy can help decrease the need for early replacements due to unexpected wear and tear or modified functionality needs.
Physical and Emotional Stability	Durability contains both physical and emotional factors. While physical durability concentrates on the ability of a material to resist weathering, corrosion, and other environmental aspects, emotional durability guides the lasting of design and aesthetics. A facade that supports visual appeal and relevancy over time is less likely to be substituted prematurely for purely aesthetical grounds (Chapman 2015).
Repair, Upgrade, and Remanufacturing	The extension of the facade's lifespan either through repairing, upgradation, or remanufacturing can act as crucial for a circular loop practice. An allowance for repair and replacement of individuals by designing the facades with modular parts, accessible connections, and maintenance-friendly details, thereby growing the overall system's lifespan. Further, incorporating flexible systems into the design without complete replacement can be adapted for future upgrades, like integrating smart glazing or photovoltaic panels. Lastly, the possibility of remanufacturing components at the end of the facade's service life can help in reducing waste and conserving resources.
Modularity and Accessibility	The modularity of the facade can consist of easily removable and replaceable parts that can assist in repairing and upgrading more efficiently and cost-effectively (Linton and Jayaraman 2005). Design details with convenient connections can help facilitate maintenance and improve the facade's lifespan by enabling regular maintenance and addressing problems before escalating.
Upgradability	Comprising flexible systems allowing the integration of new technologies or materials, such as smart glazing or photovoltaic panels in the facade, can grow and adapt to meet varying needs without needing entire replacement (Linton and Jayaraman 2005).
Remanufacturing Potential	Remanufacturing entails restoring used facade components to meet or exceed the performance of new ones, with similar or even better warranties. The strategy involves repurposing and refurbishing the materials at the end of their service life, making consideration of material choices, connection details, and disassembly processes during the design phase. Prioritising remanufacturing possibilities can drastically reduce waste and preserve resources. (British Standards Institution 2009)

Table 9. Slowing Resource Loop strategies (Adapted from Bocken, 2015)

b. Closing Resource Loops

Strategies	Details
Technology-Centric Design	The concept entails using materials or components, often called "Technical Nutrients," in product development that can safely recycled into new materials or products of equivalent quality (McDonough and Braungart 2002). In the case of curtain walls, this principle is for all aluminium components (frames, mullions, and pressure plates) since aluminium is naturally 100% recyclable. However, the main challenge lies in ensuring the proper disassembly and recovery of these components at the end of their life cycle to prevent contamination with other materials, which could impede their recyclability.
Primary Recycling Approaches	This process involves converting waste materials into new ones, yielding results comparable to the original materials (Astrom 1997). In the case of curtain walls, high-quality aluminium extrusions are reprocessed through melting and formed into new extrusions for future curtain walls while retaining their original properties in a closed-loop industrial cycle (McDonough and Braungart 2002).
Exploring Tertiary Recycling	Tertiary recycling involves breaking down materials into their core components and rebuilding them to have effects comparable to the original material (Kumar, Panda and Singh 2011). This process may have restricted application to standard curtain wall materials like aluminium and glass, which typically aren't formed of polymers. However, improvements in material science could potentially lead to the development of curtain wall components made from polymers suitable for tertiary recycling.
Bio-Driven Design	This principal circle designing products using safe and healthy materials, or "Biological Nutrients," that can produced in the natural environment (McDonough and Braungart 2002). While most curtain wall components are not biodegradable, certain materials used in gaskets, sealants, or insulation could work.
Biodegradation and Composting Focus	These processes are not directly relevant to the primary materials like aluminium and glass. However, efforts to identify and eliminate any "red list" materials, such as harmful chemicals or toxins, in the gaskets, sealants, or coatings used in curtain wall systems. Doing so would allow safer dumping or recycling of these components at the EoL (Vert, Doi, Hellwich, Hess, Hodge, Kubisa, Rinaudo and Schué 2012).
Recycling Strategy Emphasis	The strategy involves designing products with materials that can be downcycled into lower-quality products or burned for energy recovery (Lee, Lye and Khoo 2001). While this is not the ideal scenario for a circular economy, it's worth considering how to minimise the negative impact when designing curtain walls. For instance, selecting materials that are separated easily and recovered for recycling can help reduce downcycling or ensure that burning is done with the highest energy recovery.

Table 10. Closing Resource Loop strategies (Adapted from Bocken, 2015)

5.2.6 Conclusion

In this chapter, the significant contribution of the construction industry to global greenhouse gas emissions is explained, with 11% attributed to embodied carbon. However, the chapter also offers solutions for reducing emissions through a circular economy, which promotes material circulation. Strategies for achieving circularity, such as The Value Hill business model, the Circular Built Environment (CBE) approach, and the Layers of Change concept, are explored. Additionally, key principles of circular building design, including designing for disassembly, adaptability, and sustainable materials, are highlighted. The chapter concludes by emphasizing the importance of adopting circular economy principles in the construction sector, which can promote sustainable practices. Achieving circularity requires partnerships across the value chain, legislative support, incentives, and fiscal policies. Education and awareness-building efforts are also necessary to shift mindsets and promote circular strategies.

5.3 *Circular Loop* in *Facade* industry

The present discourse revolves around the intricate relationship between the life span of building components and the embodied carbon emissions associated with them. As per the "7S" model (Figure 64), every building model comprises different layers, each with varying life spans. The "6S" model, arranged in decreasing to increasing order of life span, includes Stuff (1-5 years), Space Plan (10 years), Services (25 years), Skin (50 years), Structure (100 years), and Site (∞) - the sixth layer added in 2011 by David Bergman (Clark 2013).

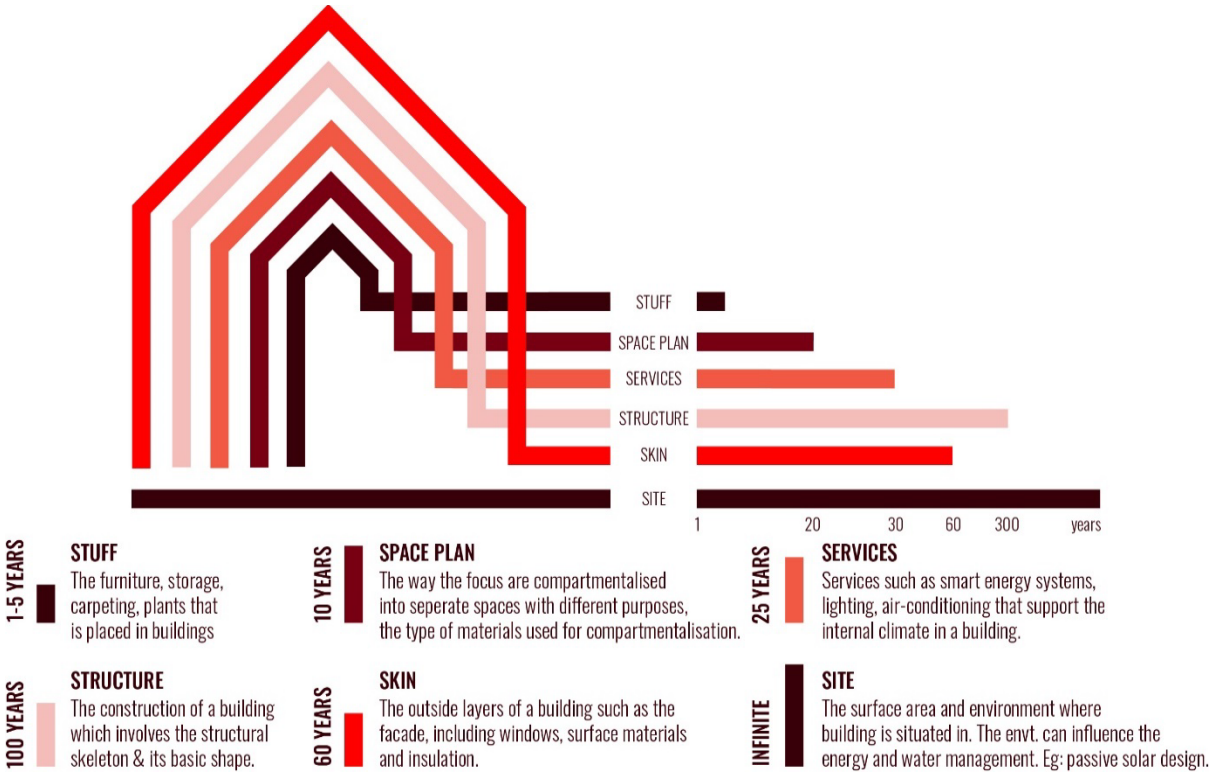


Figure 64. Layers of building (WBCSD, 2018)

In chapters 2 and 3, the discussion was on "the impact of facades", particularly aluminium curtain walls or similar components like window wall systems, on the embodied carbon footprint of buildings. While they may not be the most significant contributors, it is worth examining how a few square meters of a

building’s skin, can add between 10-30% of embodied carbon emissions (Clark 2013). Furthermore, the life span of building skins, estimated to be 50 years as per the "7S" model, is a matter of concern. Specifically, aluminium curtain wall facades which even though having a theoretical life span of 60 years may be replaced or demolished well before that timeframe, to accommodate renovations or new buildings that align better with market demands and trends (Hartwell, Macmillan and Overend 2021, 133). The common reason for it might be complexity due to the multi-component nature of facades, as they're heavily influenced by the connection. For instance, the aluminium framing of a curtain wall has a longer life span compared to components like sealants and gaskets. The need for early replacement is primarily driven by two factors:

Obsolescence: This factor occurs when entire facade's thermal performance(R-value) or aesthetics gets outdated, initiating replacement of the entire system even if the structural components are still good condition.

Differentiated Lifespan of Components: The various components within a facade system have broadly different lifespans. While the aluminium framing might last for decades, sealants and gaskets typically degrade within 10 years, requiring frequent maintenance or replacement. Although it's technically possible to refresh a curtain wall by modifying individual components like the Insulated Glazing Units (IGUs), caps, or spandrel material, this is only possible if the original interior mullion system is designed to adjust such changes.

This difference in component lifespans and the absence of flexibility in many existing facade systems raise a crucial question: Why aren't original designs be more adaptable to individual component advancements, thus eliminating the need for the costly demolition and replacement of the entire facade

5.3.1 Introduction

Improvements in building operational performance have heightened the significance of the initial embodied carbon in a structure's envelope. However, the complex nature and exposure levels of modern facade systems often result in short service lifetimes for some components (Brand 1994, 7). This frequent replacement not only increases a building's embodied carbon over its lifespan but also contributes significantly to the construction sector's solid waste, accounting for over 4 million tonnes annually in Canada alone. This waste represents a lost opportunity for the construction industry, which generated $141 billion in GDP in 2020, to reintroduce value from these materials into the economy at the end of its life cycle (Beck 2021, 5).

To delve deeper into this issue, engaging with stakeholders across the facade supply chain (Illustration 27), including Clients & Developers, Architects, Main Contractors, Facade Contractors, Material Manufacturers, Demolition Contractors, and Recycling facilities, was essential. According to Illustration 28, the survey respondents were comprised of 19% individuals from the UK, 30% from various European countries, 41% from North America, and 10% from Oceania and Asia. These stakeholders play pivotal roles and exert considerable influence in the realm of facade design and specification.

The primary goal of the circular loop in the facade industry is to understand how high-value recovery of facade systems and their components as a standard practice could be applied. Achieving this goal required stakeholders to address key questions, such as:

1) *What factors influence the choice of materials for unitised aluminium curtain walls?*
2) *Why are locally sourced materials not being considered to reduce embodied carbon?*
3) *What obstacles hinder the reuse of components from older buildings in new constructions?*
4) *How can unitised aluminium curtain walls be designed to facilitate easy removal, replacement, or future reuse and modifications?*

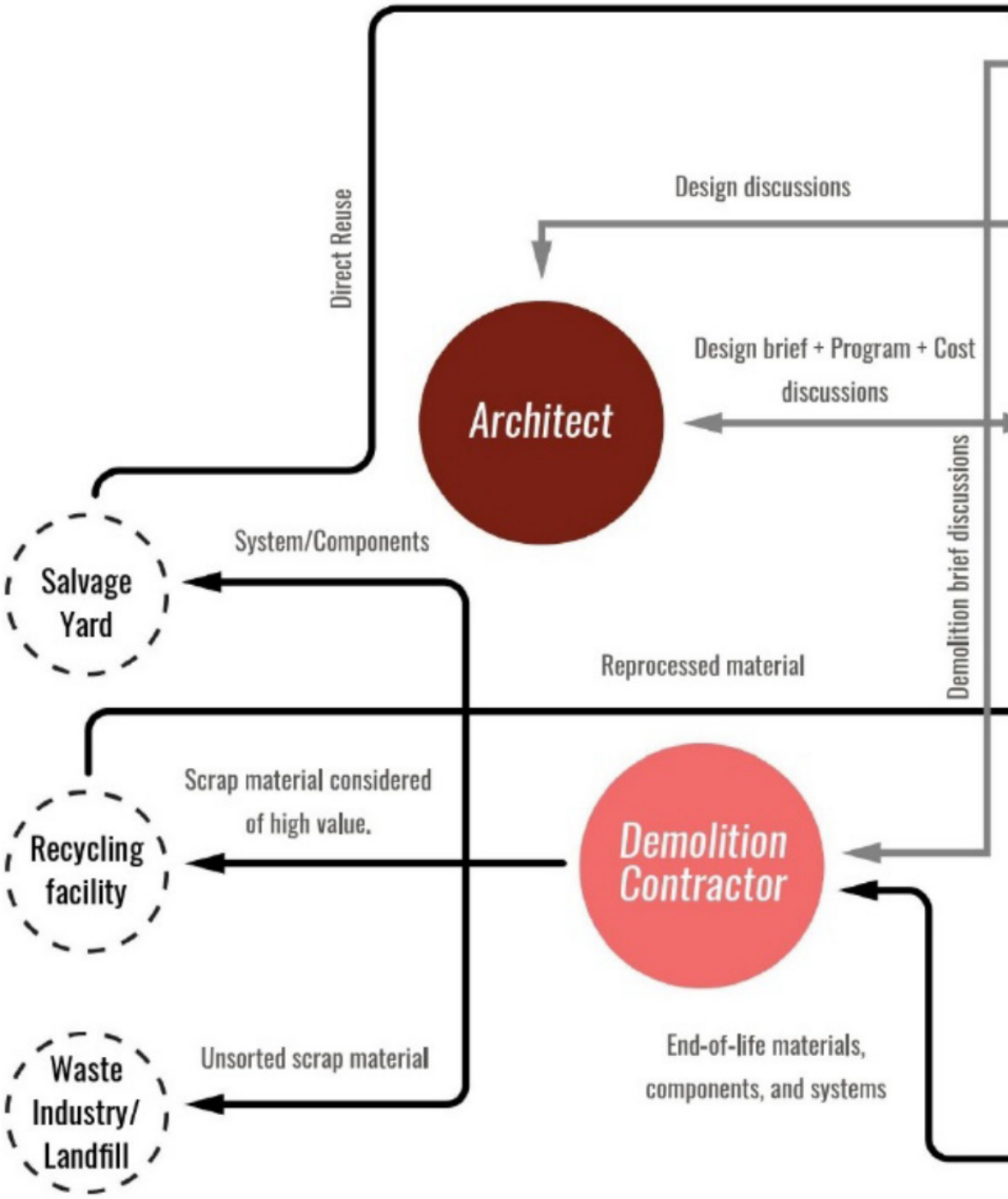
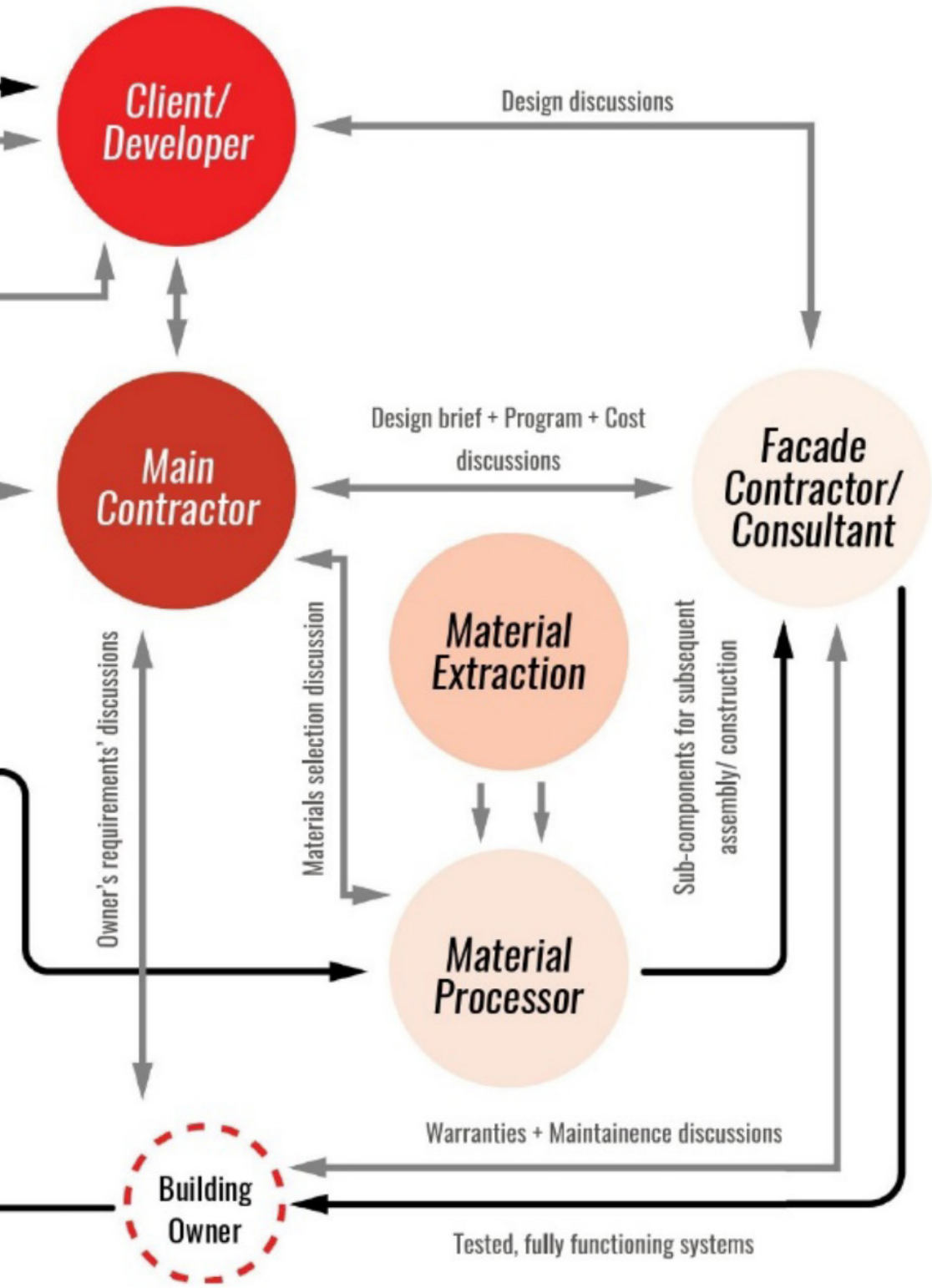


Illustration 31. Stakeholders across supply chain c



of facade industry (Adapted from Hartwell, 2021)

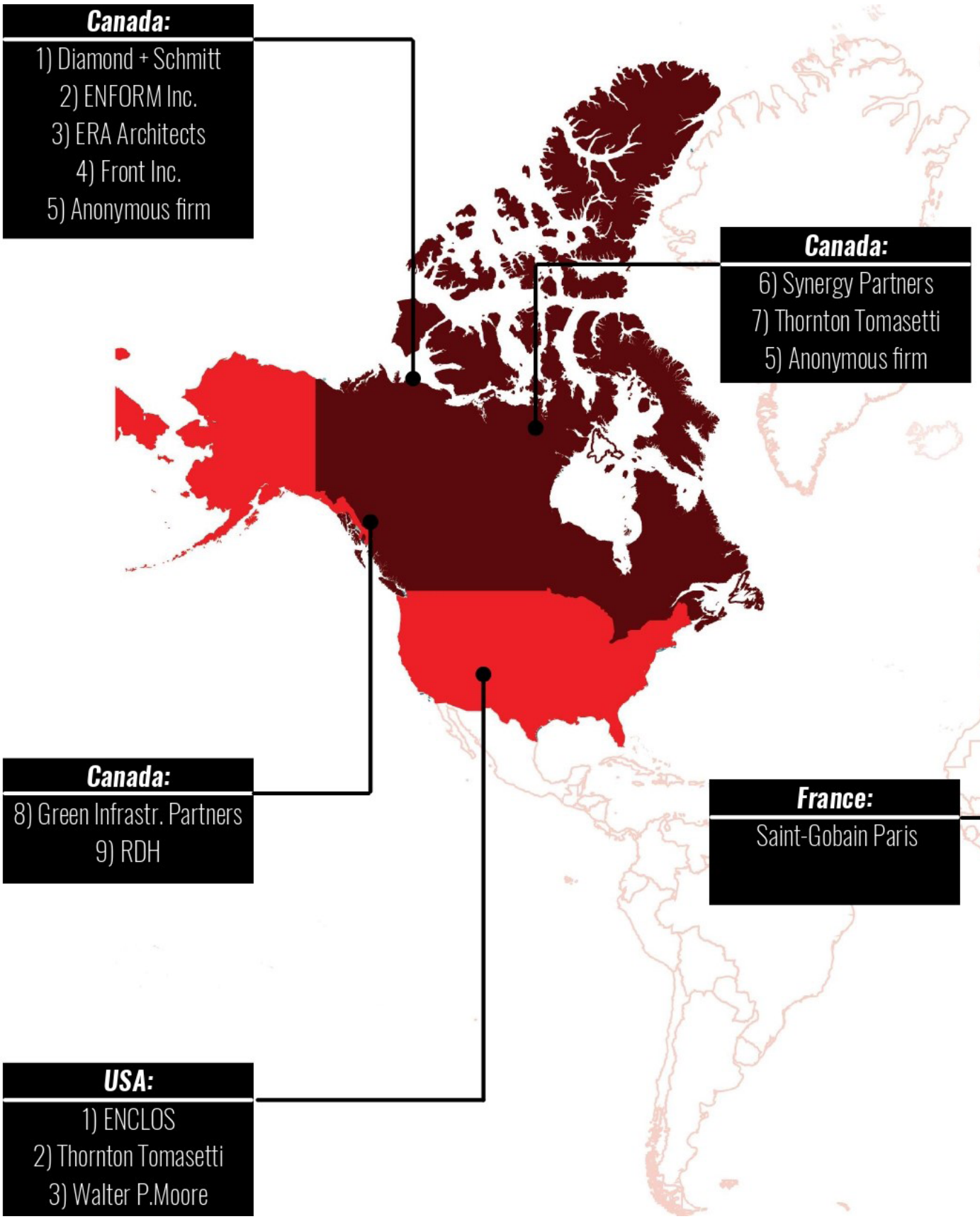
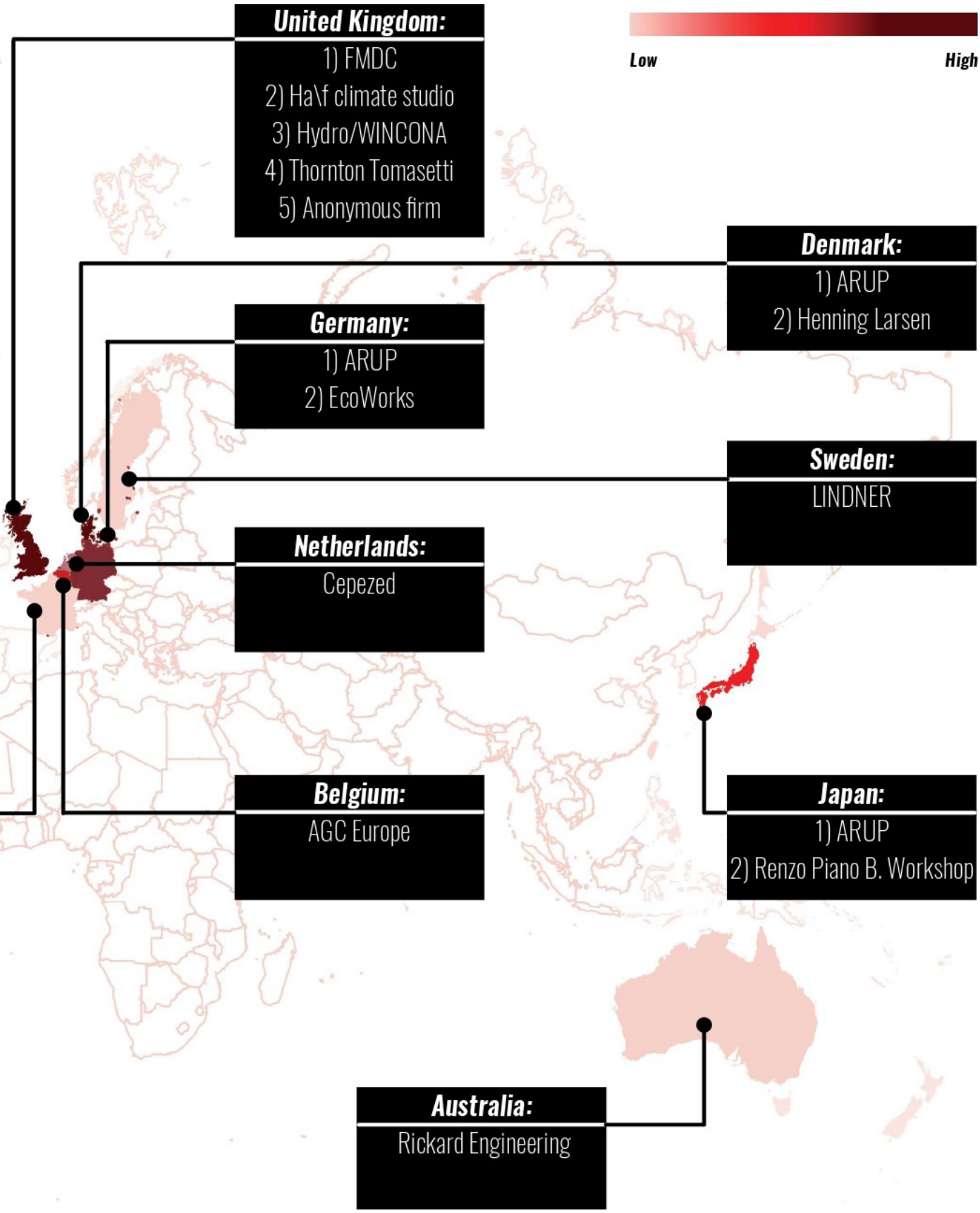


Illustration 32. Stakeholders interviewe



d worldwide (Created by Author, 2024)

5.3.2 Results

Virtual meetings were conducted via web conference lasting 30-60 minutes between January and February 2024. The approach was made to respondents with or without practical experience in the reusability of facades. Initially, respondents from the professional field were connected through emails, providing a brief description of the thesis, and the aim to conduct the meetings. Later, 30 stakeholders representing a wide range of background experience were talked to, out of many stakeholders. Appendix 'A' shows that the meeting format was divided into three segments:

1) How can we think "Building Less"?
2) How can we think "Building Intelligently"?
3) How can we think "Building for the Future"?

With the questions above, considering "we" as stakeholders involved in construction industry, the core questions included core questions intended to gain a better understanding of aluminium curtain walls or similar components. As shown in Illustration 30, the questions aimed at identifying key influences in the design process, the expected lifespan of these components, the sensible choice of repurposing, or perceived reasons for facade replacement. Second, considerations for locally sourcing materials were explored. Lastly, the main barriers and drivers to the incorporation of Design for Disassembly (DfD) in facade design were investigated. Results from all closed-ended questions and experiences of building element or facade reuse were collected and stored for statistical analysis.

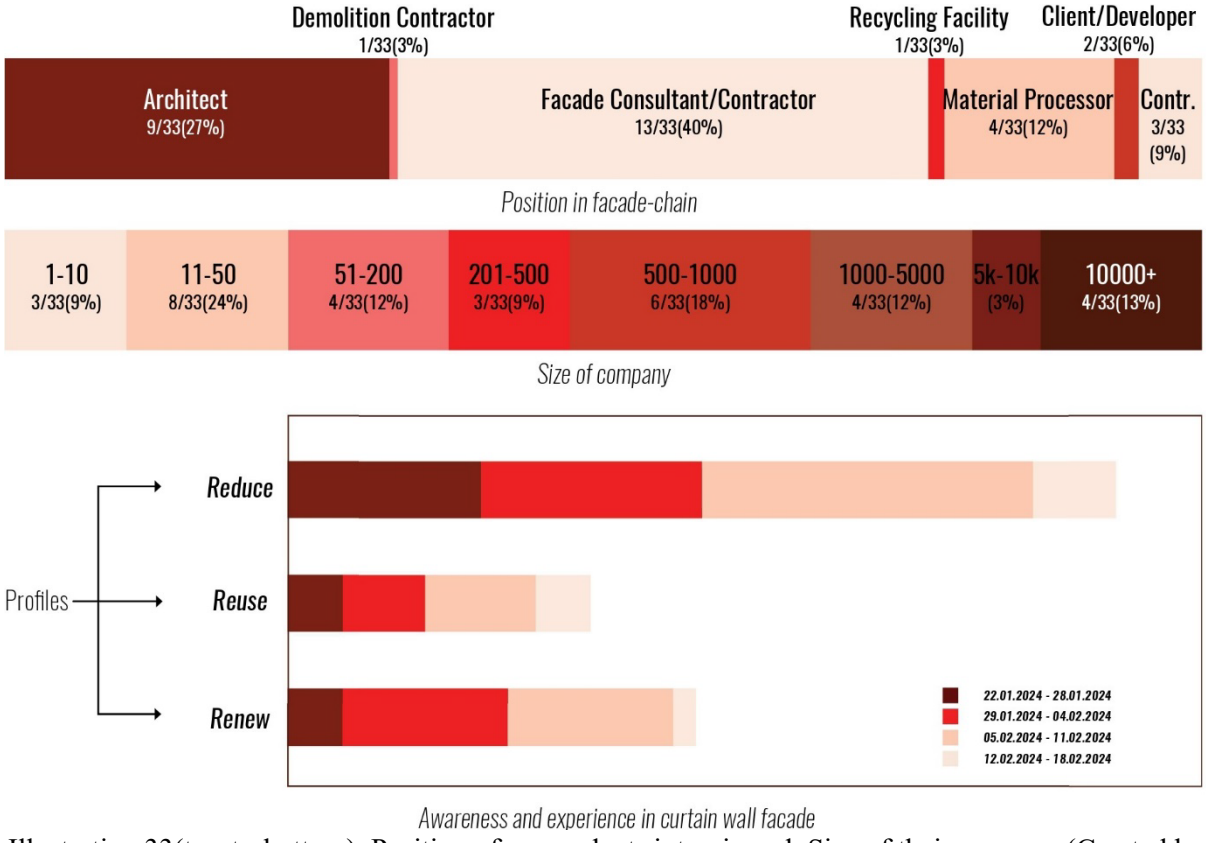


Illustration 33(top-to-bottom). Position of respondents interviewed; Size of their company(Created by Author, 2024)

5.3.2.1 Build Less!

b. Barriers for Retaining

The participants were asked to share their insights on why facades are replaced before reaching their end of life, as shown in Illustration 31. Based on feedback from various stakeholder groups, such as clients/developers, architects, main contractors, and facade contractors, it was found that the most frequent reason for facade replacement is "Aesthetics". This comes as no surprise as individuals often feel the desire to update their buildings due to either aesthetic preferences or economic pressures from their surroundings.

The second most common reason was "Maintenance Cost", which can play a significant role in the decision to replace a facade, especially if the cost of repairs exceeds the cost of replacement. "Energy Performance" was also mentioned as a reason for replacement, as older facades tend to be less efficient in terms of energy consumption. "Energy Efficiency" was also mentioned as an important factor, as newer facades are designed to reduce energy consumption rather than increase energy bills. Lastly, "Legislation" such as building codes or environmental regulations, requiring meeting certain standards, was least talked about.

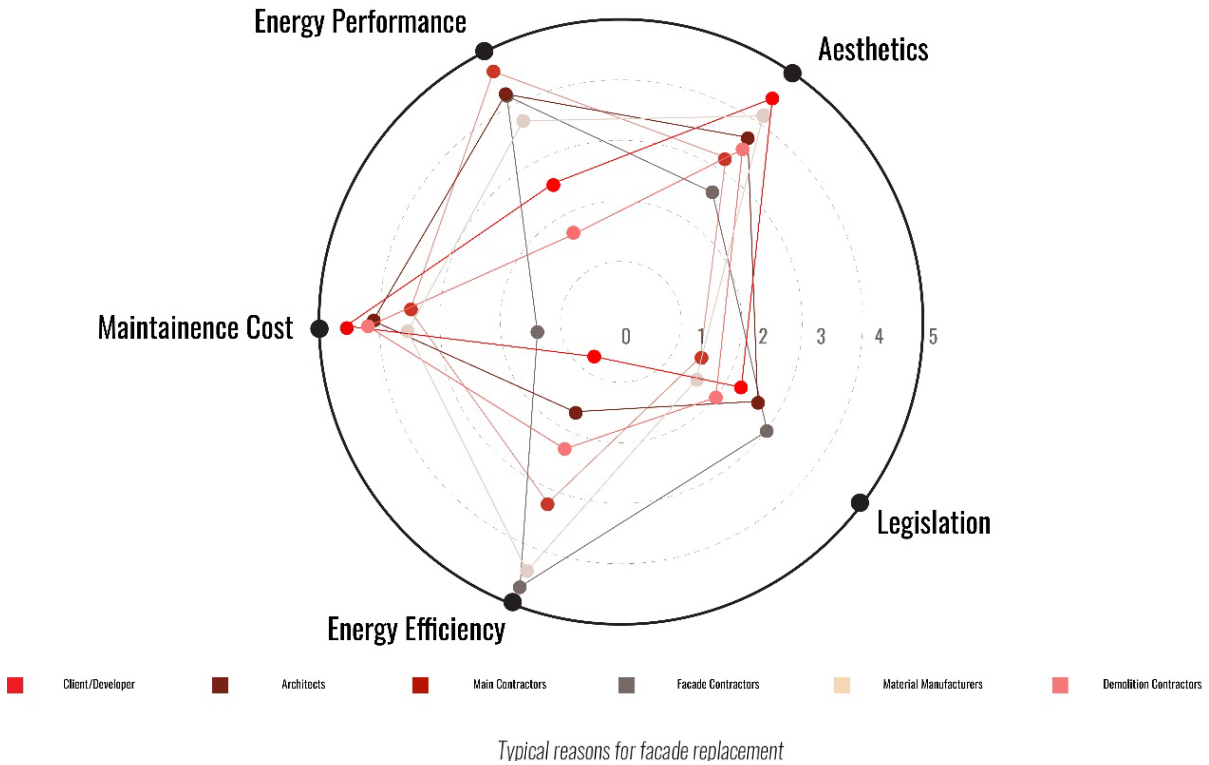


Illustration 34. Typical reasons for facade replacement The Inertia Principle(Created by Author, 2024)

c. Lifespan Expectations

The second part of “Build Less” aimed to assess the respondents' knowledge of the expected lifespan of aluminium curtain wall facades (Illustration 32) to gain an overall understanding of perceptions and beliefs regarding the durability of such facades. The results revealed that 20% of respondents estimated an EOL (expected end of life) between 50-100 years, indicating a high level of confidence in the long-term performance of aluminium curtain wall facades. Meanwhile, 33% estimated an EOL between 25-50 years, which still indicates a moderate level of confidence in the durability of these facades.

Additionally, 29% of respondents believed that aluminium curtain wall facades would last between 10-25 years; this estimate is more conservative than the previous two, suggesting that some respondents may be less confident in the long-term performance of these facades. Meanwhile, 15% of respondents estimated discontinuation of windows and curtain walls after 5-10 years, indicating a relatively short lifespan for these facades. Lastly, surprisingly, 3% of respondents assumed that the EOL of aluminium curtain wall facades would be between 1 and 5 years, which is a relatively low estimate and may reflect a lack of education and awareness with few regarding these facades in the industry.

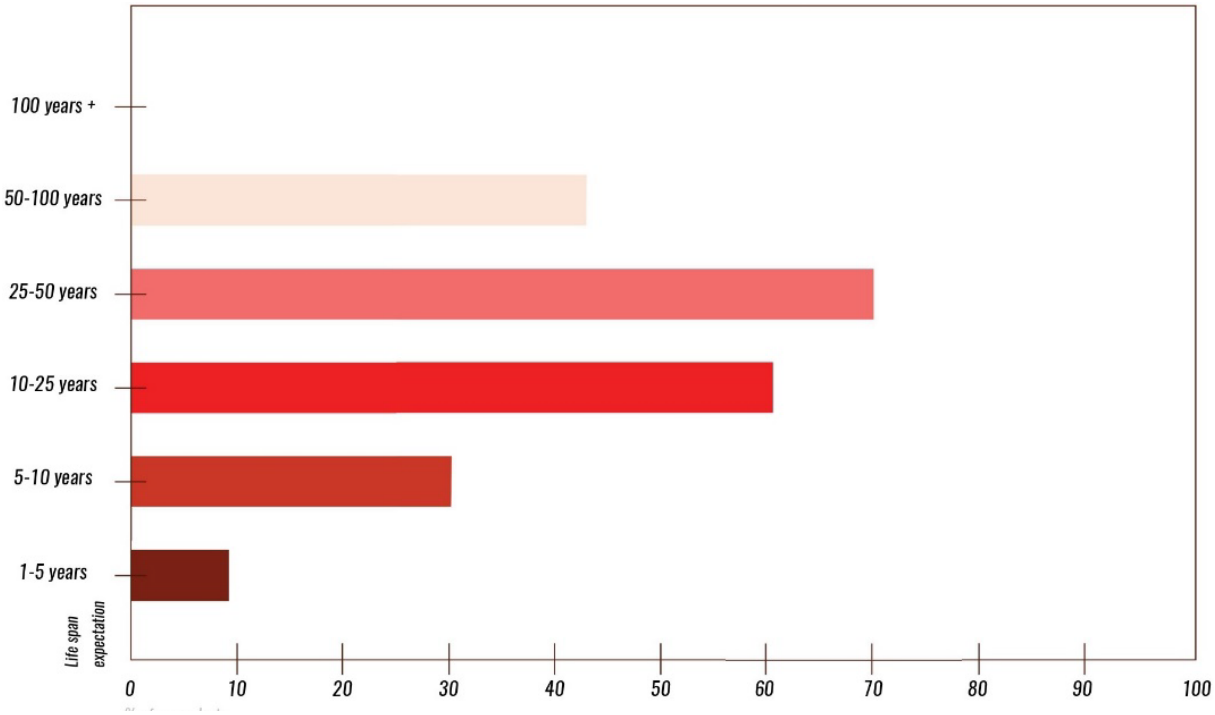


Illustration 35. Knowledge of expected lifespan of Aluminium curtain walls(Created by Author, 2024)

5.3.2.2 Build Intelligently!

a. Barriers for Repurposing

In the primary discussion in the second segment(Illustration 33), the stakeholders were asked to weigh in on the feasibility of repurposing components and materials from aluminium curtain walls for future use. The conversation scooped a fascinating array of perspectives in the facade supply chain.

Clients and Developers attributed 50% of the challenge to factors like energy efficiency, adherence to national codes, the need for education, and a prevailing sense of apathy. However, they pointed to 100%

client requirements and a dearth of sustainable alternatives as key barriers. Architects echoed similar sentiments, citing less than 50% explained to disinterest and client demands, while more than 50% was attributed to education, energy efficiency, regulatory codes, and the lack of sustainable options. Main Contractors shared comparable views, with under 50% citing national codes and sustainability as hurdles, but up to 70% pointing to client demands and the perceived inefficiency in reducing energy costs. Facade Contractors emphasized energy efficiency, client specifications, sustainable alternatives, and education, ranging from 55% to 85% in importance, while national codes and dispassion were deemed less significant at under 25%. Material Manufacturers highlighted energy efficiency (up to 50%), client demands (around 25%), and national codes coupled with the absence of sustainable options (about 75%) as the primary barriers to repurposing. In contrast, Demolition Contractors and Recycling Facilities unanimously agreed that repurposing was currently unfeasible. Demolition Contractors cited national codes, sustainable options, and apathy as reasons, while Recycling Facilities proposed a shift from "nobody cares" to education as a key factor.

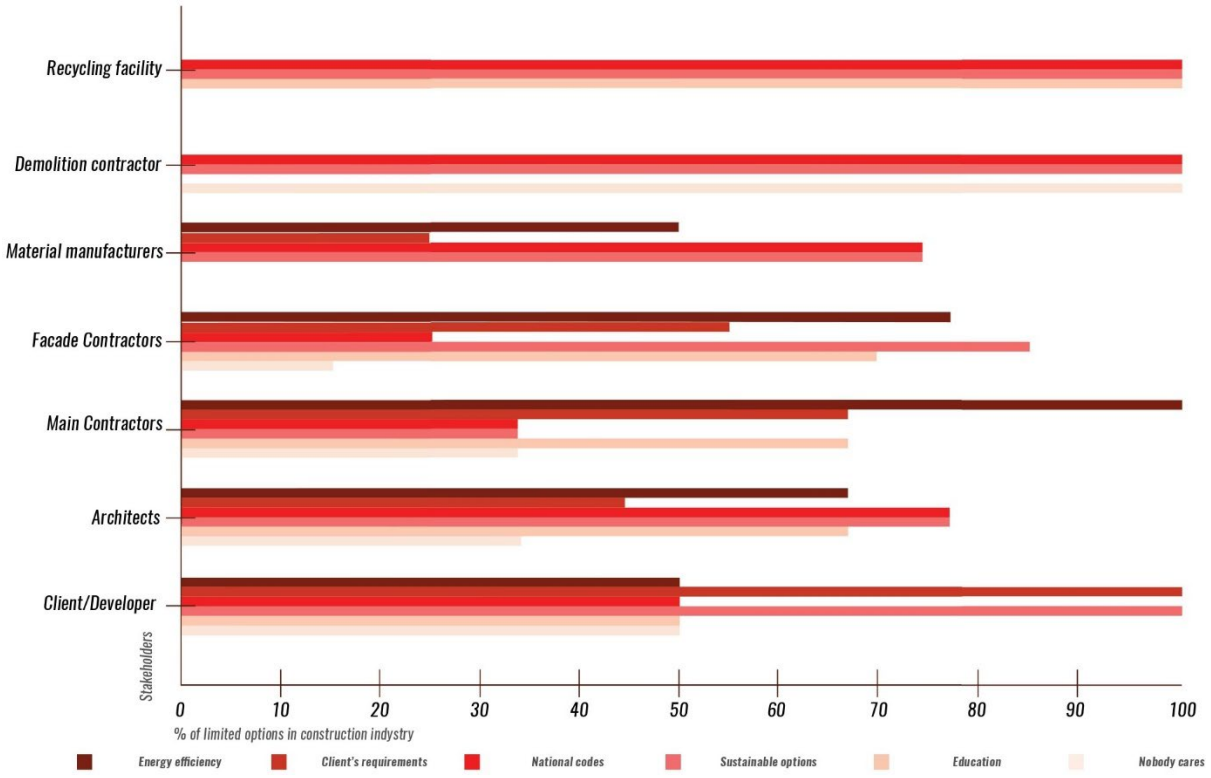


Illustration 36. Sensibility of components and materials(Created by Author, 2024)

b. Local Sourcing

During the conversation on "Build Intelligently," a question was presented to discuss the ethical implications of a specific action and the reasoning behind it. The question involved choosing between obtaining building materials locally and enhancing the energy infrastructure of the region or selecting global sourcing, which is faster and cheaper but might worsen the living conditions in the local area. As shown in Illustration 34, the discussion revealed that various stakeholders, such as clients, contractors, and recycling facilities, found the idea of local sourcing impractical due to several factors including the cost and availability of resources. However, the architects expressed optimism about the approach, as it could reduce the carbon footprint and create more job opportunities in the local area. Interestingly, the material manufacturers, architects, and demolition contractors were among the staunch supporters of local sourcing, as it would benefit them in multiple ways. The architects emphasized the importance of

sustainability and how local sourcing can help achieve that goal. The discussion helped highlight the complexities of ethical decision-making in the construction industry and how different stakeholders perceive and prioritize sustainability and practicality in their decision-making processes.

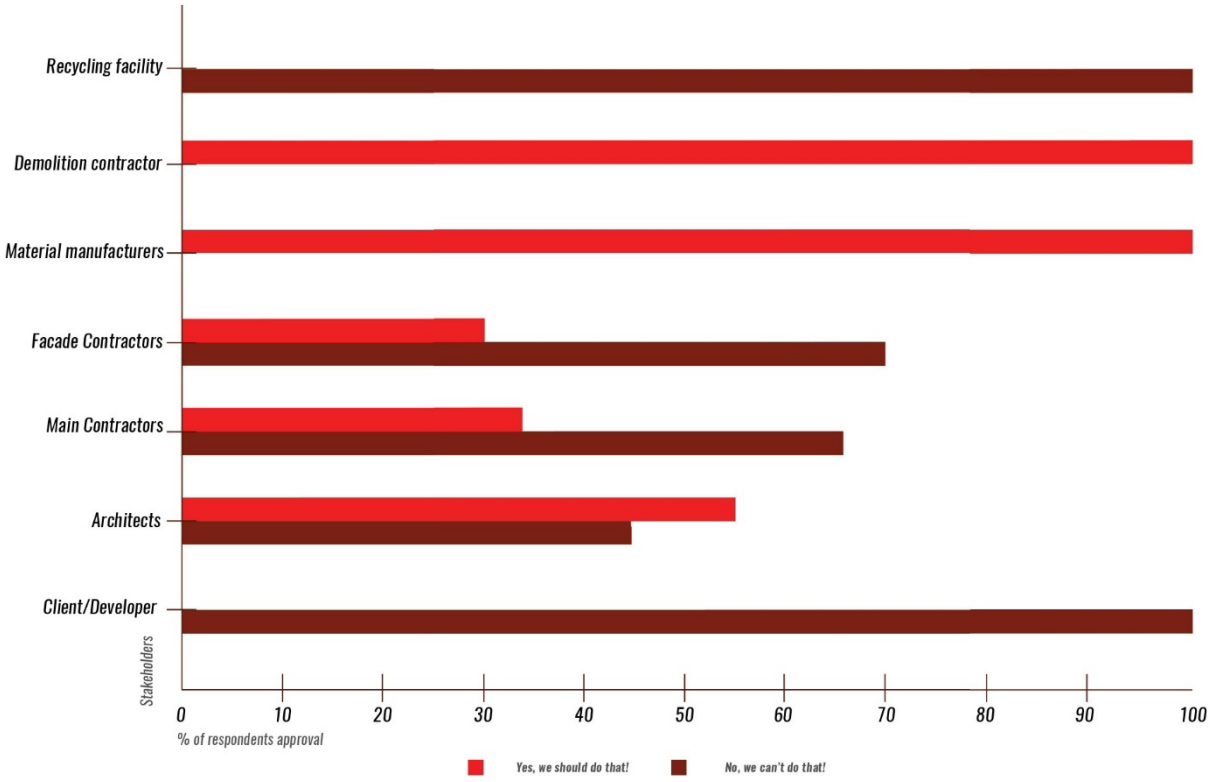


Illustration 37. Potential of locally sourcing the materials(Created by Author, 2024)

5.3.2.3 Build for the Future!

a. Barriers for Reusing

The study aimed to investigate the main obstacles to reusing facades. To achieve this, participants were asked about the primary barriers to it. The answers were analysed, and the keywords were grouped into six categories: Governmental, Financial, Technical, Supply-chain, Knowledge gap, and Behavioural reasons. These categories are displayed in Illustration 35. The findings revealed that several "Behavioural" constraints, including Aesthetics and Risk Aversion, were the most common reasons why reusing facades is still a challenge in the industry. Following "technical" constraints, such as uncertainties in functional performance, non-standardised sizes that may cause components not to fit together, technical limitations arising from how something was originally designed to be dismantled, and lack of information regarding the selection of available materials. These obstacles were found to be the primary reasons why reusing facades is still a challenge in the industry. The third most common barriers were "Supply chain" issues, which included Logistics, Lack of Demand, and Availability of supply for the reused materials. The study also found that the "Knowledge gap" was a significant barrier to the reuse of facades, including limited education and lack of available information. Finally, the two least common keywords included Governmental and Financial barriers, with Regulation and Economic Cost being the barriers, respectively.

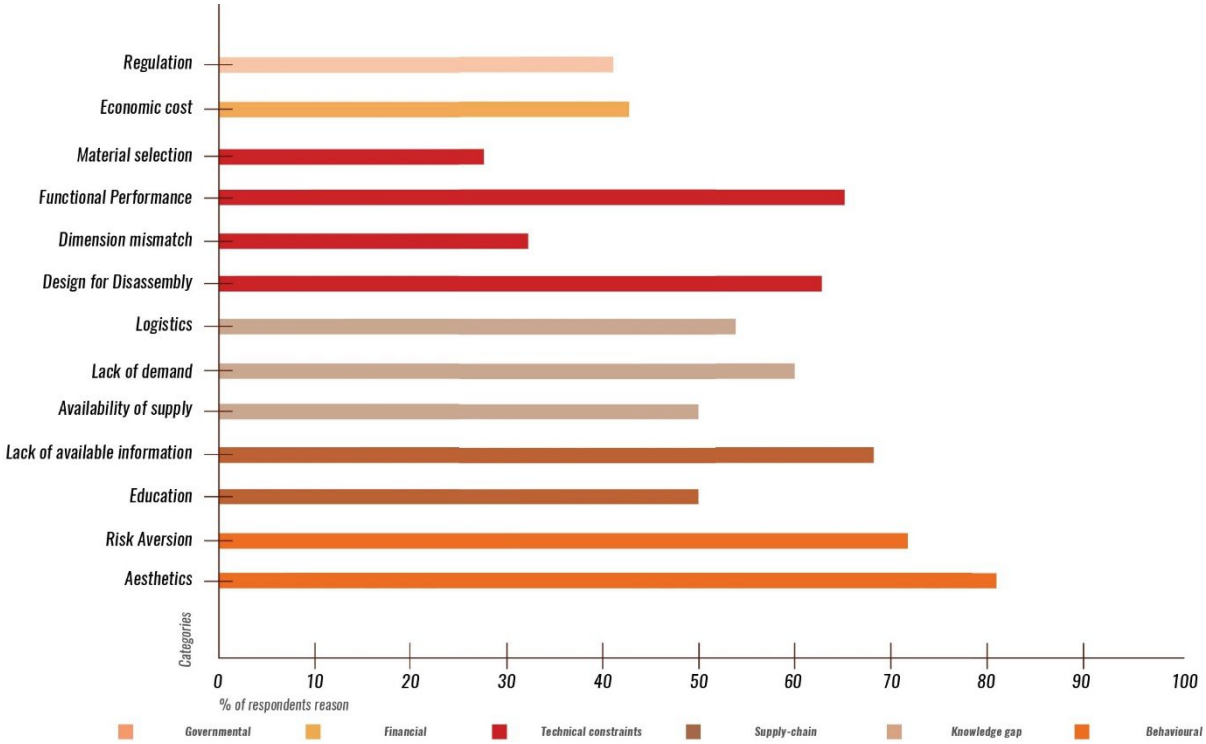


Illustration 38. Barrier across supply chain for reusing curtain walls(Created by Author, 2024)

b. The Breakdown

Based on the information presented in Illustration 36, it appears that the primary obstacles to reusing facades, as identified by clients, were dimension mismatch, lack of available information, and aesthetics. In contrast, architects cited design barriers for disassembly and functional performance as the biggest challenges to reusing aluminium curtain walls.

Main contractors, however, perceived a combination of DfD (Design for Disassembly), functional performance, and lack of demand as the primary barrier. In terms of Facade contractors/consultants and material manufacturers, considerations for aesthetics, lack of available information, and DfD were assigned the highest importance. Demolition contractors, on the other hand, believed that all barriers contributed to the lack of reusability while recycling facilities removed material selection and aesthetics from the list. These findings demonstrate the varying perspectives and priorities held by different stakeholders in the construction industry, which should be considered when developing strategies to improve the reusability of facades and promote sustainable practices in the field.

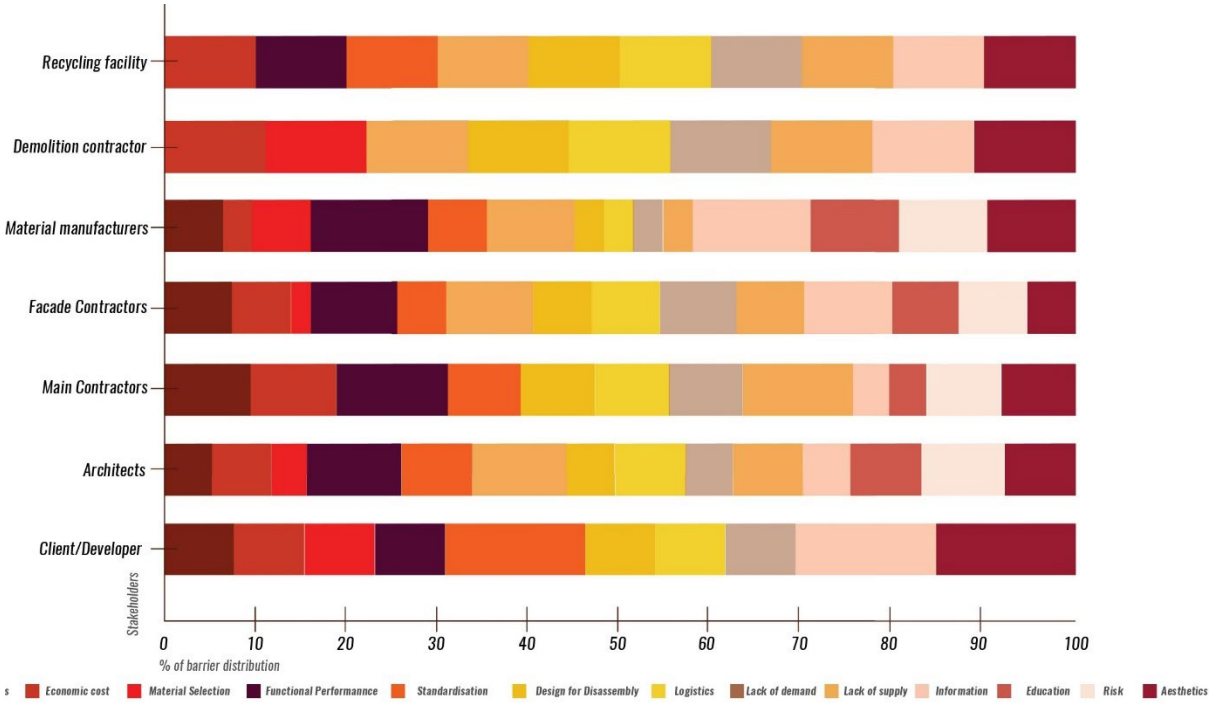


Illustration 39. Stakeholders indicating percentage distribution for each barrier(Created by Author, 2024)

Summarising common vision on circularity by different types of stakeholders in the construction industry, and what priorities at present are mentioned below: -

- Clients/Developers: They are increasingly aware of embodied carbon emissions from buildings. However, the adoption of circular practices like Design for Disassembly is perceived as distant due to a lack of quantifiable measures.

- Architects: They are enthusiastic about circularity in the building industry but feel that early design stages focus more on aesthetics and cost rather than sustainability. Reusability or recyclability is not a top priority until later stages. Awareness among clients and developers is increasing due to legislative changes, climate concerns, and the commercial value of sustainability.

- Facade Contractors/Consultants: They are not the primary decision-makers in the design and development of facade components, with architects and clients holding the main decision-making power. Consultants note that conversations on reducing embodied carbon are starting, but they often need to align with developers' priorities rather than leading with circular practices. Incentivizing clients and developers could promote reuse, recycling, and remanufacturing in the facade industry.

- Material Processors: They are driving the conversation and application of circular practices in construction, particularly for materials like aluminium, glass, and sealants. While the current focus is on aesthetics and performance, processors are optimistic that considerations for reusability, recyclability, and remanufacturing will increase in the future.

- Demolition Contractors: They operate based on profit maximization, avoiding landfill taxes, project types, location, and worker health and safety. There is a potential shift towards Design for Disassembly (DfD) practices if legislation incentivizes them. This could lead to less waste going to landfills, increased investment in circular practices, and more green-collar jobs.

In sub-topics 5.3.3 and 5.3.4, the dynamic world of regenerative practices for aluminium curtain walls, will be explored, delving into their strengths, weaknesses, opportunities, and threats in our construction industry.

5.3.3 Challenges & Opportunities

Through interviews with stakeholders in the facade supply chain, it was understood that there are numerous challenges and future opportunities for circular practices in the construction industry(shown in Table 11). To address these effectively, a categorization into three priorities: Least, Medium, and Highest priority, has been done. Prioritizing these challenges and opportunities is a significant step towards closing the loop of circular practices in the facade industry, including aluminium curtain walls. This chapter serves as a roadmap for actionable strategies to drive sustainability and innovation in construction, with a focus on curtain walls.

Priority	Challenges	Opportunities
Least priority This section explores common misconceptions among stakeholders (We), including clients, developers, and contractors, regarding reusability, recyclability, decreased value of facades, and aesthetic obsolescence. By addressing these misconceptions or challenges, an identification of opportunities (We're listening now!) for future changes in the construction industry can be understood.	*We can't compromise!* Worries regarding potential performance compromises and design restrictions, along with a noted negative social perception, emphasize a strong preference for newer over old curtain walls or window wall components.	*We're listening now!* Despite many reports indicating no difference in strength between new and recycled aluminium extrusions, material manufacturers note a greater demand for recycled aluminium products compared to five years ago. By investing in research and development to improve the recycling processes and the quality of recycled materials, the industry can address concerns about performance and aesthetics. Additionally, exploring alternative facade systems that are inherently more conducive to disassembly and reuse can help to overcome the limitations of unitised curtain walls
	We've high expectations! Meeting visual expectations is already a challenge due to high standards and limited flexibility in requests, especially within the glass industry. Also, very less successful examples of projects showcasing incorporated recycled materials without compromising design quality, demonstrates the non-feasibility of circularity.	*We're listening now!* In countries like the UK, changes in legislative codes (UK Green Building Council n.d.) have incentivised clients and developers to be more flexible in the process of disassembling for component reuse and recycling. The increasing focus on sustainability and embodied carbon is driving a shift towards more flexible design approaches. By embracing modular design principles and incorporating standardized components, the construction industry can facilitate disassembly, reuse, and recycling. Additionally, exploring alternative

		materials and facade systems that offer greater design flexibility can help to address the challenge of meeting high aesthetic expectations while promoting circularity.
	We think it's risky! The adoption of mechanical demolition over manual deconstruction practices is thought of as uncommon and risky work related to wealth, health, and safety requirements in today's world. Many countries, including Japan (Web Japan n.d), have effectively utilised mechanical demolition methods in different scenarios, customising their strategies to tackle specific challenges. Given the limitations of space and the need for efficient demolition in densely populated urban areas, Japan has engineered worldly-wise mechanical destruction techniques that prioritise accuracy and safety. These methods often include technical machinery and detailed planning to minimise hazards and safeguard the welfare of workers and adjacent structures. adoption of mechanical demolition over manual deconstruction practices are thought as uncommon and risky work related to wealth, health and safety requirements in today's world.	*We're listening now!* Discussions have highlighted the importance of considering the economic aspects and cost models of various recovery options in the construction industry. This includes understanding the upfront capital investment needed for setting up a reuse/recycling supply chain. One approach is to conduct pre-development and pre-deconstruction audits to address any missing data on building design and composition, thereby mitigating health and safety risks. Additionally, boosting demand for recycled or reused projects could be achieved by offering financial incentives for surpassing specific embodied carbon targets. For example, offering financial bonuses for exceeding these targets could lead to significant community benefits, similar to the success of the Community Wood Recycling group in the UK (Wood Recyclers Association. n.d.). In 2015, they managed to reuse nearly half of the 17,000 tonnes of waste wood they collected and provided training and work experience opportunities for over 600 unemployed individuals.
	We've limited Supply and Demand! The construction sector faces a significant mismatch between supply and demand. This issue is exacerbated by the uneven nature of the global supply chain, which limits supply and demand opportunities in terms of quantity and quality. Many stakeholders are unaware of second-hand material markets, involving the quantitative aspect of the mismatch. In addition, the tendency to prioritise specific materials such as brick or stone(typically used in shorter	*We're listening now!* Demand and supply issues highlight shortcomings in the facade industry, but they also present economic benefits. As circular practices necessitate a new industry in Canada, many stand to gain green-collar jobs. Implementing material passports for components like Aluminium Curtain walls can streamline sectors such as transportation, adaptation, refurbishment, and restoration. Expanding on material passports,

	buildings) over multi-component systems like aluminium curtain walls (commonly found in taller structures) is more while evaluating their qualitative aspects. This preference for single-material structures may lead to missing the potential for reusing and recycling within more complex facade systems.	contractors may consider embedded barcoding, material grades, stress factors, and the life expectancy of components, facilitating efficient collaboration with manufacturers on deconstruction sites. High-value salvaged components are sold directly to architectural salvage yards, further enhancing the industry's sustainability.
Medium priority This section outlines the key priorities that stakeholders (We), including clients, architects, facade contractors, and the government, should focus on and know the opportunities (We're up for it!) it's promoting for more circular practices in the facade industry.	*We're not Local, Not Aware, Not Available!* In countries like the UK, using recycled or reclaimed materials such as aluminium and glass in projects is common. However, finding locally sourced components and materials related to these can be challenging. Limited and costly space in highly developed areas leads to higher prices and a lack of awareness about recycled and reused products. Financially, adding third-party costs to the purchase price can make reclaimed products less appealing than new ones. Additionally, there is a lack of information and availability regarding the recycled content of materials in the surrounding area. As a result of such a mindset, countries like Canada and the USA are still trying to apply circular approaches in the built environment.	*We're up for it!* While locally sourcing reused materials like aluminium and glass may not be widespread yet, salvage yards are increasingly available locally for materials such as timber, brick, and stones. This trend is raising awareness and providing information from the North American perspective. Material processors are now disseminating trade-offs on reused and recycled products, aligning with firms' requirements on aesthetics, functions, performance, and cost. This shift indicates a growing acceptance and integration of circular practices in the construction industry.
	We think 'E.o.L' is absent! In the North American context, there's a strong emphasis on building performance, which often leads to compromise in End-of-Life (E.o.L) design criteria. Even in countries known for sustainability, like the UK and Netherlands, expressing E.o.L criteria in clients' briefs can be challenging, as deconstruction practices are not always a priority. These barriers result in a gap between different construction stages and the consideration of E.o.L in them, creating a persistent challenge in sustainable design thinking.	*We're up for it!* When we quantify the environmental benefits and integrate them into the performance specification for facade design, we move beyond mere reuse and recycling considerations. Instead, we focus on incorporating sustainability into the very fabric of the design. This awareness emphasizes the impact of design decisions on end-of-life (EoL) criteria, urging to prioritize EoL design. Such prioritization would require incentives that promote the idea of reducing carbon footprints. Additionally, we need better assessment methods to fully grasp

		the whole-life environmental impacts of our designs.
	We know there's no difference! In the construction industry, the extent of recycling depends on the material type and how manufacturers operate. Stakeholders must understand the difference between pre-consumer and post-consumer recycling, as these terms are often mixed up. While some manufacturers recycle pre-consumer materials, post-consumer aluminium recycling is less common and seen as unconventional.When communicating with recycled aluminium manufacturers, they mentioned that aluminium scrap is also collected from industries like automobile manufacturing in the post-consumer process.	*We're up for it!* Manufacturers of recycled aluminium curtain wall products, such as WICONA and Saint-Gobain for recycled glass products (WICONA 2023), see post-consumer recycled materials as a growing industry with significant growth prospects. While glass recycling has been practiced for centuries due to its natural recyclability, comprising post-consumer recycled content in construction products like curtain walls is still a somewhat recent development. With clear grounds established across the supply chain, the sector can rapidly grow. Clients and Developers, significant figures in the construction industry, can make this business strategy highly profitable through investment. As manufacturers finance cost-intensive processes and provide performance assurance to customers, recycled components and materials could become more general and standard in the future. It's particularly appropriate for aluminium, where the recycling process is well-established, but recycled content in construction is still arising. The industry can further leverage the existing glass recycling infrastructure to promote the use of recycled glass in curtain walls while growing the adoption of recycled aluminium content to achieve a more comprehensive approach to sustainability in facade construction.
Highest priority This section emphasizes the pressing priorities that stakeholders (We) need to concentrate on to successfully	*We believe Deconstruction Hinders!* The interviewers explained that the limited time allocated for deconstruction or carefully managing reusable items poses challenges. Such disassembly practices could be problematic due to increased costs, like revenue loss from a replacement	*We're on it!* Stakeholders like architects and facade consultants have suggested ideas for immediate application in the construction industry, considering the limited time frame for deconstruction practices. One such idea is the use of 3D cloud-

implement circular practices in the facade industry. These priorities are pivotal for advancing sustainability and innovation in the construction sector and can be leveraged to create further opportunities(We're on it!).	building, if its process gets extended for some reason. Moreover, the limited access to original drawings detailing fixing details and their contractors can also hinder the deconstruction process.	point technology in the early design stages. This opportunity can also benefit clients and developers by shifting the mindset away from landfill disposal, which has become ingrained in the demolition industry. Factors contributing to this mindset include the landfill tax, the Client brief, and market opportunities for salvaged components and materials.
	We can't Certify! A facade contractor mentioned that they, along with the client and architects, were willing to reuse many components of an aluminium curtain wall for a project's reskinning. However, because the main contractor refused to provide certification for the final product due to uncertainties about the material properties and performance of reused components, similarly how structural engineers in the steel industry approach uncertified materials, everyone had to abandon the circular practice. This reluctance to use uncertified products, particularly in structural roles, is a common hurdle to reusing materials. It's often challenging to obtain detailed information about a product's history and application, leading to a cautious approach where the worst-case scenario is assumed for reuse. To address the challenge, the facade industry can try exploring more options like specifying standardised testing and certification methods specifically for reused facade components, providing greater confidence in their performance, and encouraging wider adoption of circular practices, but it cannot be seen much till now.	*We're on it!* The lack of warranties and manufacturing data can significantly hinder future reuse opportunities, highlighting the need for certification schemes that better consider embodied carbon and whole-life carbon. This is a focal point in the Building as Material Bank (BAMB, 2020) project, where Building Information Modelling (BIM) is being integrated with Reversible Building Design and improved product data (Material Passports) to enable future reuse at various levels. Additionally, addressing contractors' concerns about certifying reused products or limiting facades to a certain amount of virgin material presents an opportunity for legislation. Implementing regulations that set minimum targets for the use of reused or recycled products through government or local planning authorities could encourage stakeholders to embrace design for disassembly. This approach could be further incentivized through tax breaks and incentives, encouraging a shift towards more sustainable practices.
	We know it's Customized! In the world of facade design, the focus has long been on creating structures that last, often at the	*We're on it!* Amidst the complexity and rigidity of assembling aluminium curtain walls, an opportunity arises to

	expense of easy disassembly. This approach has made modern facades incredibly complex, especially those using cutting-edge technology. There's a growing concern that the more advanced a facade is, the harder it is to reuse. Many current facades are seen as difficult to recycle, like unitised curtain walls where the use of sealants makes it hard to reuse glass, often leading to downcycling. Adding to the challenge, existing systems are not designed for easy removal, further hindering reuse efforts. Stakeholders have also noted a lack of standardisation, with changing requirements for dimensions and functionality making it hard to repurpose components. An illustrative example is the shown nature of aluminium curtain walls, where each one is custom-made for a specific project, leaving no secondary market for the components. This raises the question of whether pricing these highly customised facades at a premium could incentivise a shift towards more standardised and easily repurposed designs, promoting a circular economy in facade construction.	prioritize disassembly over the assembly. This approach involves considering disassembly at every stage of project development, promoting a profitable and sustainable mindset that emphasizes longer-term stakeholder connections over instant profits driven by shareholder interests. Additionally, introducing a universal composition standard for individual aluminium and glass panes in the construction industry could prevent extreme customisation, thereby improving recycling efforts. While problems exist about the possibility of increased transportation carbon due to global sourcing, regional or national standards could be designated to mitigate this issue. By concentrating on standardising materials within a specific geographic area, the facade industry can enable localised recycling processes and minimise transportation distances, eventually decreasing the overall carbon footprint associated with material transportation. This approach counterbalances the advantages of standardisation for recycling with the need to minimise transportation-related emissions.
	We believe Reuse is Tough! Most stakeholders were unaware of the potential demand for reused systems and components. One stakeholder pointed out that the skills for dismantling are available; the challenge lies in finding buyers and reusing opportunities. Additionally, stakeholders often fail to recognize their role in creating demand for reused products and recycled materials. They suggested that a change in approach from central leadership or other stakeholder groups would be necessary to stimulate demand.	*We're on it!* Architects and Facade contractors could have been dicey if the conversation of circular loop practices had been about five years from now, but the way the construction industry is transforming with climate change, the stakeholders are optimistic about committing their time to embodied carbon footprint and its assessments related to reuse strategies. They even included that the initiation of reusability started from the client itself, the budget, aesthetics, and other principles can be kept aside, and all focus primarily shift towards circular practice, however even if it's not the

		focus of the clients/developers the firms are slowly and steadily moving towards regenerative practices for their future design and research. While developed countries might be conducting the charge in circular construction, developing nations could also play a crucial role in this evolution by adopting the reuse of materials.

Table 11. Challenges and Opportunities for Unitised curtain walls(Created by Author, 2024)

5.3.4 Recommendations & Conclusion

a. Recommendations

After conducting rigorous interviews, discussions, and reviewing reports from professionals worldwide, several recommendations have emerged for applying regenerative practices for window-wall systems or stick curtain wall systems rather than investing money and time in unitised curtain walls in the facade industry. These recommendations highlight the need for a comprehensive approach to move closer toward circular practices in the construction industry. The insights gained underscore the importance of understanding the challenges and opportunities inherent in implementing these strategies. The key takeaway is the necessity for a concerted and rigorous effort to apply these strategies effectively, driving the industry towards circular loop practices in the construction industry, with a specific focus on alternatives to unitised curtain walls.

i. Prioritise Embodied Carbon

In our current professional practice, there's a substantial focus on operational carbon in building design, while embodied carbon is often unnoticed. This approach needs to shift. Just as professionals have modified their approach to building operations due to national codes, a similar legislative push is needed to reduce embodied carbon footprints. To address this, several immediate actions need to be taken such as Design should consider end-of-life recovery implications, allowing greater flexibility in achieving desired aesthetics. Proper metrics, such as Life Cycle Assessments, should be used for calculating embodied carbon, distinguishing between reuse and recycling. Design for Disassembly practices should be considered for facades, considering the service life. Implementing these changes will help eliminate wasteful factors in the supply chain. In this thesis, embodied carbon can be prioritised by reusing old, unitised curtain wall components for upcycling or downcycling purposes and by designing the new facade to be easily dismantled with the highest amount of circularity.

ii. Revise Certification and Testing Procedures

As stakeholders prioritise functional performance in facades, material contractors face substantial pressure for certifications, leading to a negative stigma around certifying reusable components and materials. Revisions to certification schemes are needed to evaluate whole-life environmental impacts more comprehensively, while new testing procedures offer an alternative for performance evaluation. Additionally, developing new reconditioning methods to mitigate system/component deterioration and continuously revising acceptability criteria are crucial. These efforts would enable performance assurance and support warranties, addressing the perceived high level of risk associated with specifying reuse.

iii. Mandate Pre-demolition and Renovation Audits

Pre-demolition and renovation audits, ideally executed by independent parties, offer a worthy tool to evaluate the actual reuse levels achieved in a project and compare them to the proposed levels. Such audits have been successfully enforced in countries like Hungary and Finland, revealing their significance in promoting reuse within the construction industry. To achieve reusable goals for facades,

exploring standardised designs as seen for window-wall systems, incorporating design redundancies for adaptability, creating systems with fewer components, and designing reversible connections that promote fast deconstruction rather than overengineered customised unitised curtain walls. As a result, these efforts can contribute to a more sustainable construction process and encourage a shift towards circular practices, where materials and components get reused and recycled to minimise waste and resource depletion.

iv. Invest in Research and Development

To enable the highest disassembly and reuse of components for new alternatives for aluminium curtain walls and maximum circularity achieved from the existing ones, further Research and Development(R&D) are crucial. Utilising data management, including Building Information Modelling (BIM), can help assess the reuse potential of components and undamaged materials from fixings in new developments, driving a significant shift towards circular practices in the construction industry. Additionally, R&D should focus on understanding non-disassembly issues from existing designs and provide better techniques for circularity, such as exploring alternatives to traditional sealants, such as high-performance tapes and gaskets for stick curtain walls or window-wall systems. Although gaskets can effectively seal in specific applications, additional R&D can help to understand their long-term performance and compatibility with various facade systems. This deeper understanding could lead to much better end-of-life outcomes in terms of future reuse.

v. Adopt Stakeholder Awareness and Client Engagement

Stakeholders are generally unaware of existing reuse options for facades, and clients/developers rarely advocate for reuse. To increase the supply of recovered components, clients will need to provide financial support and reasonable timeframes during refurbishment/demolition. Demonstrating reuse through projects can reveal economic feasibility based on logistical costs and savings from avoiding primary material sourcing. Recognising the benefits of reuse/recycling can incentivise the supply chain to develop new business models and support infrastructure. It's important to entirely explore all options for recovery to avoid resorting to less environmentally friendly options.

vi. Develop Training and Accelerate Information Sharing

Enhancing training and information distribution about available to-be-reused products within the facade supply chain is paramount. Clients/developers can leverage this knowledge to incorporate specifications for reuse and design for deconstruction in the client brief, ensuring that architects' design intents remain intact without compromising on the late adoption of reuse strategies. This approach also incentivizes facade contractors and material processors to innovate new ways of integrating reconditioned components, thereby boosting demand and market value. Collaborative efforts within the supply chain are vital to ensure all stakeholders are well-informed, actively involved, and ready to take responsibility. Effective management of supply and demand involves matching surplus products and materials with potential users through mechanisms such as stockholding facilities (like reclamation yards) and material exchanges/reuse platforms, facilitating optimal use and maintaining clear traceability.

vii. Promote Manufacturer Innovation in DfD:

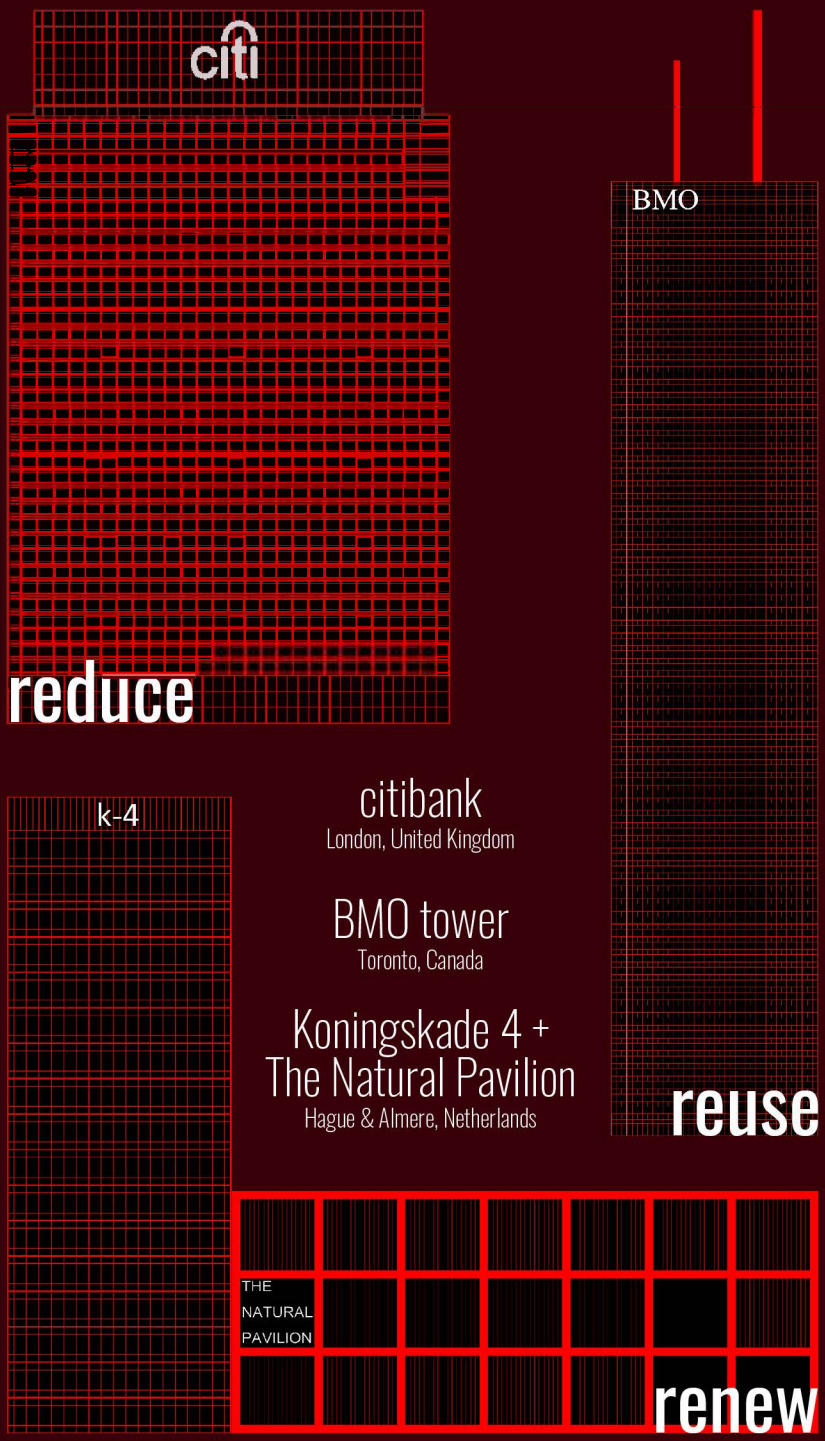
Encourage manufacturers to produce and market easily dismantled facade systems, particularly for high-rise buildings, where unitised curtain wall alternatives with standardised measurements and simple connection methods can encourage disassembly and reuse. Emphasize the growing demand for such systems driven by increasing interest in circularity and resource efficiency within the construction industry.

b. Conclusion

"If you'd asked me about circular practices in the aluminium curtain wall sector five years ago, I wouldn't have believed it possible. But as we embrace a regenerative mindset, I see exciting changes ahead in the next decade."- A facade contractor from United Kingdom.

After speaking with the facade contractor and 29 other participants from various parts of the world, it became clear that there are several obstacles to adopting circular practices for unitised aluminum curtain walls. A paradigm shift is needed to achieve circularity in the facade industry. The complexity of disassembly and reuse highlights the need for alternative facade systems that prioritize these principles. By reducing embodied carbon, standardizing testing and certification, and developing a circular economy for facade components, we can transition to a more sustainable built environment. Recommendations in this chapter include focusing on reducing embodied carbon, revising certification schemes, promoting reuse through audits and standardization, investing in research and development, increasing awareness and training, and promoting collaboration and information sharing within the supply chain. These initiatives will minimize environmental impact, generate economic benefits, and foster a more sustainable built environment for future generations.

6. Case Studies


citi
reduce
BMO
reuse
k-4
citibank
London, United Kingdom
BMO tower
Toronto, Canada
Koningskade 4 +
The Natural Pavilion
Hague & Almere, Netherlands
THE
NATURAL
PAVILION
renew

In this chapter, the case studies that were explored, explain the implementation of reduce, reuse, and renewal culture in architectural practices globally. These studies provide insights into the Strengths, Weaknesses, Opportunities, and Challenges (SWOC) encountered when applying circular strategies, shedding light on both the original structures and their transformed states. Forensic analysis, encompassing both quantitative and qualitative assessments, as well as carbon analysis and building circularity results, was employed to evaluate the success of these strategies. Additionally, the concept of donor, non-donor, and receiver mentalities in circularity and the potential savings associated with shifting from linear to circular thinking. A Life Cycle Assessment (LCA) approach is developed to comprehensively explore the life cycle stages and the holistic view required for a circular project. Three case studies are examined, with the first project having a thorough analysis can be conducted. The remaining two case studies are projects where a circular approach is intended to be applied.

The first case study, *"What's happening in the United Kingdom?"* explores how the carbon emissions of the Citibank Building in London can be 'reduced'. The second case study *"What's happening in North America?"* analyses the 'reuse' of existing aluminium extrusions in the curtain wall of the First Canadian Place in Toronto, Canada, where the glass spandrel panels also replaced the Italian Carrara marble. Thirdly, in *"What's happening in the European Union?"* the study examines the 'renew' strategies applied in two buildings in the Netherlands, namely Koningskade(Hague) and Floriade's The Natural Pavilion. Across all three case studies, substantial carbon savings are achieved by adopting a mindset that prioritises(McDonough and Braungart 2010) the Donor and Receiver mentalities over the Non-Donor mentality(Figure 64). To elaborate further:

1) Non-Donor mentality: This mentality disregards the potential for future reuse or recycling, leading to increased waste and resource depletion.

2) Donor mentality: Embracing the potential for future reuse or recycling, this mentality prioritizes design for disassembly and circularity to minimize waste and resource depletion.

3) Receiver mentality: Focused on easy disassembly and material recovery, this mentality actively receives materials and components for a second life cycle.

These mentalities are crucial in reshaping how the approach to sustainability in architecture, highlighting the importance of adopting circular practices to minimize waste and resource depletion.

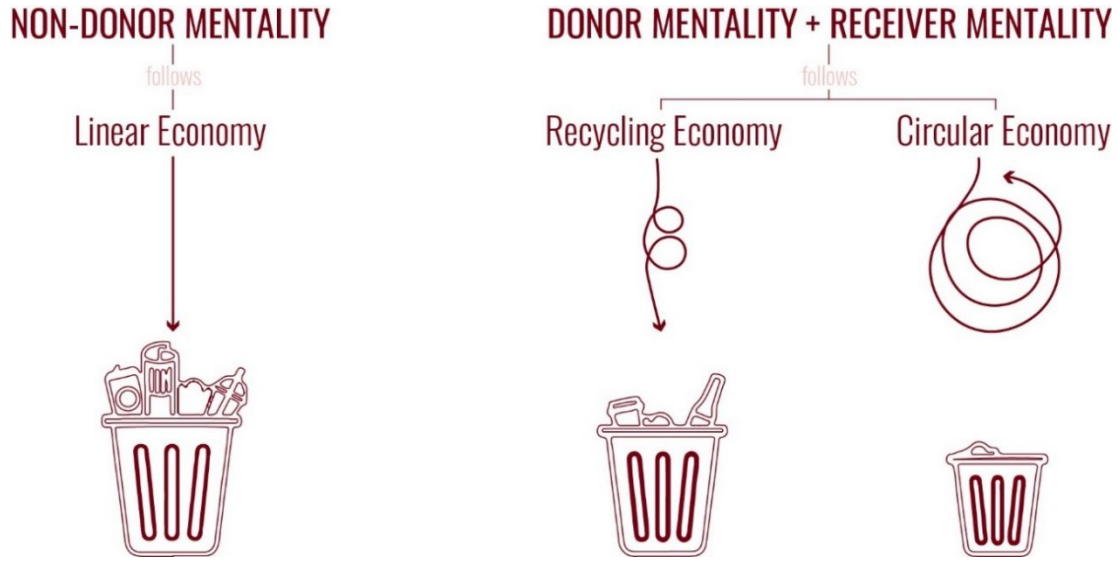


Figure 64. A comparison between Donor, Non-Donor, and Receiver mentality (Adapted from Nicholas Yiu, 2024)

6.1 What's happening in *North America*?

6.1.1 Background

The First Canadian Place(CTBUH n.d.), currently known as the Bank of Montreal (BMO) Tower, was constructed between 1973 and 1975 with a significant investment from Brookfield Properties(Figure 65). This office building is 298m (978ft) tall, making it the tallest building in North America and the eighth in the world in 1975. B+H Architects, a Canadian architectural firm, played a vital role in the project, creating a facade made of Carrara marble from Italy and aluminium and glass components(B+H Architects n.d.).



Figure 64 & 65(left-to-right). The First Canadian Place, Toronto; Render Visualisation(Roberto Portolese and B+H, 2024)

However, on May 15th, 2007, after 32 years, the building, located in Toronto's financial district, had to close due to a major storm(B+H Architects n.d.). A 140kg (310lbs), 1m X 1.2m, 0.35m thick white Carrara marble panel from the building's southern facade detached and fell from the 60th storey onto the mezzanine below. The incident was recognised as a lack of understanding about the construction materials, rather than design flaws. Several possible reasons(Architizer. n.d.) for the incident considered included the rainwater, Thermal cycles, and high wind forces on upper floors, leading to stress on the

cladding and eventual detachment of the defective or weakened panels. As a result, the First Canadian Place underwent recladding, giving the tallest skyscraper in Canada a new look by 2011.

6.1.2 Process

From late 2009 to 2012, Brookfield Properties, partnering with major organisations such as the Canada Pension Plan Investment Board (CPPIB) and Alberta Investment Management Corporation (AIMCo), formed a significant renovation project at First Canadian Place in Toronto(Construction Canada 2012). The project involved the replacement of the aging marble exterior with a new glass spandrel panel system, amounting to a total cost of $100 million. This renovation effort(Architizer. n.d.) included replacing 45,000 Carrara marble panels with new glass panels and installing 7,800 glass spandrel panels, covering 375,000 square feet while preserving the existing windows. Moed De Armas & Shannon Architects and B+H Architects were assigned with the design and execution of the project, leading comprehensive research to determine the most suitable glass spandrels meeting specific requirements for colour, size, strength, performance, economic factors, and clear-opaque interlayer technology. As shown in Figure 66, through a collaboration, a custom frit-patterned white spandrel panel, designed by Doyle Partners, was projected to create a luminous white texture on the building's facade(Skira 2010).



Figure 66.(left-to-right). Custom frit-patterned panels (B+H Architects, 2011)

This renovation involved a series of custom-designed solutions to achieve efficiency and high quality (EllisDon n.d.). A three-level suspended platform system to provide access for workers and materials, protecting the entire building perimeter. A 50-foot suspended elevator platform of 14 sections capable of accommodating 160 workers, reducing labour hours by over 1.3 million(Figure 67). In addition, a specialised scaffolding unit was designed to vertically scale the tower and allow for the organised and safe recladding of the facade(Figure 68). Panel removal and replacement were carried out in multiple shifts, with the loudest and most noisy work scheduled for night shifts to minimize disturbance.



Figure 67. (left-to-right). Movement of suspended platform (B+H Architects, 2012)

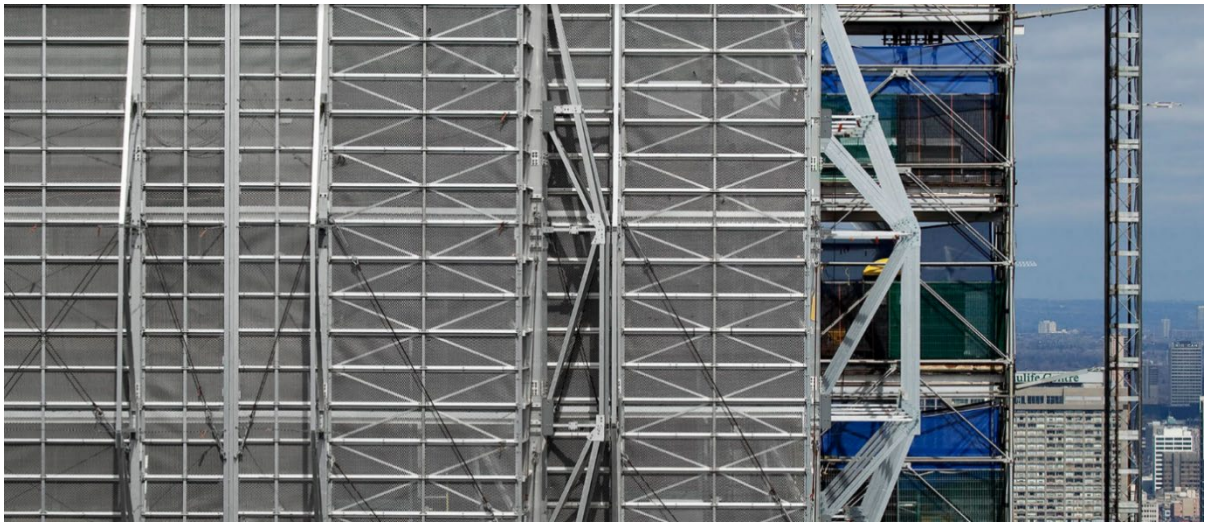


Figure 68. Close-up of suspended platform (B+H Architects, 2012)

In recladding, first assessing the structural integrity and condition of the aluminium window frames and other components was done, and later the new glazing units were installed while preserving the original aluminium extrusions as it was in good condition. Dismantling(Figure 69 and 70) each 1.2 square meter white marble panel and reusability process involved the following steps:

1. Loosening the brackets, bolts, and anchors.
2. Lifting off the white marble and setting it on a carrier.
3. Removing any remaining older elements and cleaning the area.
4. Keeping the aluminium extrusions and replacing, repurposing, and shipping the stones.
5. Adding new glass wool, sheathing, and other elements.
6. Finally, installing the new glass panels onto the facade.

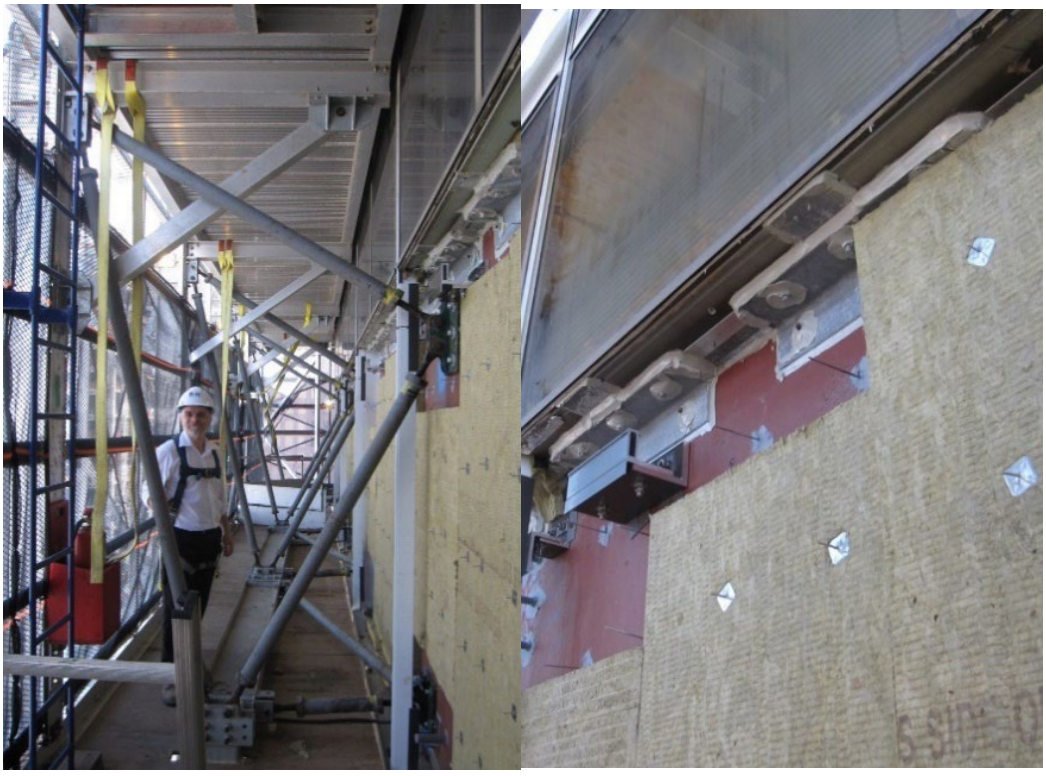


Figure 69. Installation of new insulation (B+H Architects, 2012)

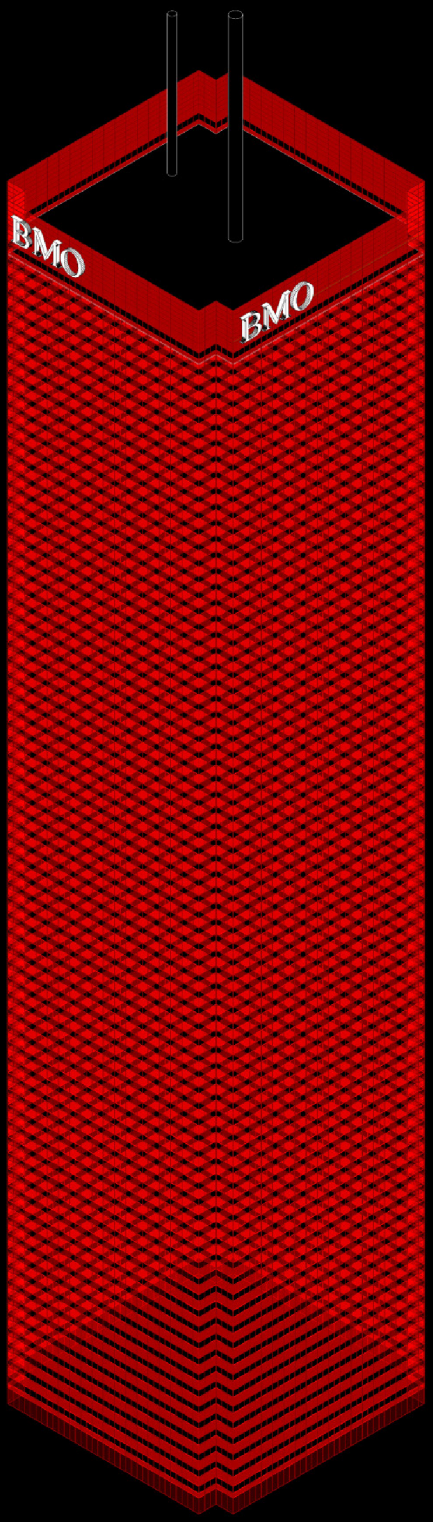


Figure 70. Installation of new spandrel(B+H Architects, 2012)

6.1.3 Life Cycle Assessment

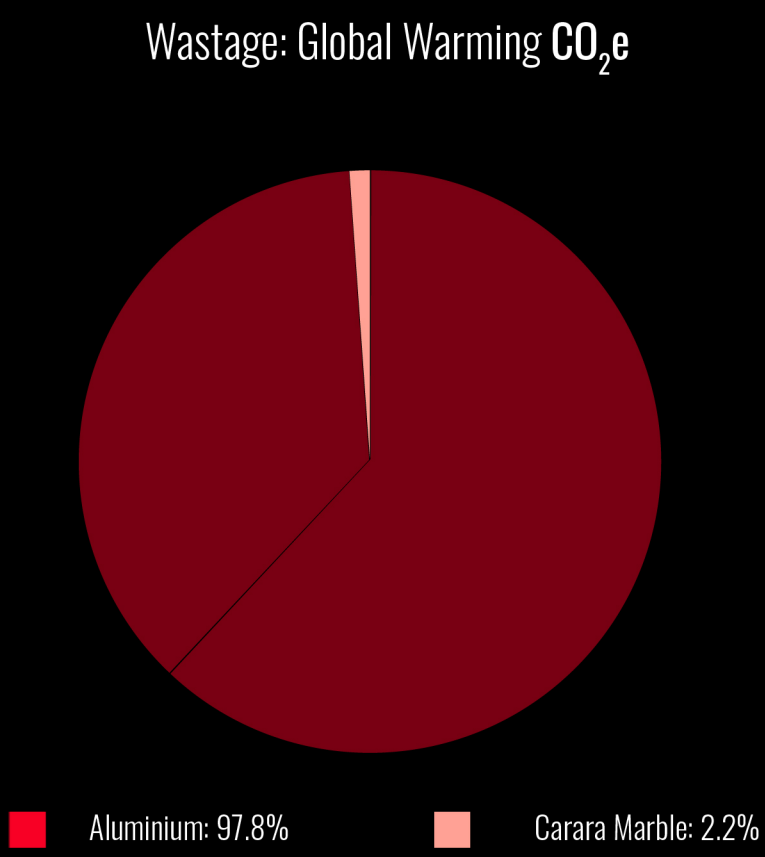
After undergoing renovation, the First Canadian Place Building improved its energy conservation measures and infrastructure upgrades, such as the recladding of the envelope, allowing it to achieve LEED-EB: OM certification (Brookfield Properties. n.d.). The building's most significant success story is its energy consumption reduction. Since the start of the energy reduction process in 2009, the building has reduced its consumption by approximately 24% to date and improved water efficiency while expecting to continue to improve as conservation measures take full effect. Compared to 2009, the building has saved about 23 million kWh of electricity and 30,000 m3 of natural gas. As part of the recladding process, the building has also made significant carbon savings, which are explained in more detail later in this chapter. As a result, 'deep energy retrofits' have reduced the amount of construction waste sent to landfills through recycling programs (Energy Manager Canada 2012). The removed stone panels from the facade were recycled and repurposed for multiple uses, including concrete, base products under roadways, landscaping, and community art projects. However, materials like Aluminium and glass showed distinct characteristics from white marble when it comes to recladding. In such a process, the aluminium extrusions were either retained or deeply retrofitted as the frames for windows and spandrels, whereas side by side the new glass panels were sourced and manufactured locally to help in reducing embodied carbon, resulting in significant carbon savings. The answer to "What's happening in North America?" is that the "Reduce" approach can decrease a good amount of embodied carbon simply by having a donor mentality. This mentality is significantly better than having a non-donor one, where the provision of quantitative and qualitative results as part of forensic analysis and Building Circularity of the project, its components, and materials was undertaken for the Life Cycle Analysis (LCA), determining how much carbon savings and material recovery achieved.

To begin this process, a Revit model with similar dimensions as the building's envelope was modelled(by author), which included the components, layers, and materials involving 34,840 m² of recladding for the project. After completion, the OneClick LCA plugin was used to analyse the carbon footprint of the materials. As a result, two scenarios were compared, the first focusing on the results achieved if stakeholders had a 'Non-donor mentality'(Illustration 37) and the other explaining how the stakeholders thought with a 'Donor mentality'. The major materials involved in both processes create approximately 12649 tonnes of embodied carbon emissions, which were assumed to be Aluminium, Clear and Tinted Glass, and Carrara marble.

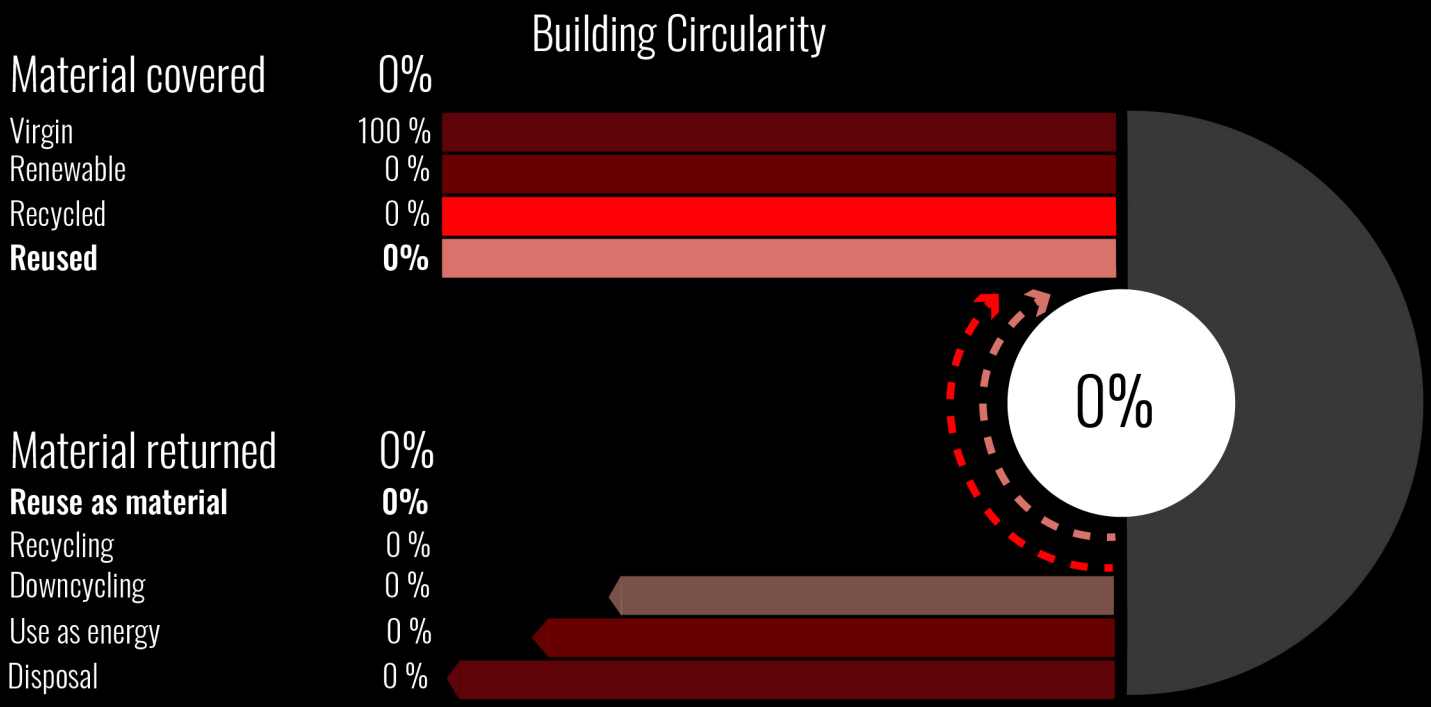


Total no. of Aluminium curtain wall units: **12000 units**

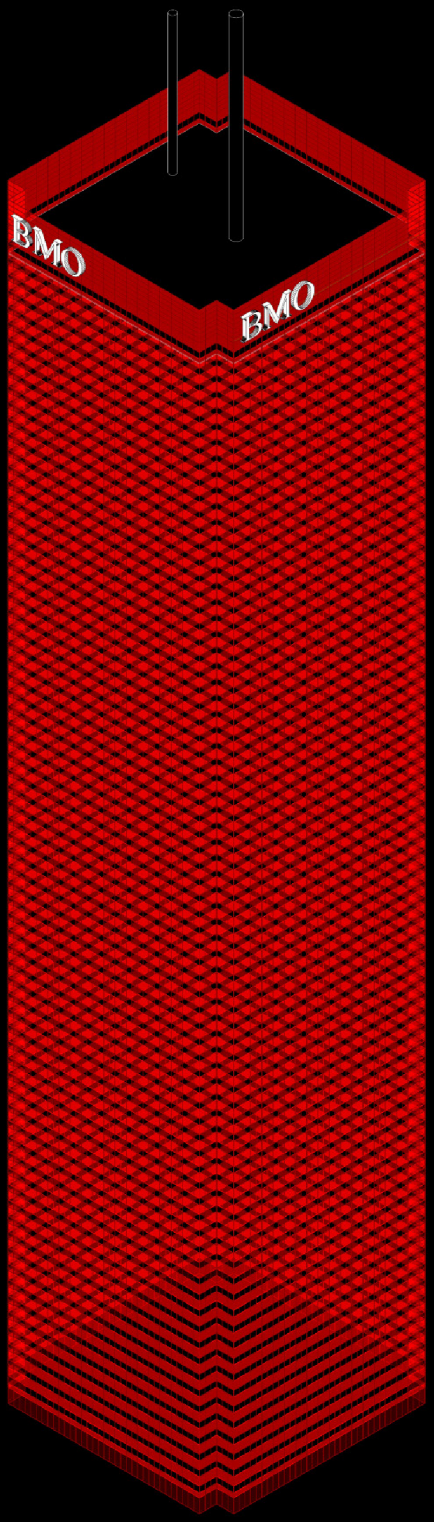
Illustration 40. Embodied emissions and Building Circul



Landfill: 12649 Tonnes CO_2e

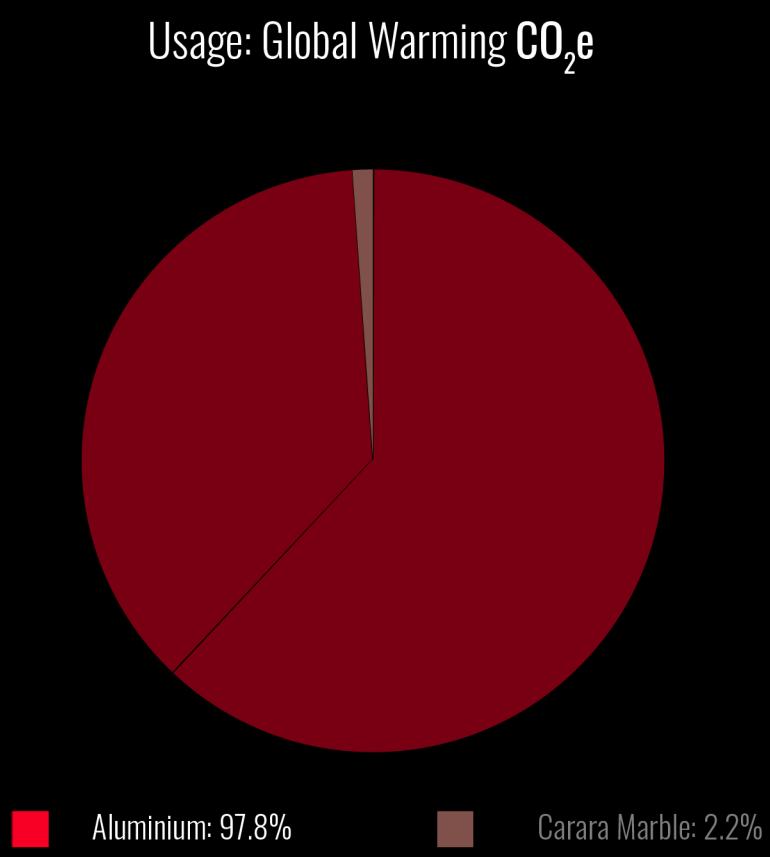


arity results with Non-Donor mentality (Created by Author, 2024)

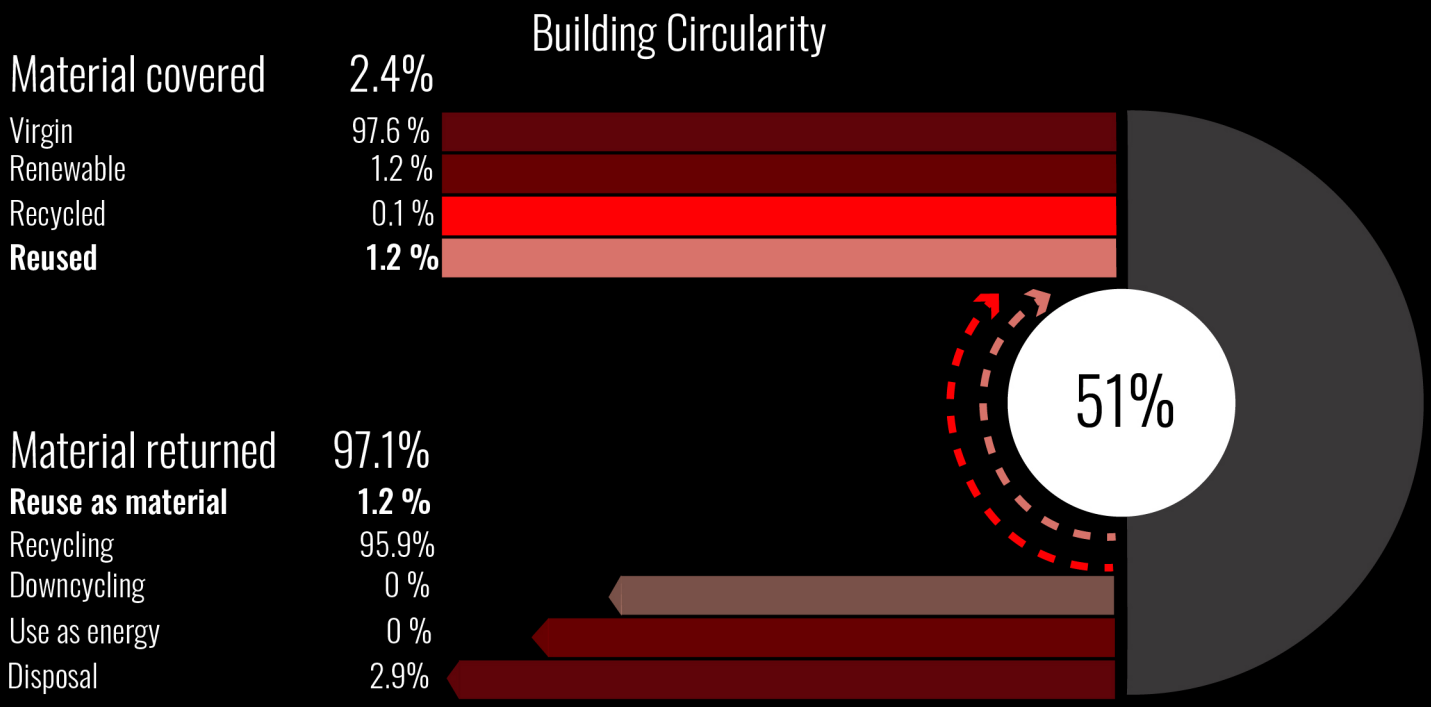


Total no. of Aluminium curtain wall units: **12000 units**

Illustration 41. Embodied emissions and Building C



Savings: 12649-278= 12371 Tonnes CO_2e



Circularity results with Donor mentality (Created by Author, 2024)

Life Cycle Stages

To illustrate the circular approach applied in this project, Illustration 39 presents a look at the facade's life cycle stages. The figure reveals that this was a refurbishment project located in B5. During this phase, the process involved dismantling(C1) stone, brackets, anchors, and rigid insulation, followed by a back-and-forth process between the factory works for new glass checking and a three-level scaffolding process on site. Additionally, waste generated during this stage should be described. The high amount of white Carrara marble stone was removed and transported (C2) for recycling and repurposing purposes (D). Anchors, gaskets, brackets, and rigid insulation were transported (C2) and placed in Waste processing (C3) or landfill (C4).

However, the deconstructed(C1) Aluminium frames served as a reusable material (D) for the recladding of the same project, avoiding the Product Stage (A1-A5) and Construction Process Stage (A4-A5) and directly entering the Use Stage (B1-B7) of the project. The circular process produced savings that can be seen by comparing the impact of a "Donor mentality" versus the traditional "Non-Donor mentality." Without implementing the circular process, the result would be dismantled materials wasted, and a new facade constructed, resulting in an additional carbon footprint and zero building circularity approach.

6.1.4 Conclusion

The recladding of First Canadian Place was a challenging three-year process that involved replacing many white marble pieces on Canada's tallest skyscraper. The project was executed with great care, considering the needs of the building's tenants and surrounding areas. The focus was on low carbon facade design and the reuse of materials to minimize the deployment of new virgin materials. As a result, the aluminium frames of the windows and other components were retained for their structural integrity and conditional assessment, while the stone was repurposed and recycled. New fritted glazed spandrel panels were installed to achieve higher performance.

Interestingly, the aluminium frames showed no signs of aging, indicating their potential for circular use in future construction projects. The weakest links in the previous facade were the anchors, gaskets, and rigid insulation, which were replaced during redevelopment. These materials had the lowest tested lifespan insurance and should be kept in mind for future designs. Ultimately, this project achieved significant carbon savings by giving main materials a second life instead of sending them to landfills with a non-donor and linear mentality in construction practices.

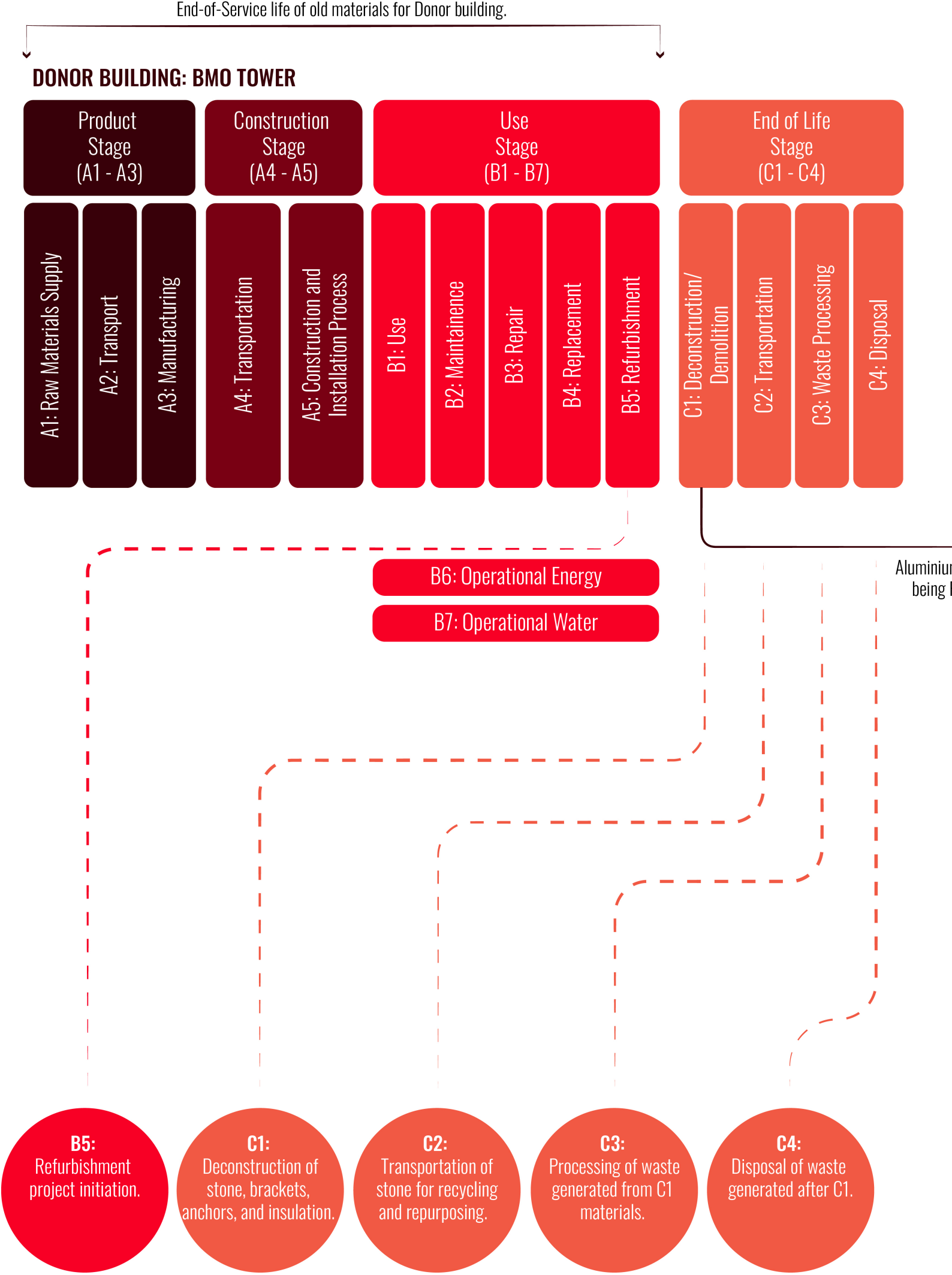
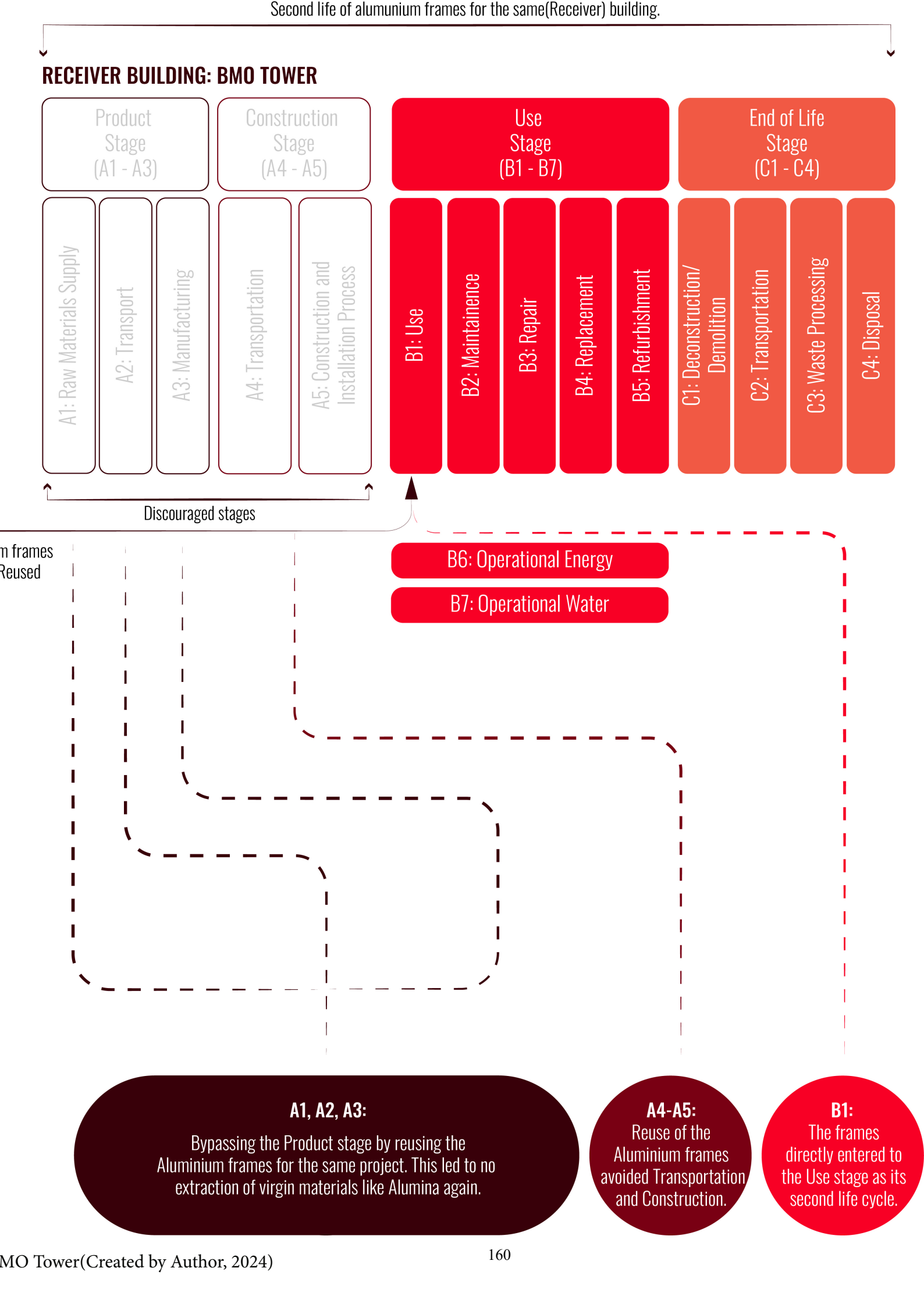


Illustration 42. Life cycle stages for B



MO Tower(Created by Author, 2024)

6.2 What's happening in *United Kingdom*?

6.2.1 Background

The Citi Bank Building(Figure 71), previously known as DS5 (Docklands Square 5) in Canary Wharf, London, United Kingdom, functioned as an office building in 1998. In 2023, a decision was made to redevelop the building for two main reasons (Kollewe 2022). To update the company's image and the building, and second, to update the workspaces, reflecting its character. As a result, American Multinational Investment Bank being the client, and the facade contractor decided to redesign 10 out of the 45 floors, which included:

i. Citi Square connectivity: Three on the ground level.
ii. Citi High Street: Three in the middle level.
iii. Citi Beacon: Four on the top level.

In developing the new facade, the client and contractor actively aimed to repurpose the existing facade panels to reduce the project's embodied carbon footprint. Therefore, the aluminium curtain wall panels for all ten floors, which didn't reach their EOL, were being assessed for new purposes within the construction market.



Figure 71. Conceptual illustration of Citigroup's main tower (Citigroup, 2022)

In the thesis paper 'Circularity of existing aluminium unitised curtain wall facades', it was documented that the unitised Aluminium curtain wall panels were powder-coated members spanning from floor to floor in height and varying in width from 0.4m to 1.5m (Teeuwen 2023, 55). The panels followed two main typologies: a stainless-steel finished spandrel and a transparent panel with a shadow box, with the same patterns replicated every 9m. It was observed that the male-female interlocking connections of the curtain wall panels resulted in distinct left and right transom framing. Additionally, the vertical-horizontal connections between two panels demanded a connection profile on the vertical side, backed by the horizontal spandrel profiles at the back. The vertical spandrels, hiding the columns at the back, included a 75mm layer of rigid insulation and 1.5mm of sheathing on both sides. While the horizontal spandrels, with the same layering, helped to cover the beams. The two other main components determined were:

a. Structural glazing material used in the profiles with internal coatings and stainless-steel caps in the form of shadow boxes with a linen finish.

b. A 75mm thick insulation layer, with an aluminium cover and steel back plate, was also included in the gap between the caps.

The complicatedness of the spandrel panels made dismantling the curtain walls(Figure 72) challenging, as discussed in the following sub-topic.

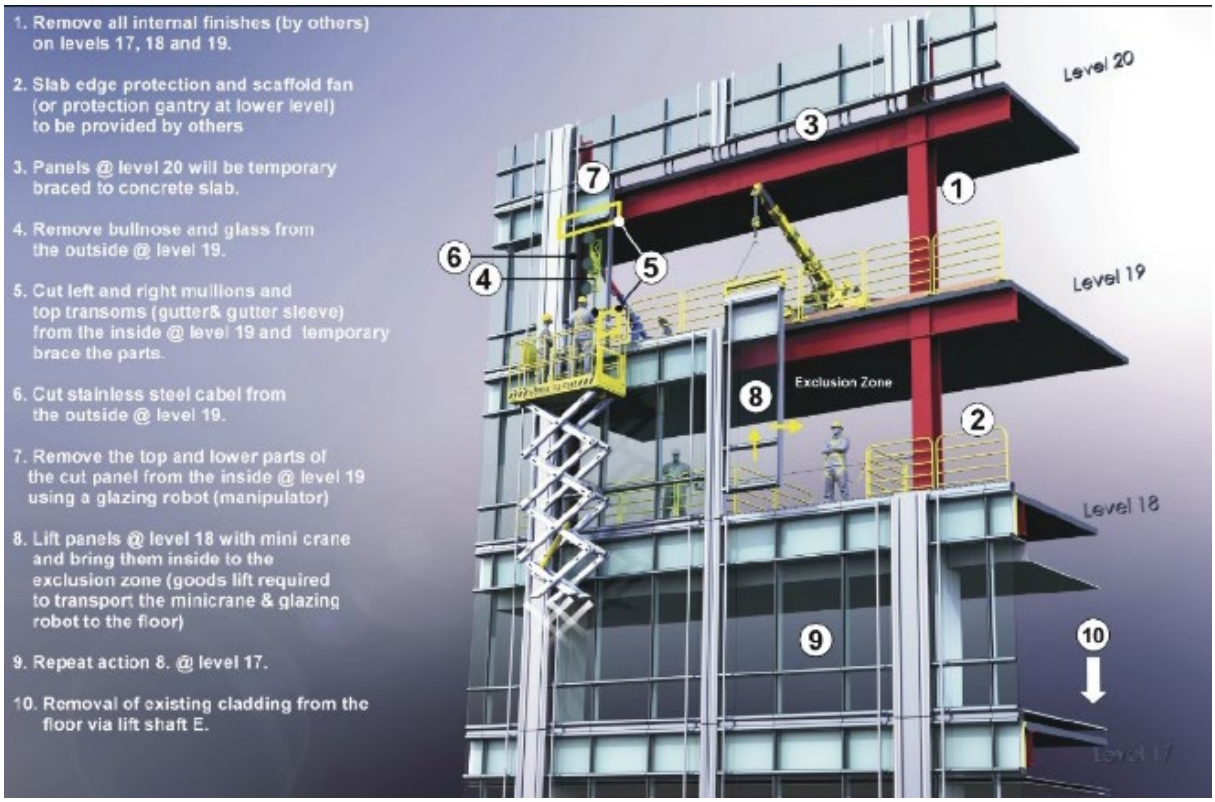


Figure 72. Dismantling of curtain wall (Scheldebouw, 2023)

6.2.2 Process

The Scheldebouw Company was assigned the task of eliminating aluminium curtain wall panels from the Citibank Building, which required the operation of two distinct methods (Teeuwen 2023, 57). The first method involved on-site dismantling, which took the removal of panels one by one starting from the top floor. The process(Figure 73) used a scaffold fan erected one floor below to ensure safety, and insulation glazing units were temporarily removed and reinstalled after the facade was dismantled. The

mullions and top transoms were cut from the inside before both panel parts were removed using glazing robots equipped with vacuum pads. The panels were then transported inside using spider mini cranes. During this process, silicone joints were cut, and the bullnose was removed from the outside using a scaffolding technique called a birdcage. The dismantled panels were then collected and stored.

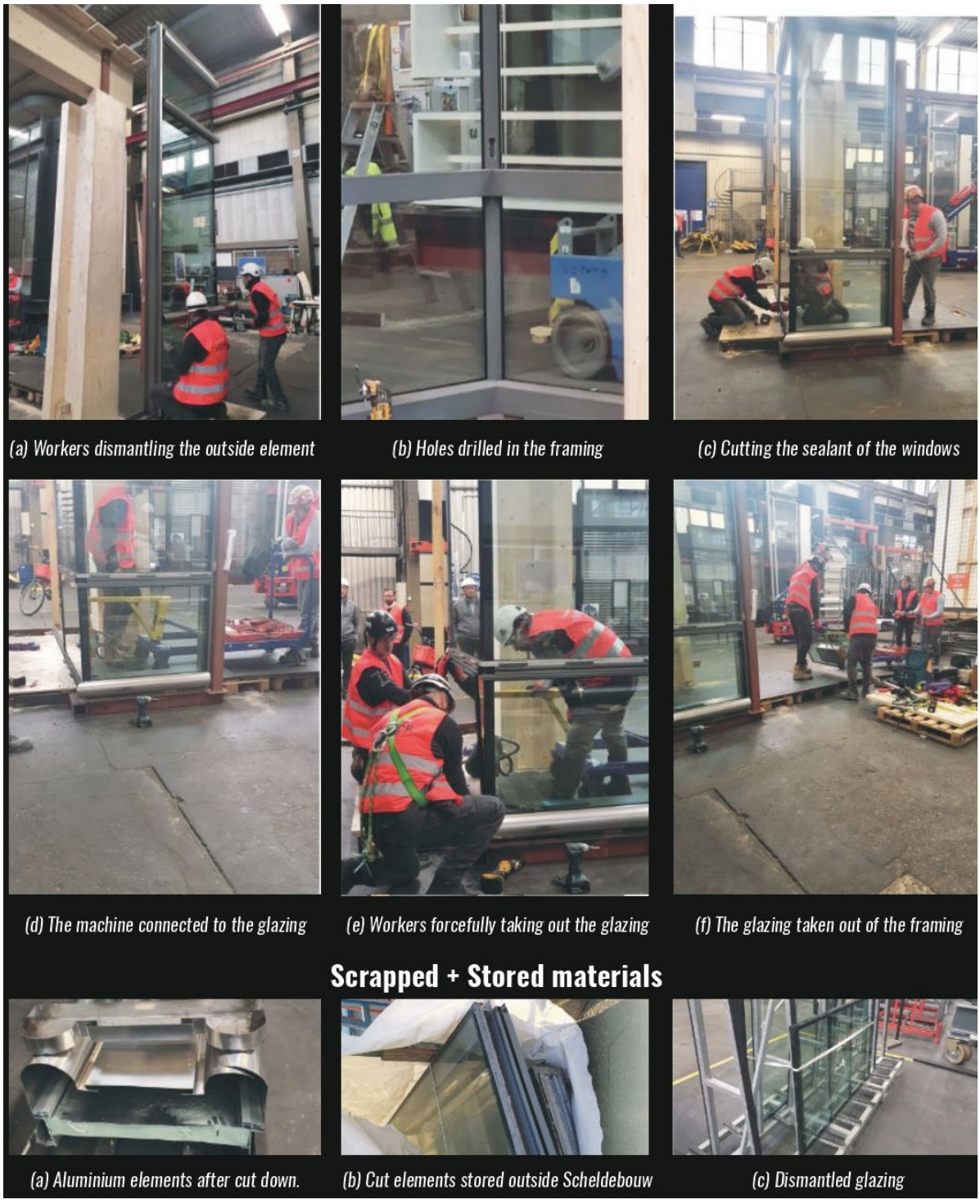


Figure 73. Dismantling process in production hall (Scheldebouw, 2023)

After years of storing the spare panels, Scheldebouw conducted a trial dismantling mock-up in 2022 to explore deconstruction options (Teeuwen 2023, 60). The trial involved three hours, 62 steps, and 30 tools. Workers began by removing the stainless-steel elements and pulling out the gaskets from the

outside framing. Then, they drilled holes in the frames, cut out old sealants from the windows, removed the glazing using various machines, and manually extracted the pieces. In one failed scenario, three smaller glazing elements were broken, while the other three big panels were removed without any damage but had structural sealant traces left over on them. In most cases, the gaskets were still in place, and large parts of the aluminium and stainless steel were still left.

Scheldebouw first conducted a virtual disassembly by taking the drawings and expertise of a colleague associated with the assembly of the panels. The most challenging connections in the facade were found to be the structural sealant that keeps the glazing units in place and the screws that connect the mullions and transoms, which were covered by a sealant for air and water tightness. Hotspot mapping was used in the dismantling process, which includes five indicators: Time, difficulty of the activity, priority of the part, environmental impact, and economic value. Three hotspots were defined: the glazing units, the aluminium frames, and the screws covered with sealing. The team realized that it takes time and damage to understand the process of deconstructing aluminium curtain walls, whether on-site or at a mock-up.

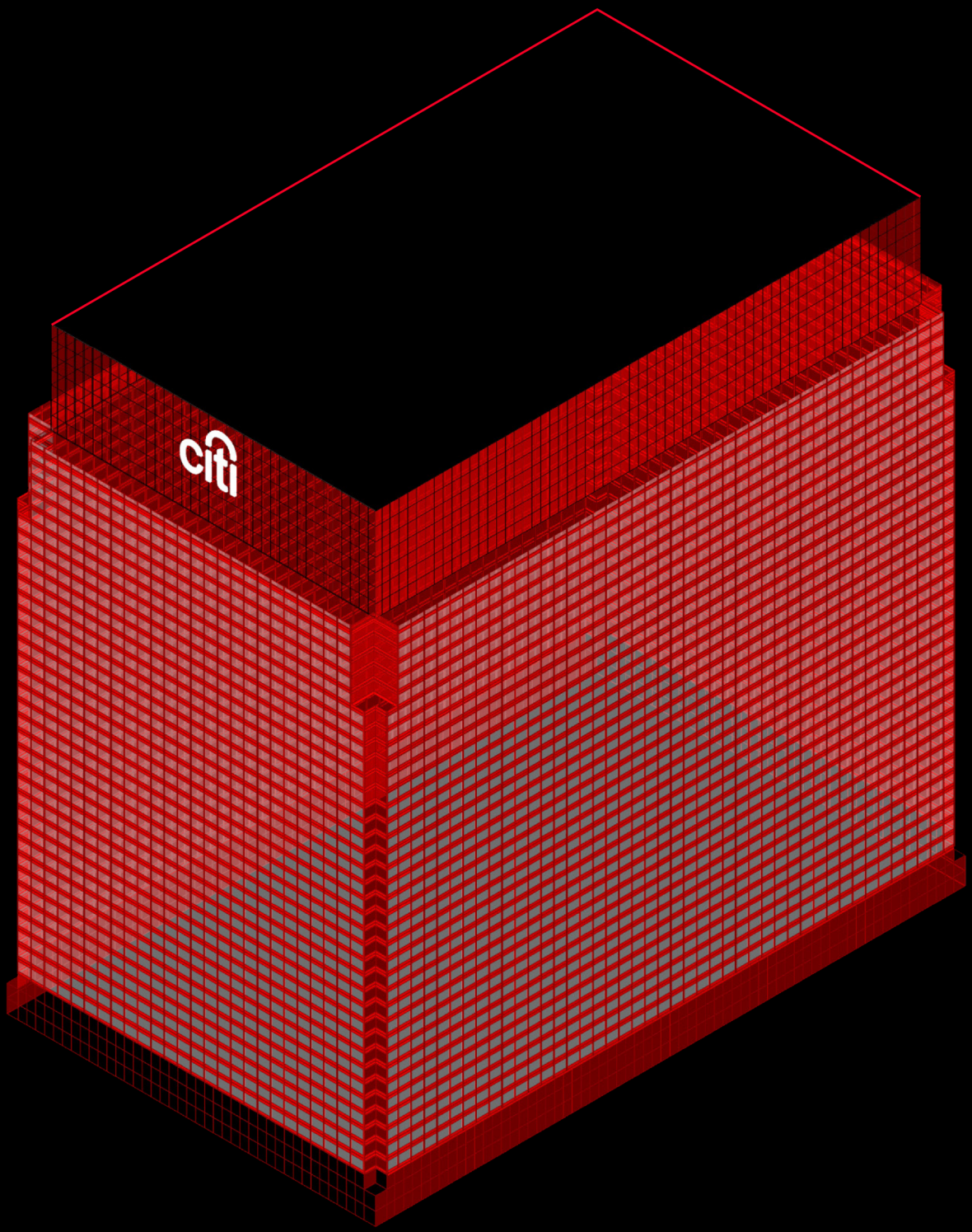
6.2.3 Life Cycle Assessment

The Revit model(by author) was developed according to the recurring pattern of a 9-meter grid that consisted of Citibank's facade, mentioned in the thesis paper "Circularity in aluminium curtain wall facades". The spandrel panels with a stainless-steel cover, were considered twice in one grid. Within the grid, there were five different panels, including two closed spandrel panels that were 800mm and 400mm wide and six transparent panels with varying widths. Two of the transparent panels were 1500mm wide and had a shadow box at the top, a large window in the middle, and a smaller window panel at the bottom.

This resulted in a total of eight panels per grid. The height of the panels varied throughout the building, with a standard size of 4100mm assumed for the research. The model estimated that a total of 1584 panels would need to be dismantled. After completion, the OneClick LCA plugin was used to analyse the carbon footprint of the materials. The major materials involved in both scenarios - Non-Donor(Illustration 40) and Donor mentality - created approximately 7405 tonnes of embodied carbon emissions. These materials were assumed to be Aluminium (37.6%), Clear and Tinted Glass (61.5%), and Rigid insulation (1.1%).

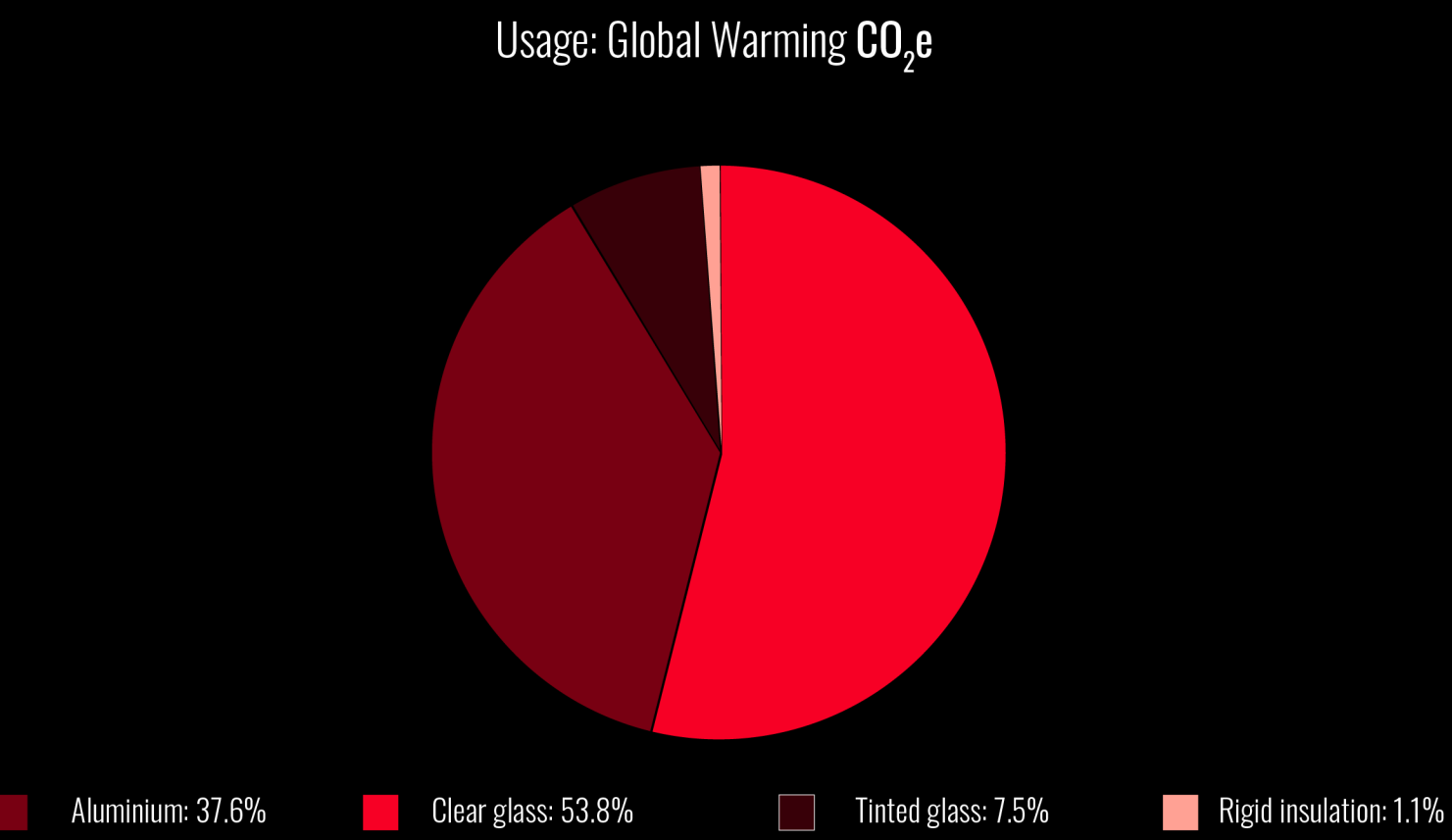
In the first scenario, with a non-donor mentality, the materials would likely have been demolished and the 7405 tonnes of CO2 emissions would have ended up in landfills, replicating the process of linear construction practices rather than circular ones. This would have resulted in a missed opportunity to achieve 0% building circularity, as virgin materials like bauxite (for aluminium), iron ore (for stainless steel), and silica sand (for glass) could have been downcycled or disposed of.

However, the client and facade contractor were more aligned towards the second scenario(Illustration 41), which is the donor mentality. They focused on reducing CO2 emissions by redirecting the materials from landfills and supporting circular construction practices over linear ones. This approach enabled the project to save 7324 (7405-81) tonnes of carbon emissions by reusing, repurposing, or recycling most of the materials like aluminium, steel, and glass. This resulted in a 94% circularity being attained in the construction process, with a significant amount of 90.7% of materials being either reused, recycled, or not discarded or downgraded to a lower quality, which was a sustainable approach compared to using a substantial number of new materials.

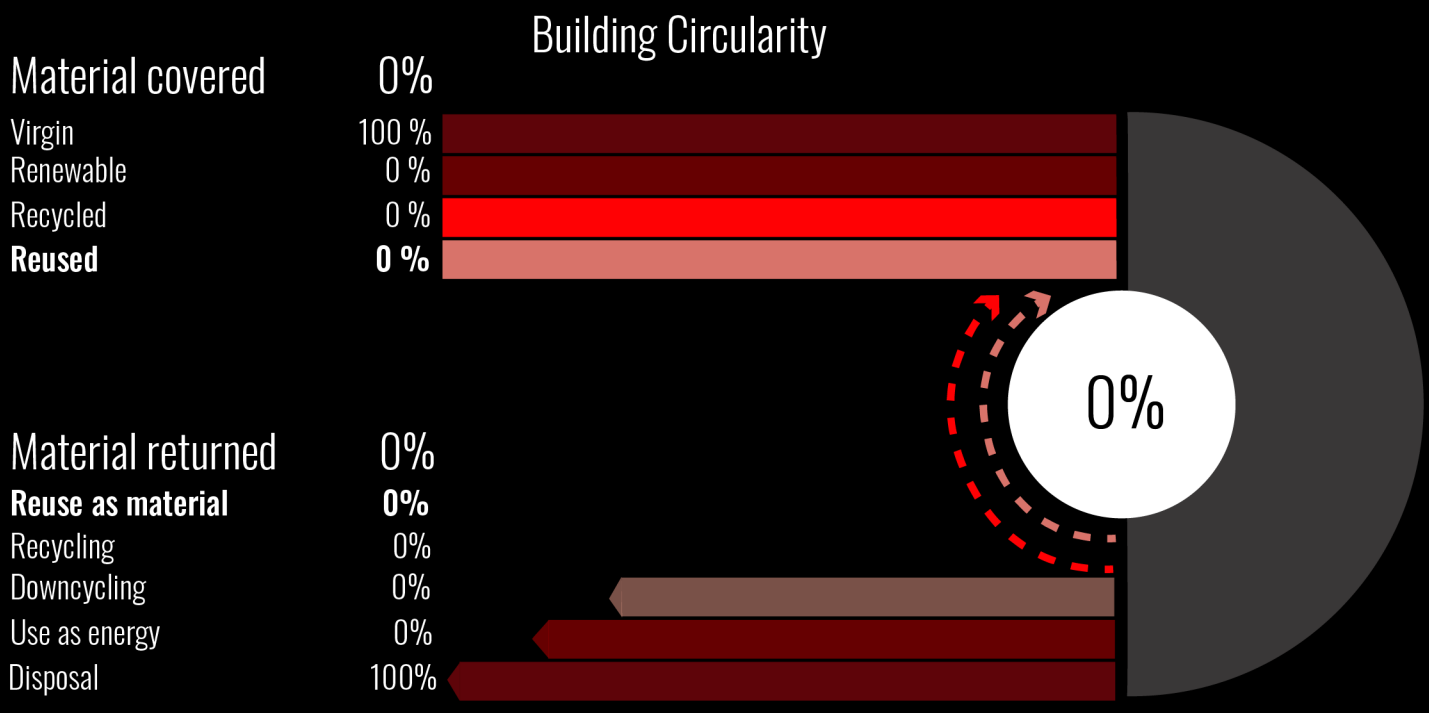


Total no. of Aluminium curtain wall units: **5000 units**

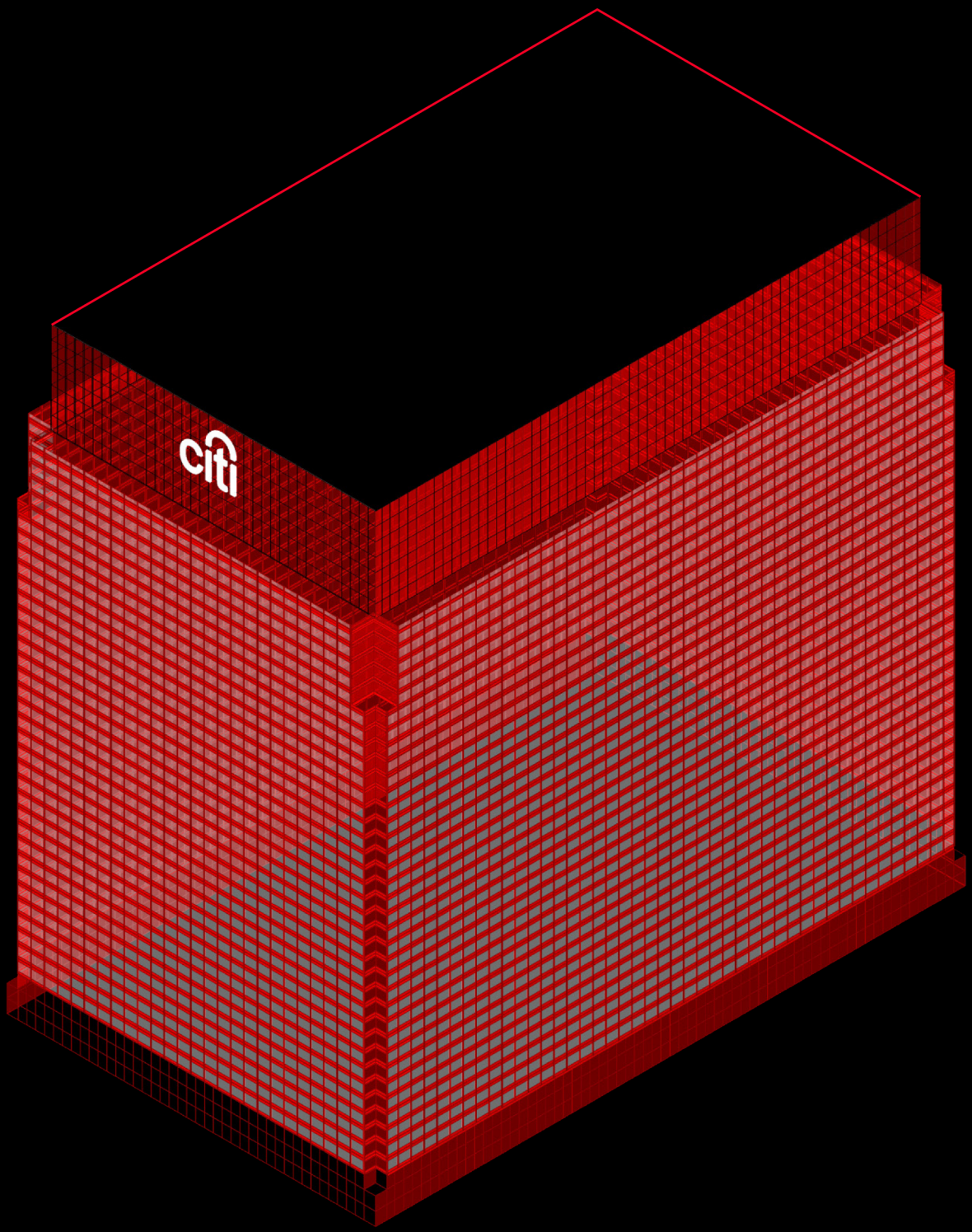
Illustration 43. Embodied emissions and Building Circul



Landfill: 7405 Tonnes CO_2e

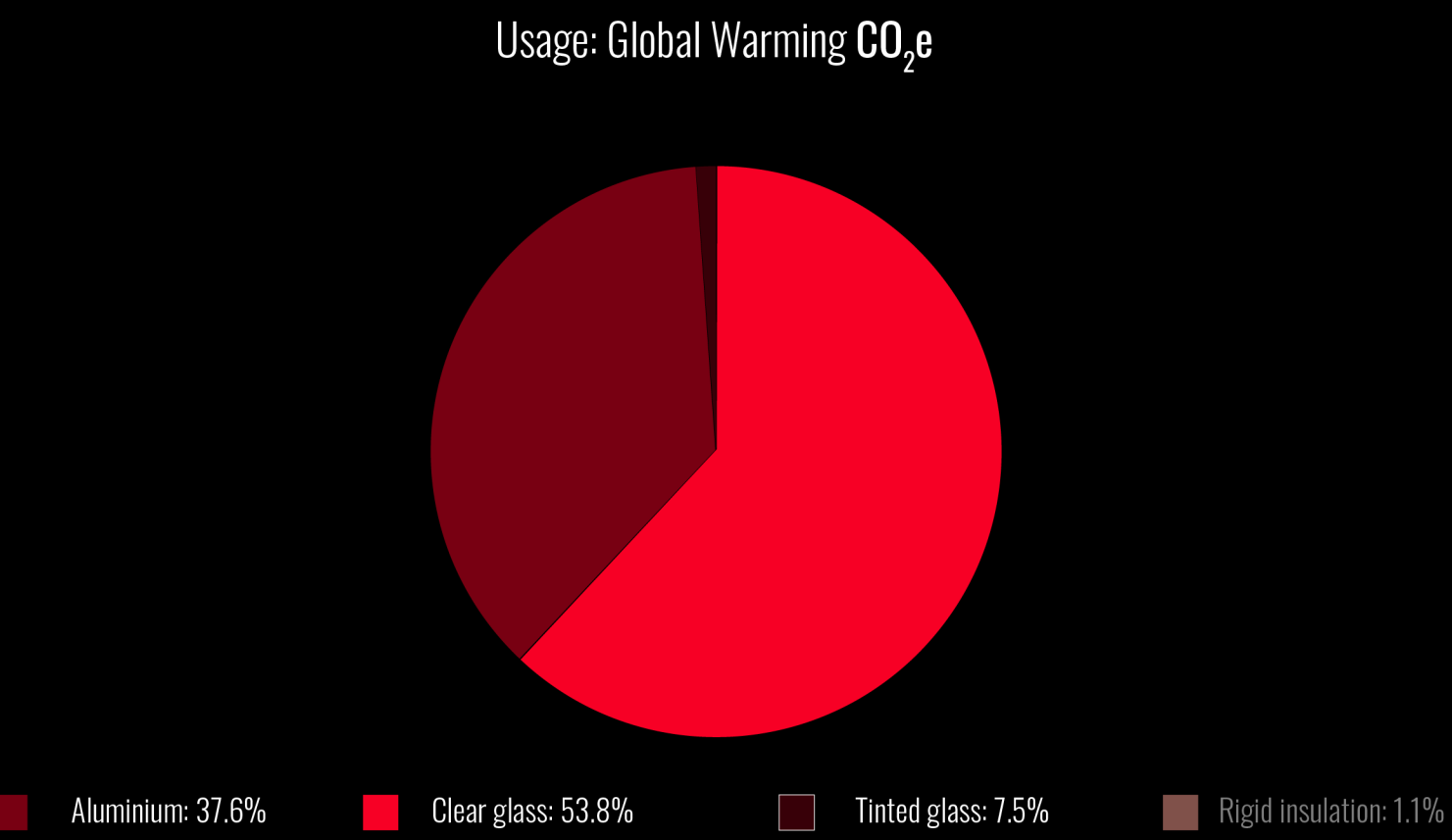


arity results with Non-Donor mentality (Created by Author, 2024)

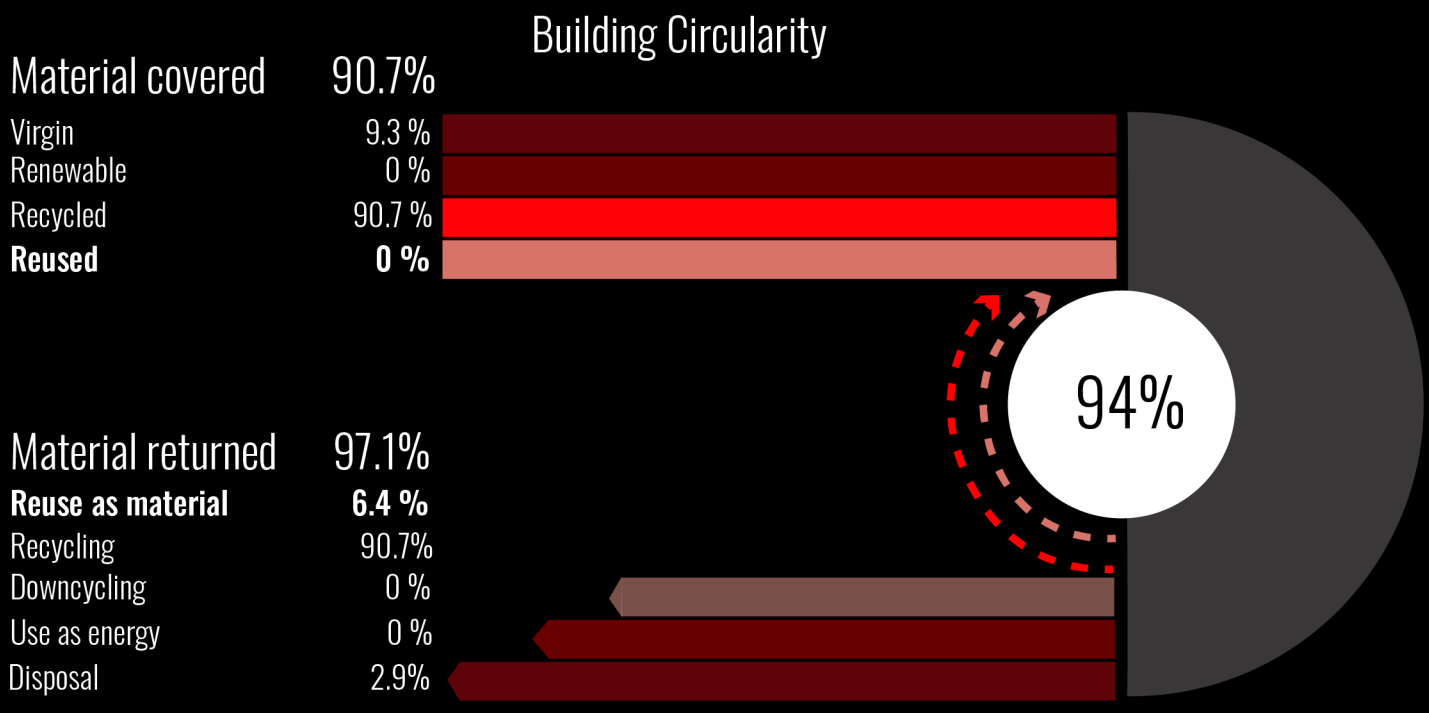


Total no. of Aluminium curtain wall units: **5000 units**

Illustration 44. Embodied emissions and Building C



Savings: 7405-81= 7324 Tonnes CO_2e



Circularity results with Donor mentality (Created by Author, 2024)

Life cycle stages

In the life cycle stage of the Citibank Building, the product stage (A1-A3) included the supply of raw materials, transportation, and manufacturing of unitised curtain walls. This was followed by the construction stage (A4-A5), which involved the transportation and installation (A5) of spandrel panels on site. These stages helped to understand the major elements involved in carbon emissions of the typical panel (Illustration 42) in the curtain walls, such as Aluminium profiles (powder-coated), Glass, Electricity, Stainless Steel, Transport, Aluminium sheets (Anodised), Steel sheets (pre-galvanised), and others. After 25 years of a commercial building in the 'Use stage', it was found that the facade required a new appearance and upgrade, leading to the deconstruction process(C1) of the existing facade. This process involved dismantling materials like Glass, Aluminium frames, Steel sections, sealants, gaskets, and others on the site itself for the 10 floors through machines and workers, transported (C2) to the production hall for further usage of the materials, and starting the 'Beyond the Building Life Cycle Stage' (D).

From the mock-up in the production hall, the materials such as insulation, EPDM gaskets, and structural sealants, due to their limitations, needed to be transported (C2) for waste processing(C3) and disposal at the (C4) site. However, materials like Aluminium, Stainless steel sections, and glass could be upcycled by reusing (D1) for future purposes, even if they were a little damaged. These reusable (D stage) components such as Aluminium profiles (powder-coated/anodised), Stainless steel elements/sheets, or even the old glass for a similar project could bypass the Product and Construction stage (A1-A5) and directly be considered for a receiver building, for its 'B1' phase in Use stage (B1-B7).

6.2.4 Conclusion

The deconstruction of ten floors at Citibank Building was a rigorous process, involving the dismantling of all aluminium curtain wall components. Scheldebouw, the facade contractor, utilised their knowledge and techniques to find a solution that allowed for the direct reuse, refurbishment, or re-manufacturing of removed materials. As a result, aluminium extrusions, stainless sheets, and glass were carefully stored for future use or recycling, while sealants and gaskets were disposed of. These materials remain in the production hall and will continue to be sought after for a new building project, extending their lifespan. Surprisingly, no wear or tear was observed in any of the components after being stored for the same duration as the original building.

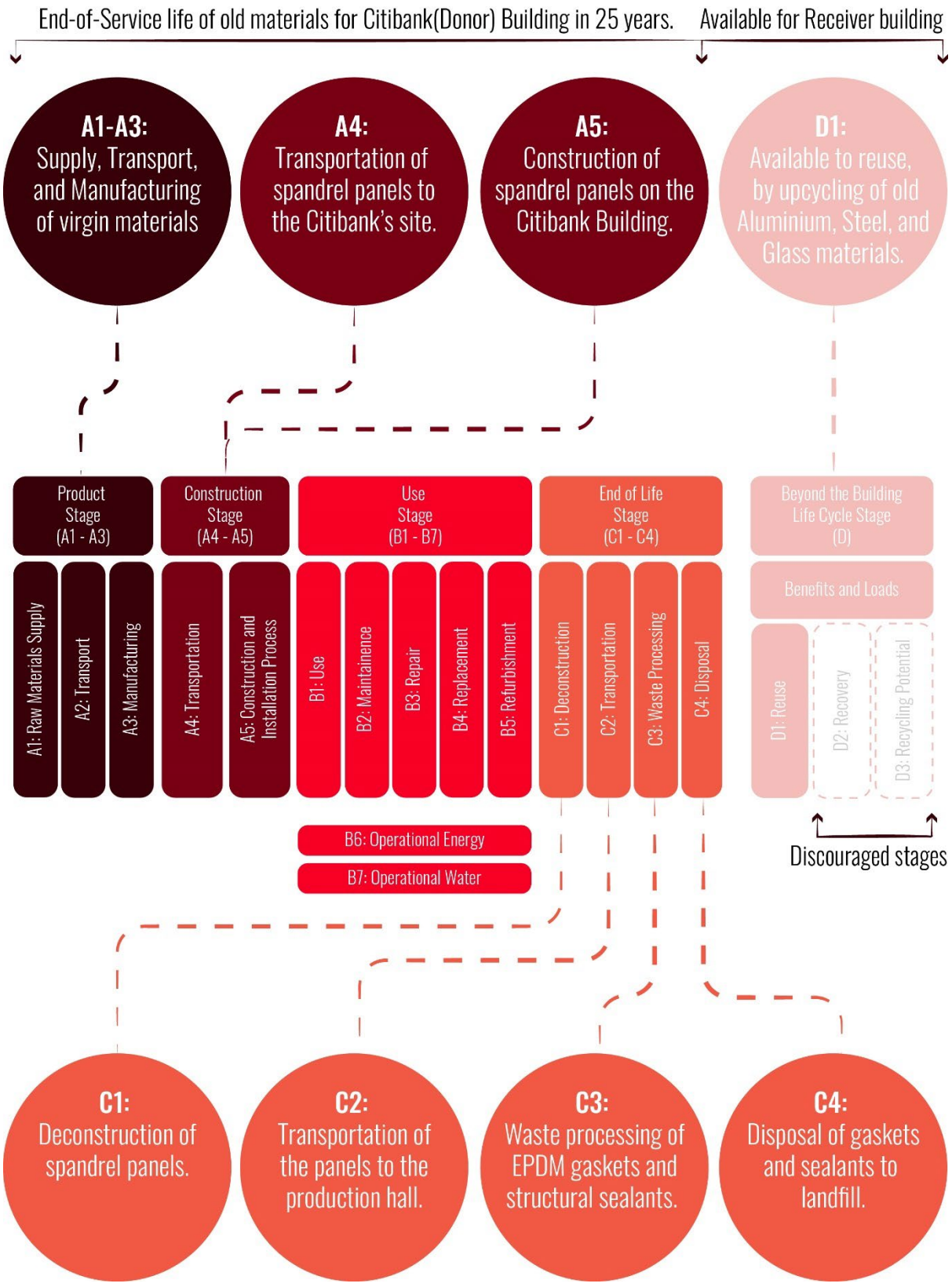


Illustration 45. Life cycle stages for CitiBank Building(Created by Author, 2024)

6.3 What's happening in *European Union*?

6.3.1 Background

The Koningskade 4(Figure 74) is a historical and architecturally significant office building in The Hague, Netherlands. It was built in 1969 as a major investment by the Netherlands' Instituut voor Toegepaste Geowetenschappen (NITG). The building has a unique double skin facade, being the first of its kind in the Netherlands, credited to Scheldebuow, a facade specialist firm that has been active in the Netherlands for over six decades (Permasteelisa Group n.d.). The facade comprises aluminium curtain walls with large-sized gaskets and sheets of float glass, which were never coated or had additives. However, like many buildings of its time, Koningskade 4 did not comply with regulations and had to remain vacant for seven years due to Sick Building Syndrome. It experienced extreme temperatures in winter and summer.



Figure 74. The Koningskade 4 Building, Netherland (Biedboek, 2011)

In 2000, a plan was initiated to renovate the building. Over the next three years, the double skin with an air cavity was refurbished to meet indoor climate requirements while retaining its original features (Bam 2001). However, in 2021, the outer shell of the building had to be replaced with laminated safety glass for safety reasons. The refurbishment followed 'reuse' criteria to ensure a more comfortable indoor environment without compromising the aluminium facade's characteristics. This involved replacing the EPDM gaskets, retaining the original aluminium profiles, and adding new glazing with appropriate thickness according to modern standards. The replacement (biedboek. n.d.) of 2215 panels showed a clear difference after the old EPDM gaskets were removed, but the difference in glazing thickness was not significant.

The overall weight of the infill, including the aluminium framing and glazing, remained comparable to the old infill, requiring no additional structural measures. The refurbishment of Koningskade 4 serves as an example of how modern technology and design can be incorporated while maintaining the historical significance of a building and improving its functionality and safety. The use of laminated safety glass enhances safety and also improves the building's energy efficiency and indoor climate control. Preserving original features, such as the aluminium framing and double skin facade, adds to the building's historical and architectural value. On the other hand, material like glass was further taken from Koningskade Building, and reused for the Natural Pavilion project (Figure 75).



Figure 75. The Natural Pavilion, Netherland (Paula Pintos, 2022)

6.3.2 Process

As mentioned in the thesis paper "Circularity of existing aluminium unitised curtain wall facades", the deconstruction of this office building required several facilities such as a 'Hefsteiger' or in general ‘scaffolding hoist’ to access the higher floors, which used to relocate to a new position after every completion of each elevation (Teeuwen 2023, 50). For the lower parts of the facade, scaffolding was used for accessibility, whereas for the upper parts, the same technique continued. In this construction process, the steps involved were:

i. Removal of the original glazing from the EPDM gaskets.
ii. Removal of the EPDM profiling and trim any remaining sealant from the original profiling.
iii. Cleaning out the existing profiles and the space between the windows inside and the curtain walling. (Figure 76)
iv. Deliver the aluminium profiles to the site in parts.
v. Usage of new EPDM framing for the remaining aluminium profiling.
vi. Placement of the vertical mullions, followed by horizontal mullions, after connecting the corner piece and mechanically connecting both.
vii. Arrangement of EPDM frames for water tightness and positioning supporting parts for the glazing.
viii. Fixation of the new laminated glazing in the original framing.
ix. Placement of the exterior framing, held in place by EPDM gaskets and mechanically connecting to the frame.



Figure 76. Removal of curtain wall elements (Teeuwen, 2023)

To prevent any contamination the float glass extracted from the original panels was carefully stored in a designated container in the storage room, whereas old gaskets were sent to landfill (Figure 77) When the new glazing arrived at the site, it was installed onto the frames, and the collected glass was shipped to Saint-Gobain France. Detailed construction reports underscored the significance of using sealant between the gaskets and the newly positioned framing, noting its importance for any future refurbishments.



Figure 77(left-to-right). Old gaskets; Disposal of old gaskets to landfill (Teeuwen, 2023)

6.3.3 Life Cycle Assessment

The second criterion of this chapter called "Renew," focused on the integration of circularity. During the tender phase, stakeholders prioritised the renewability mindset, where clients adopted a "donor mentality" and a "receiver mentality." This introduced three levels in the process:

i. Regenerating products with a similar function.
ii. Reprocessing products for different functions; and
iii. Re-claiming materials to make new products.

The following text is understood and rewritten from the thesis paper "Circularity of existing aluminium unitised curtain wall facades", where the circular loop extension Koningskade 4 is explained, and how its implementation in the Natural Pavilion project (Figure 78), is a bio-based and demountable building. Once calculated (by author), out of the estimated total amount of glass used in the project (approximately 170000 kg), 12500 kg found new life in another application, an impressive equivalent of around 400 pieces. However, the glazing panels that were not suitable for reuse were responsibly recycled, due to their thickness and size. Any remaining float glass was properly recycled as well, and Saint-Gobain has confirmed that this float glass was fully circular. The Natural Pavilion's refreshed appearance at Floriade in Almere, Netherlands in 2022 was largely thanks to the 400 reused glazing pieces. As shown in Figure 79, in a unique approach to design, the window frames were created to fit the glass plane, rather than cutting glass to fit frames. These frames and glazing are 100% bio-based and circular, meaning they can be used again and again. The project was a collaboration between various companies, which contributed to its success. In addition to the glazing, parts of the facade were reused in 50 solar panels. Although the efficiency of these panels is not expected to be high, the energy generated is used for the installations and operation of the windows and lamellas. The Natural Pavilion was initially intended to be dismantled after the Floriade. However, it is now being used as an office, meeting, and congress location, with plans for its parts or the whole building to be repurposed in the same or a different location after dismantling (Teeuwen 2023, 72-81).

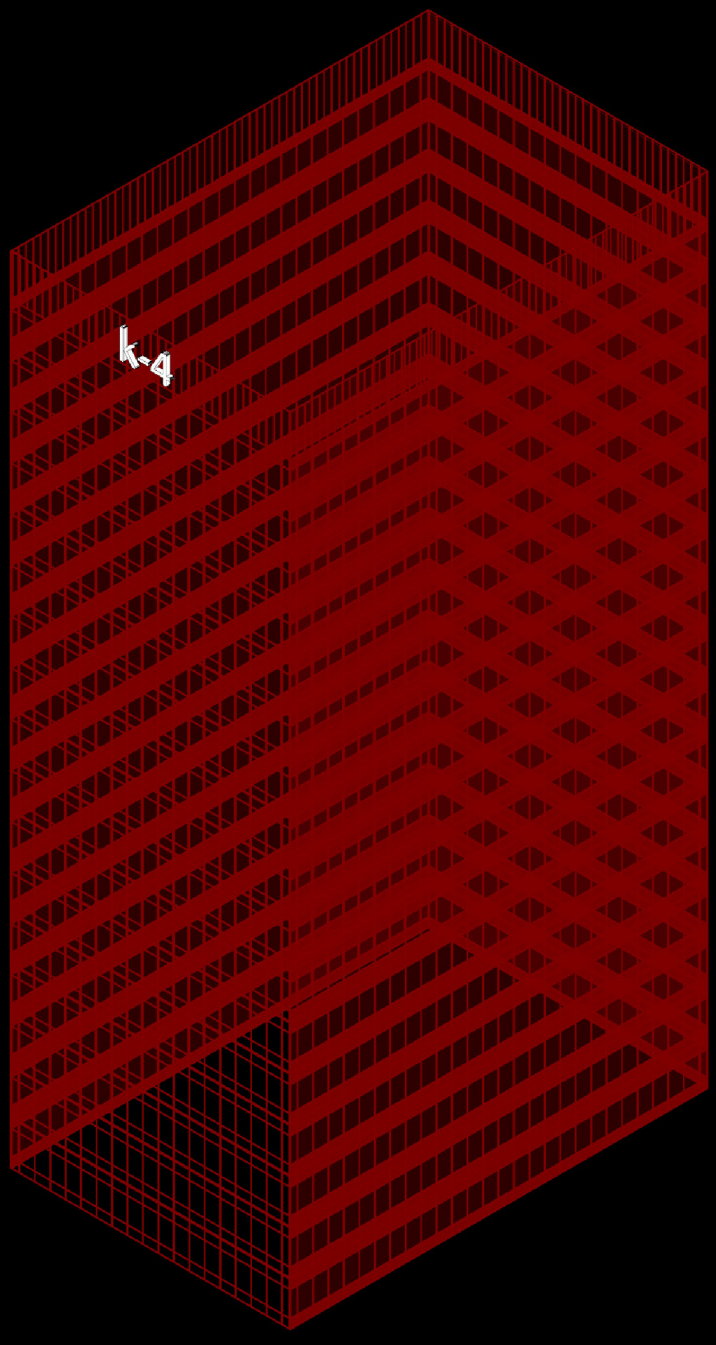


Figure 78. Front Elevation of the Natural Pavilion (Paula Pintos, 2022)



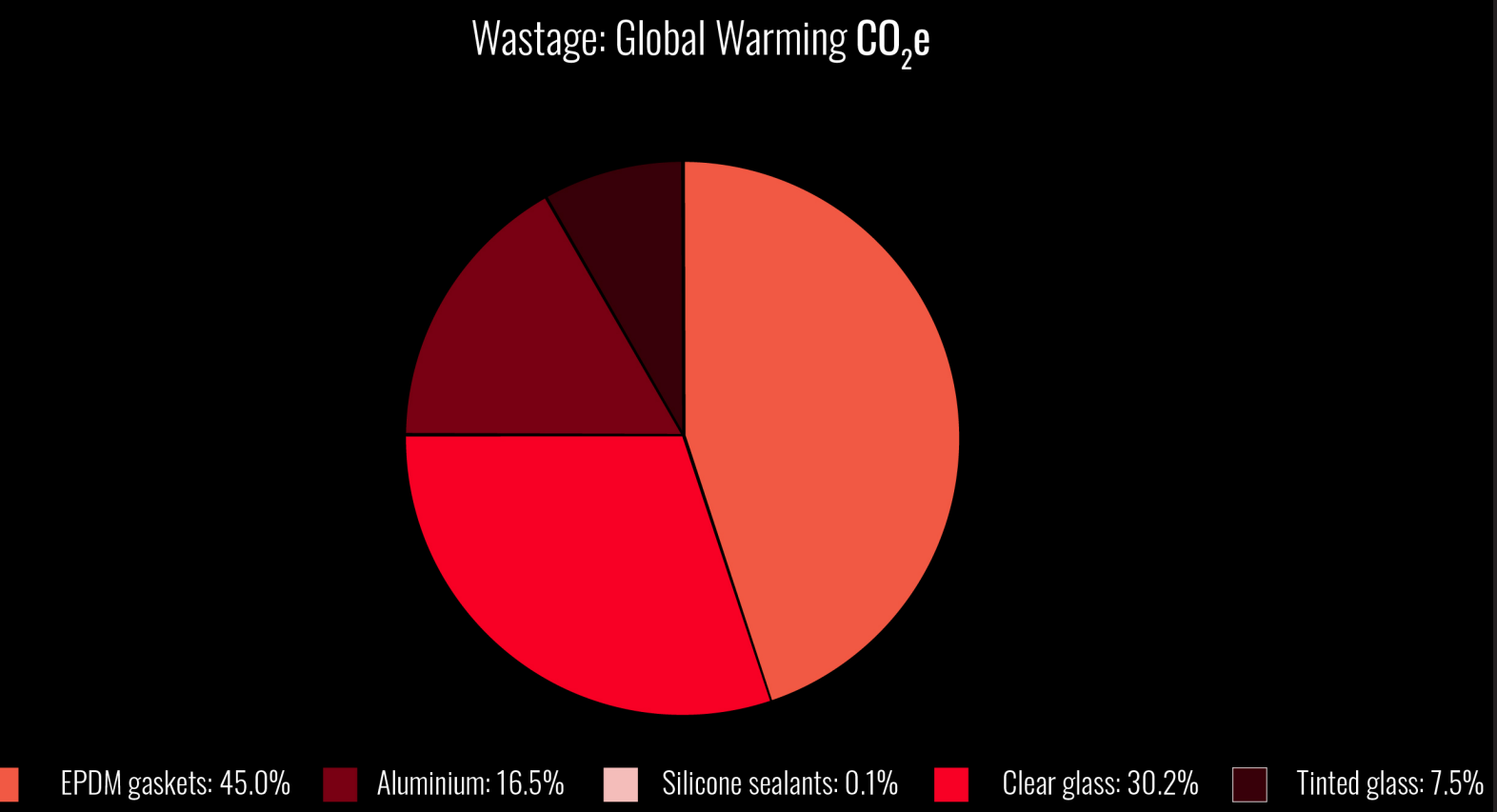
Figure 79. Reusing of glass panels (Paula Pintos, 2022)

As mentioned in the same thesis paper before, the renovation of Koningskade 4 incorporated circular practices that align with the three pillars of circularity: Reduce, Supply, and Manage(Illustration 41, 42, and 43). To minimize waste, the original frame was preserved, and energy efficiency was enhanced by upgrading the glass. Recycling was vital, as old glazing was repurposed as new float glass, and some float glass found new uses. Supply chain strategies involved the careful removal of original EPDM gaskets and sealant to extract the glazing and the introduction of new framing with EPDM gaskets. Management practices included finding new homes for old glazing, conducting extensive tests on the renovated facade, and maintaining a clear understanding of the materials' status throughout the process. These endeavours showcase a comprehensive circular approach and demonstrate how sustainability can be integrated into all aspects of construction projects.

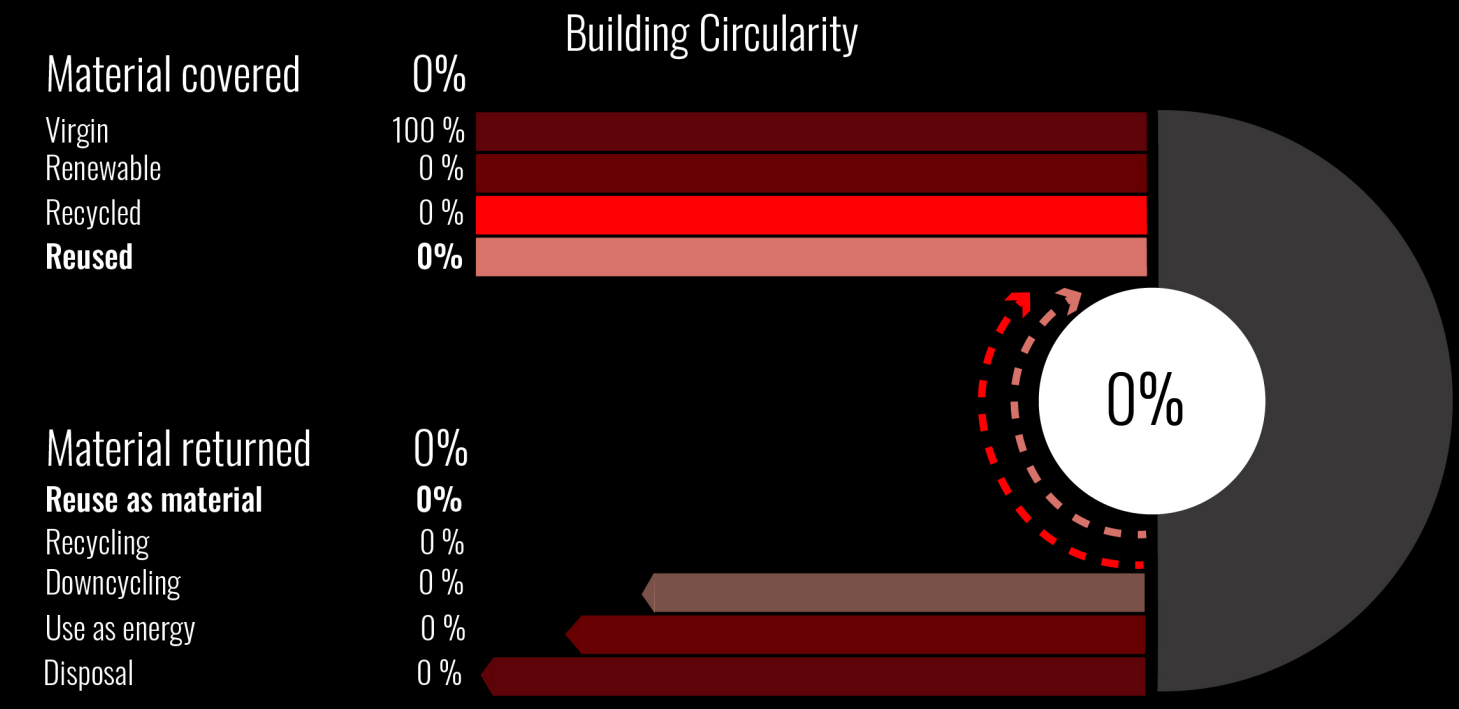


Total no. of Aluminium curtain wall units: **2300 units**

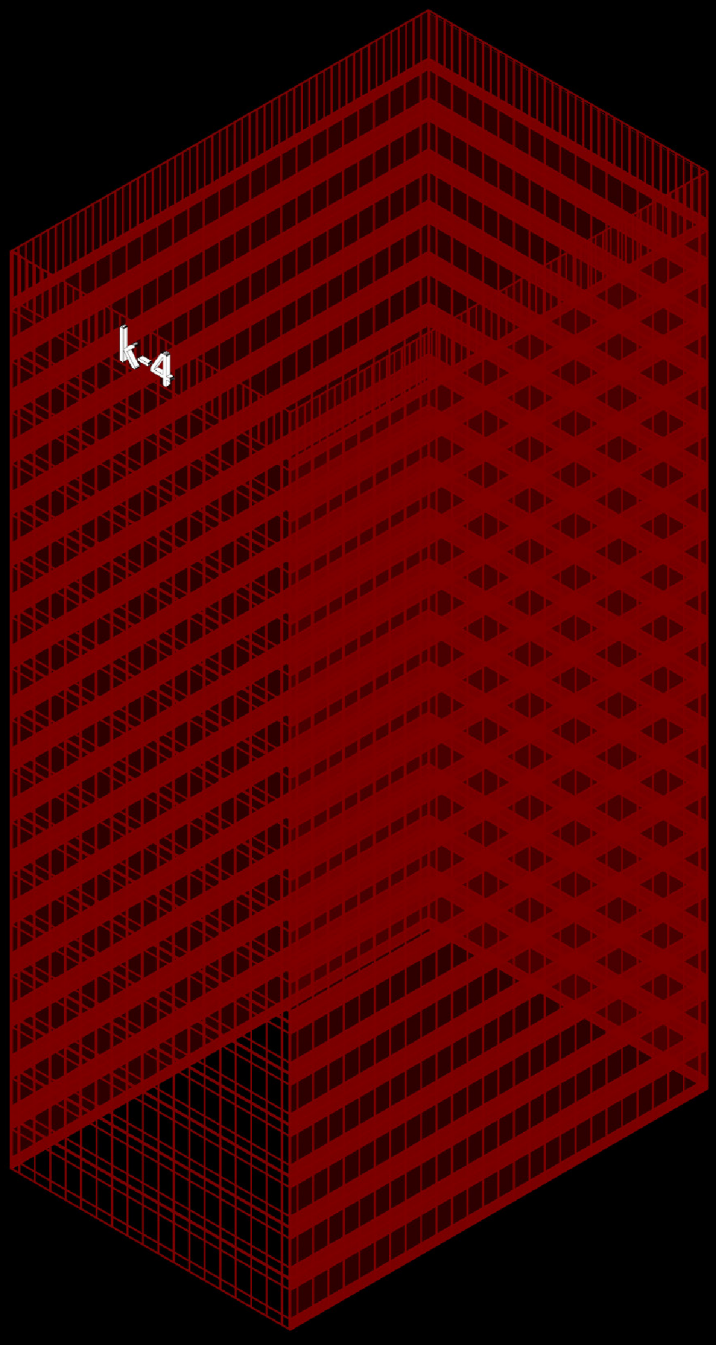
Illustration 46. Embodied emissions and Building Circul



Landfill: 1450 Tonnes CO_2e

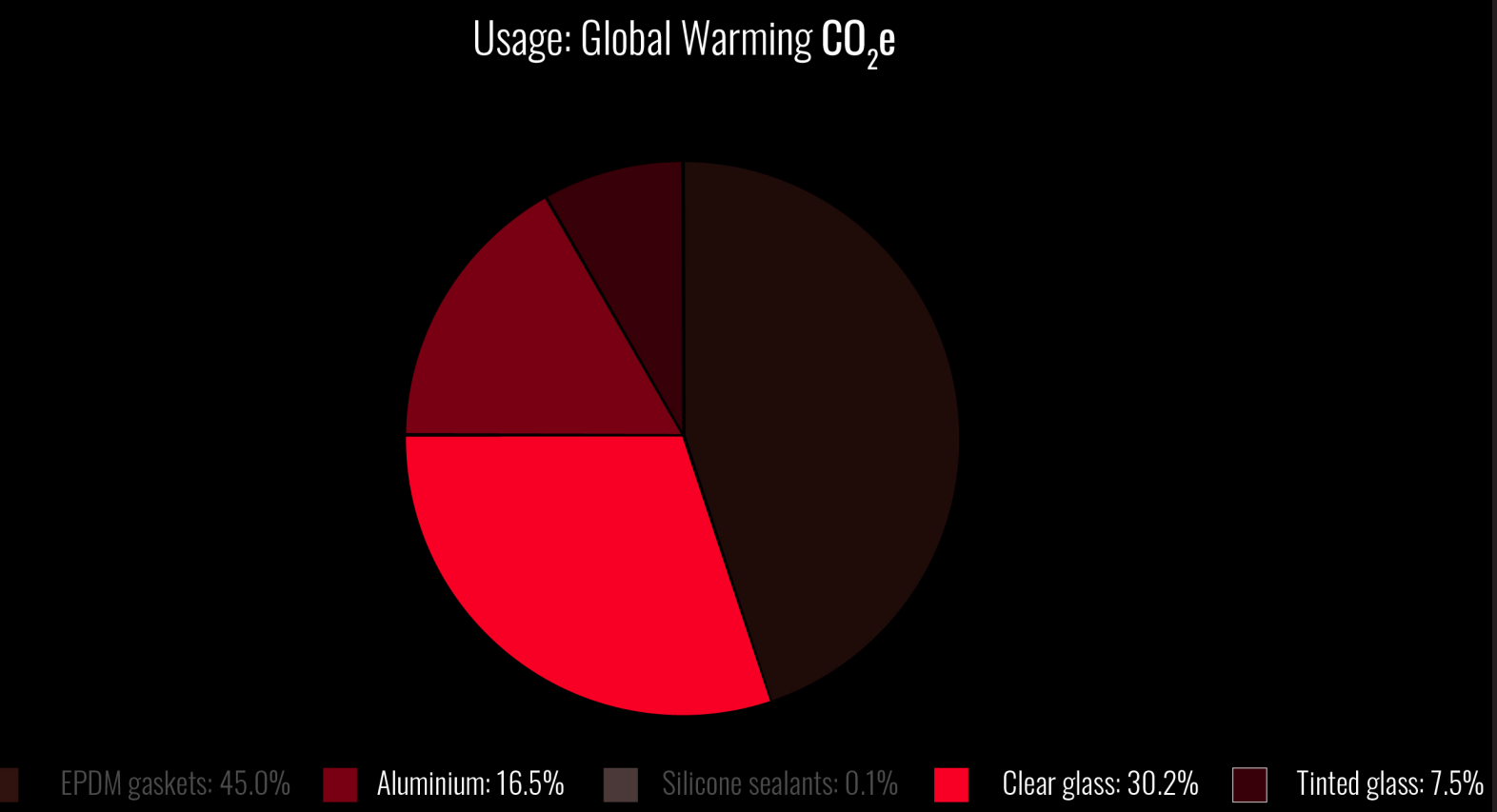


arity results with Non-Donor mentality (Created by Author, 2024)

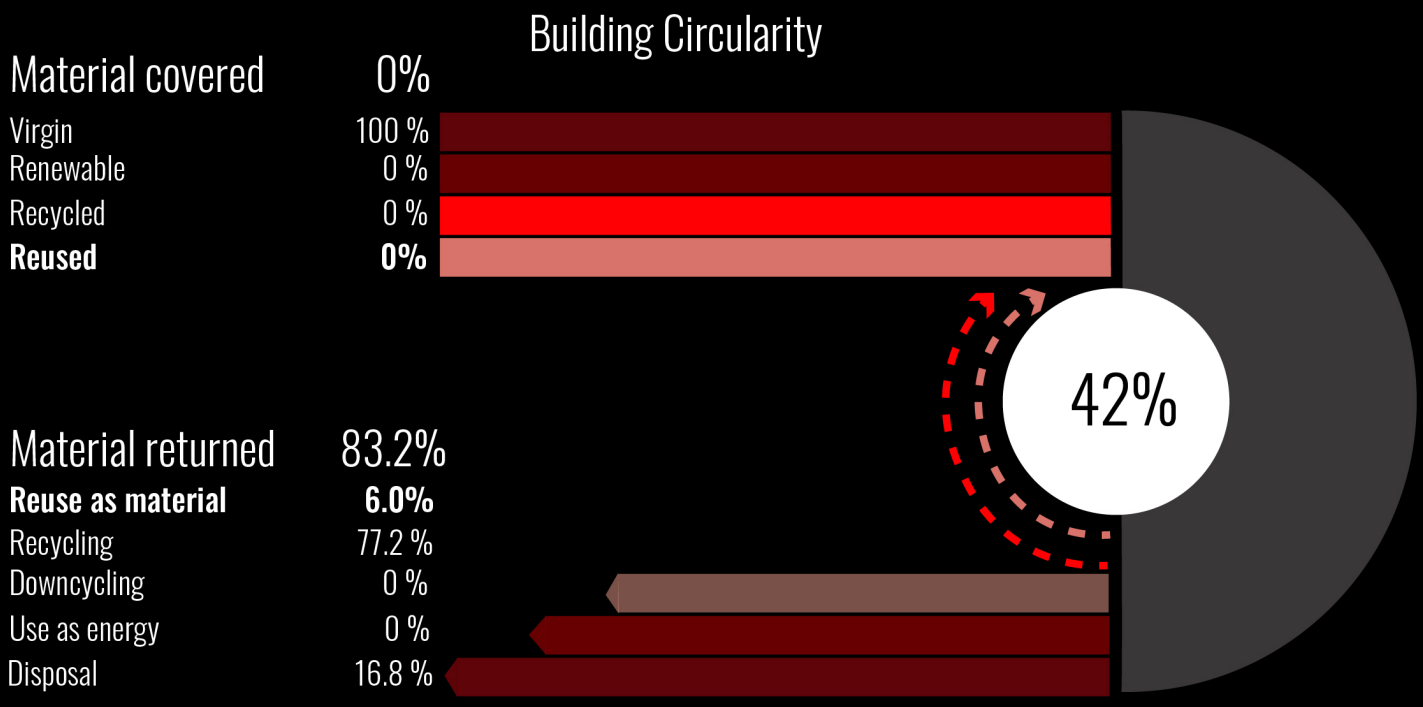


Total no. of Aluminium curtain wall units: **2300 units**

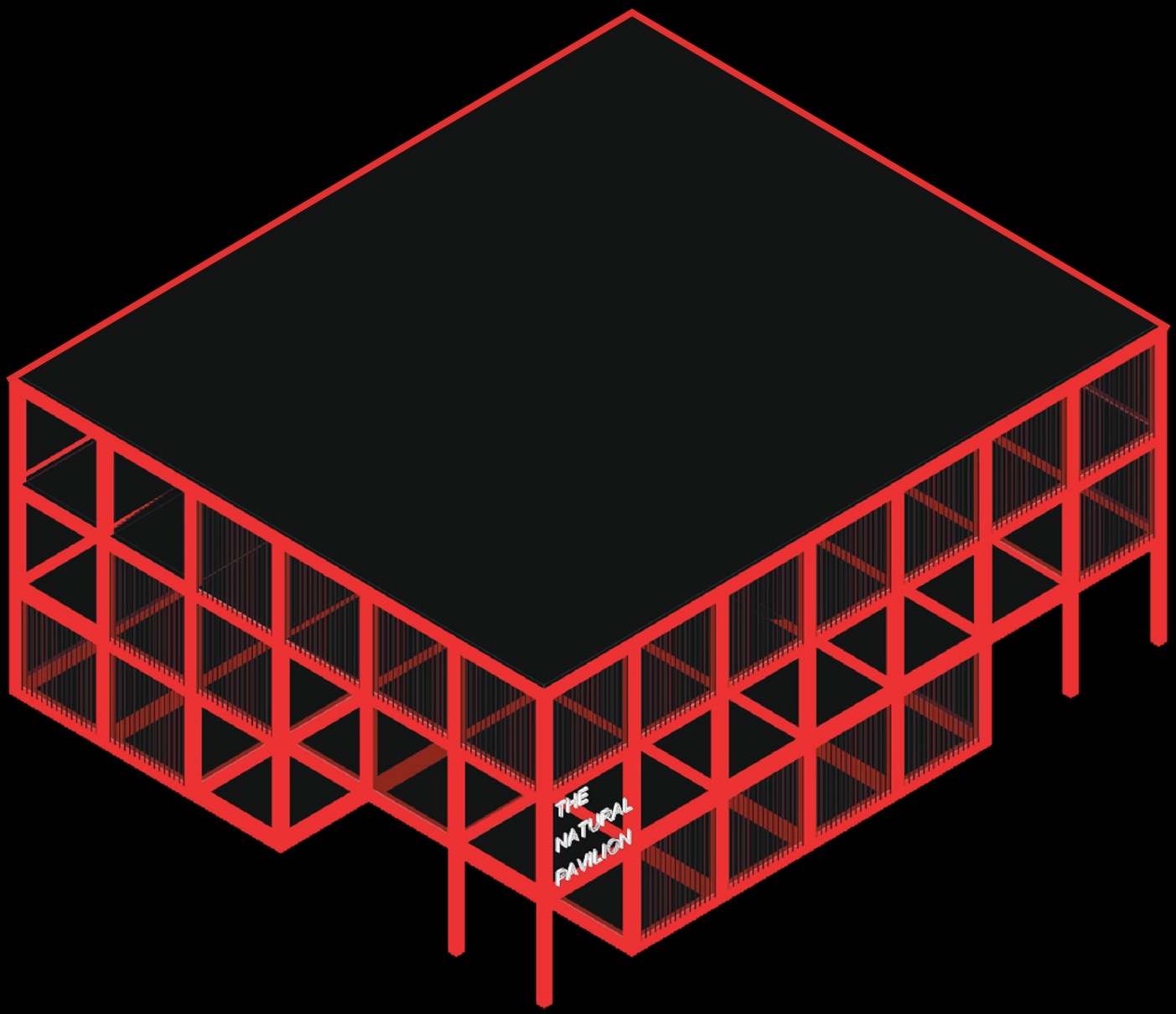
Illustration 47. Embodied emissions and Building C



Savings: 1450-796= 654 Tonnes CO_2e

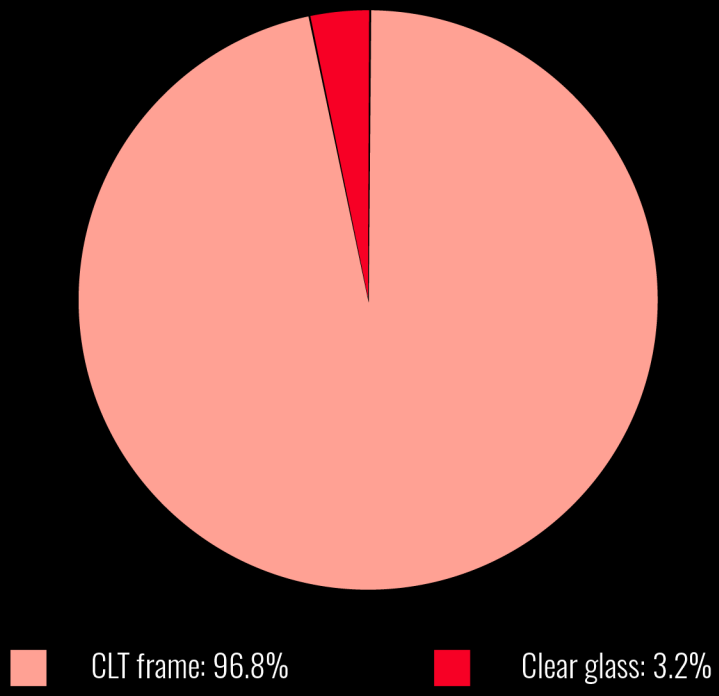


Circularity results with Donor mentality (Created by Author, 2024)

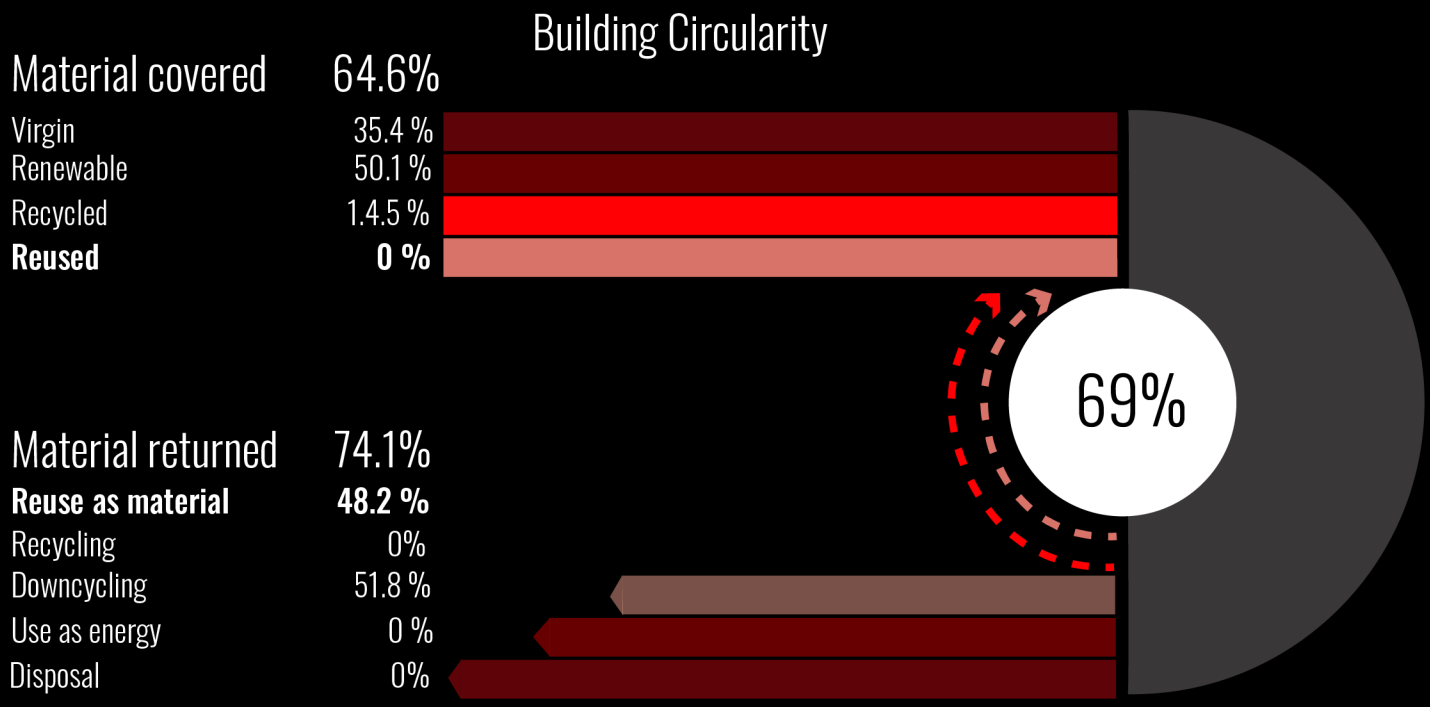


Total no. of Aluminium curtain wall units: **60 units**

Illustration 48. Embodied emissions and Building Cir



Target Savings: 14-0= 14 Tonnes CO_2e



rcularity results with Receiver mentality (Created by Author, 2024)

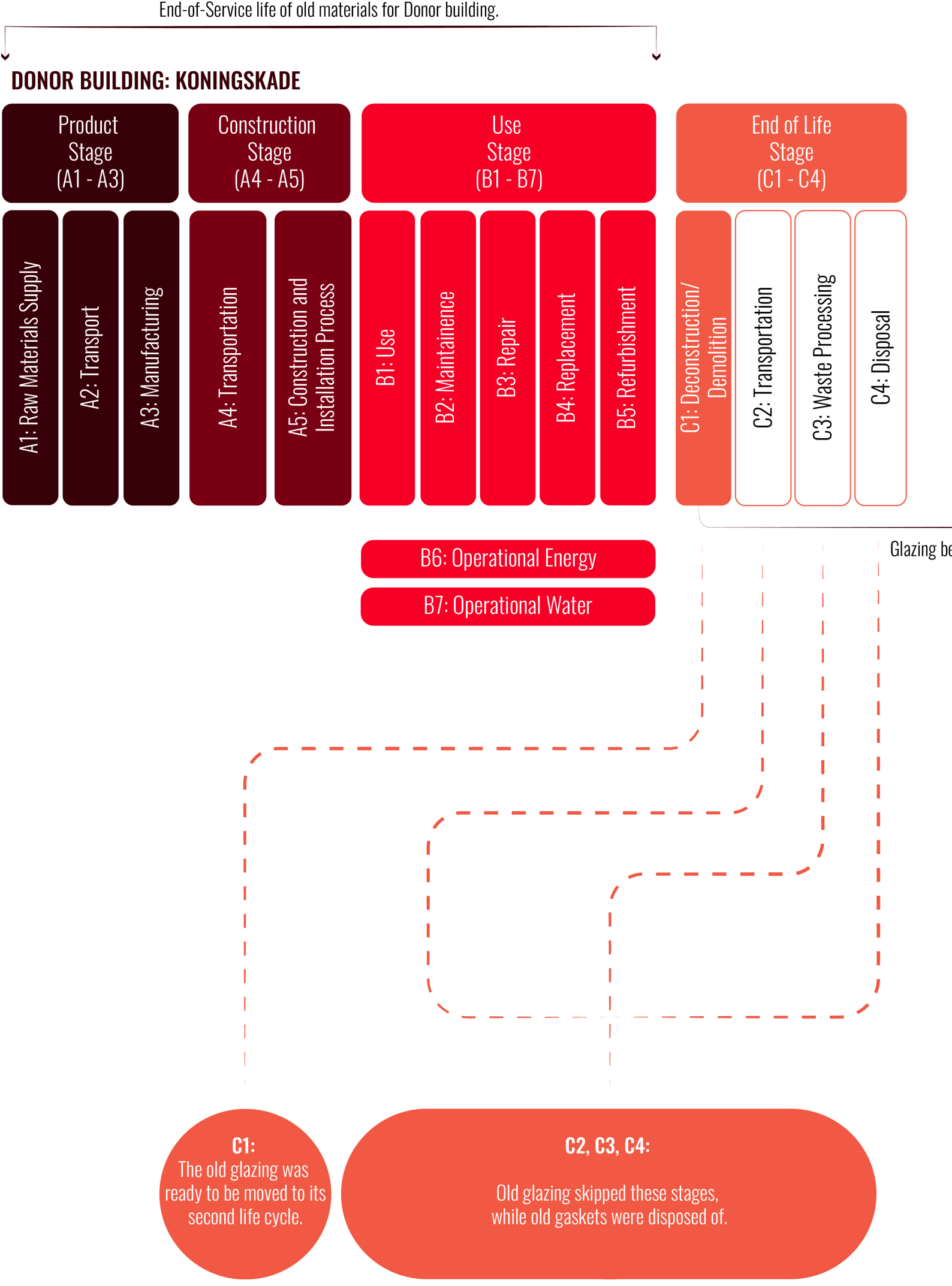
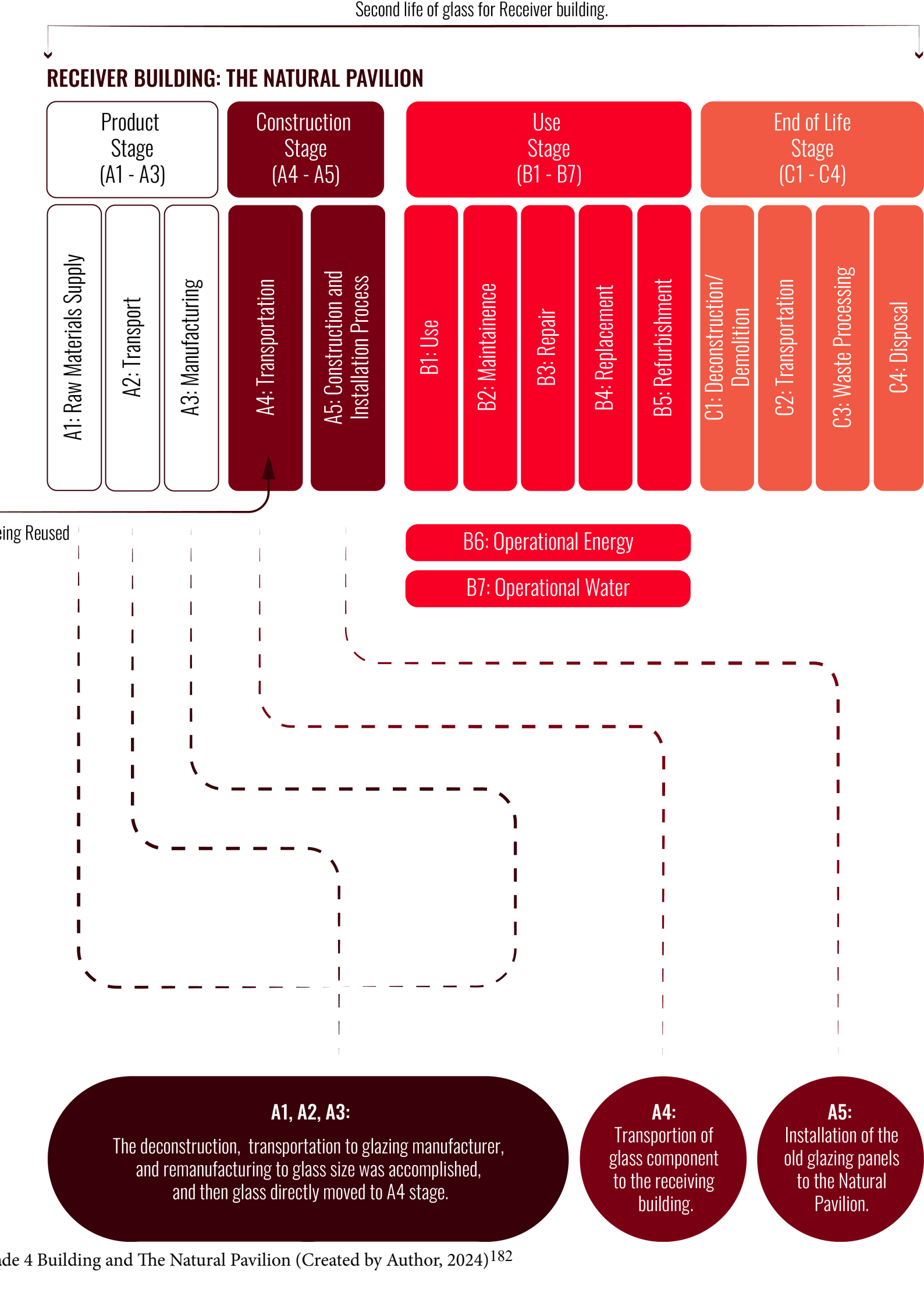


 Illustration 49. Life cycle stages regarding Koningska



ade 4 Building and The Natural Pavilion (Created by Author, 2024)[182]

Life Cycle Stages

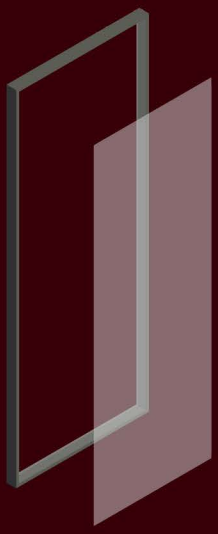
This project demonstrates a circular approach, as depicted in Illustration 46. It illustrates the various stages of the project's life cycle. According to the image, the Koningskade project (Donor) was in stage B4 when it became involved in the refurbishment or renewal stage. At this phase, a replacement of the old structural sealants, thick EPDM gaskets, and outdated float glass with new and improved materials, including glazed windows, new aluminium frames, and EPDM gaskets (A1-A5), was conducted. The removed gaskets reached their end-of-life (EOL) stage and were later transported (C2) for recycling or landfill. Figure 77 depicts a photo of the discarded gasket (C3 & C4).

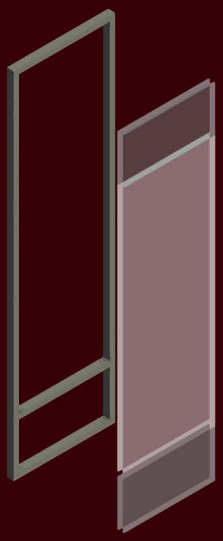
Similarly, the old glazing underwent a similar process as the gaskets, except for the portion reused in the Floriade project. This section was directly transported (A4) to the new project site, bypassing stages A1, A2, and A3. The circular process also involved the reuse of the glazing in the Natural Pavilion (Receiver), resulting in carbon savings by avoiding carbon in the product stage. The new 'bio-based' framing used in the project accounted for savings in stages A1, A2, A3, and A4.

6.3.4 Conclusion

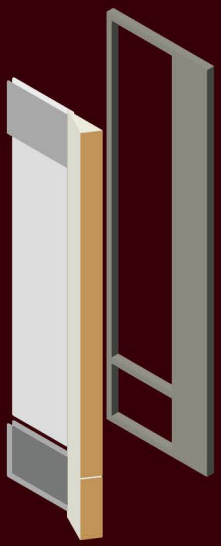
The Koninskade 4 project stands as a testament to the power of collaboration and innovation in promoting sustainability in construction. By replacing end-of-life components and embracing renewable materials, the project not only revitalised a historic building but also set a new standard for circularity in construction practices. This commitment to sustainability extended to The Natural Pavilion at Floriade, where reused and bio-based materials were utilized to create a truly innovative and environmentally friendly structure. The project exemplifies the potential for design for deconstruction practices to minimize waste and maximize resource efficiency. Through the concerted efforts of stakeholders and a consortium of companies, the project has paved the way for a more sustainable future in construction, demonstrating the tangible benefits of embracing circular principles.

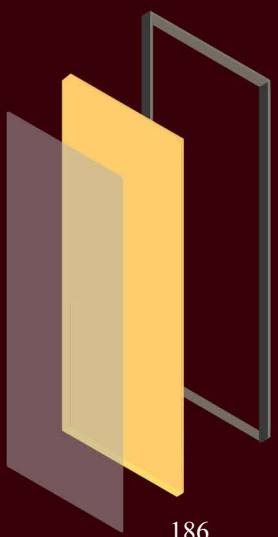
7. Design *for* Disassembly

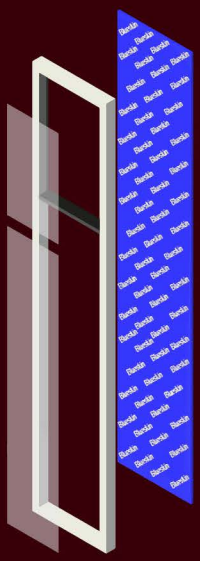












In previous sections, particularly in chapter 5, the concept of Design for Disassembly (DfD) was introduced. Despite its potential to significantly reduce waste and promote a circular economy in the construction industry, DfD remains largely overlooked after discussions with various stakeholders, contributing to the significant waste generated during demolition. However, by integrating disassembly considerations into the initial design phases, the life cycle of facade components can be extended, aligning with the circular economy principle of 'designing out waste'. In the Canadian context, the CSA Group's “Z782-06”: Guideline for Design for Disassembly and Adaptability in buildings provides a comprehensive framework for achieving this goal. It emphasizes key objectives such as waste reduction, resource conservation, and extended building lifespan through modular design, reversible connections, mindful material selection, and inherent flexibility. These principles offer a multitude of benefits, spanning environmental, economic, and social realms.

While the lack of quantifiable measures has hindered the widespread adoption of DfD, there is a growing belief among stakeholders that with appropriate legislative incentives and standardised guidelines, this practice can flourish. Implementing regulations that mandate minimum targets for reused or recycled products, coupled with tax breaks and incentives, could foster a paradigm shift towards sustainable construction practices. However, as discussed in Chapters 3 and 5, the prevalence of unitised curtain walls in commercial buildings, including healthcare facilities, presents significant performance challenges and limitations in reuse. Even in the best-case scenario, the envelope of the SickKids Patient Support Centre's 30-year-old unitised aluminium curtain walls will likely require remanufacturing or refurbishing for maximum circularity. Conversely, exploring alternative window wall components with strong circular economy potential for the next life cycle of the research site is a commendable approach. This aligns with broader sustainability goals and can yield substantial long-term benefits, such as the opportunities and advantages of Design for Disassembly methods for such assemblies and components. It's important to explore the potential for a broader impact on the facade industry and the contribution to a more circular economy.

7.1 A *Simple* Idea!

To fully understand the Design for Disassembly concept, it is vital to outline the various phases involved in the process. Firstly, about Illustration 47, consider the PSC Building as the donor building. Materials such as aluminium, glass, and steel are harvested from the building's old, unitised curtain walls and then remanufactured or recycled in the best condition according to their future requirements. After dismantling the building's envelope components, refurbishment activities can occur on-site or within a reasonable distance from the city of Toronto, possibly in a production facility. During this phase, various refurbishments may be necessary, and steps can be taken to minimise transportation to and from the facility. Ultimately, the refurbished panels can be reused for similar purposes in mid-rise healthcare or commercial buildings. Hydro CIRCAL serves as a prime example in this regard (Hydro n.d), as the company is involved in collecting aluminium scraps, waste, and consumer products from construction, demolition, and industrial sectors, sorting and recycling them, and reintroducing the aluminium extrusions into the construction market.



Illustration 50. Options available for Donor building to transfer materials for a second life.(Created by Author, 2024)

When considering the reuse of the unitised curtain wall components of the PSC Building, it's important to explore alternatives to simply disposing of the materials in landfills. Additionally, for future projects, it is beneficial to consider alternative commercial building envelope systems that are more adaptable for reuse and meet higher contemporary performance standards. This may involve improving the assembly/disassembly process and finding ways to meet current construction assembly goals and standards. For example, the glazing used in curtain walls can be downcycled for performance and aesthetic upgrades or repurposed for interior elements such as partition walls or furniture after approximately 30 years of use. Similarly, a window-wall component used in future envelopes can be dismantled, reused, and upcycled for other purposes.

It's important to note that if the principles of Design for Disassembly are diligently applied, a single type of wall from the PSC Building, such as the 'W5' (953 Aluminium Unitised curtain walls, measuring 4.5m x 1.2m), has the potential to yield over 1334 glass panels, considering a 30% waste due to non-standard deconstruction practices. Post-consumption, the glass panels can be reintegrated back into the SickKids Research Building, creating 1111 standard-sized partitions (3m x 2m), or a greater number of smaller partitions, 890 screens of an average size of 1.5m x 1m, or roughly 2000m2 of wall cladding (assuming an average wall height of 3.6m), with possible modifications or sub-division into smaller components, or a few larger art pieces in various spaces.

Expanding the potential impact, the repurposed panels could effectively serve approximately 66 to 133 Canadian homes, providing windows, doors (with an estimated 10-20 windows and doors per home), or 266 to 444 shower enclosures, with each home requiring 3 to 5 panels. This example highlights the significant difference the repurpose of building envelopes can make, rather than resorting to disposal. It also underscores the enormous potential when considering the reclamation and reuse of materials from 3599 other PSC wall assemblies, including aluminium and steel, for a wide range of secondary applications. Many categories depend on curtain walls for the relationship between donor and receiver buildings. These categories include lifespan, thermal, acoustic, structural, safety, and aesthetic requirements.

7.2 Good, but *Hard.*

The idea of circularity in construction, particularly the reusing of unitised curtain walls for the SickKids PSC Building (Figure 80), holds great promise for increased sustainability in the next three decades. However, achieving this vision may pose challenges in the Canadian context, making it a "Good, but Hard" endeavour. Specifically, when it comes to aluminium unitised curtain walls used in the building's envelope, obstacles such as disassembly complexities, material degradation, cost-effectiveness, and market demand could complicate this ambitious journey. Furthermore, logistical hurdles in storage, transportation, and inventory management could further complicate matters. Even the seemingly straightforward task of connecting and disconnecting curtain wall components may present obstacles. This section will explore these multifaceted challenges, emphasizing the necessity for innovative solutions, collaborative efforts, supportive policies to make circularity in facade components, and extreme difficulties in reusing the unitised curtain walls.

Challenges in Standardization

The existing Canadian certification and labelling system for reused building materials does not adequately account for Aluminium, Glass, and Steel, posing difficulties in assessing the quality and performance of unitised curtain walls from PSC's envelope. This lack of standardisation prevents implementing a systematic reuse strategy, leading to warranty concerns for facade elements during and after construction. Issues around liability and performance warranties have deter building owners and designers from utilizing reused components.

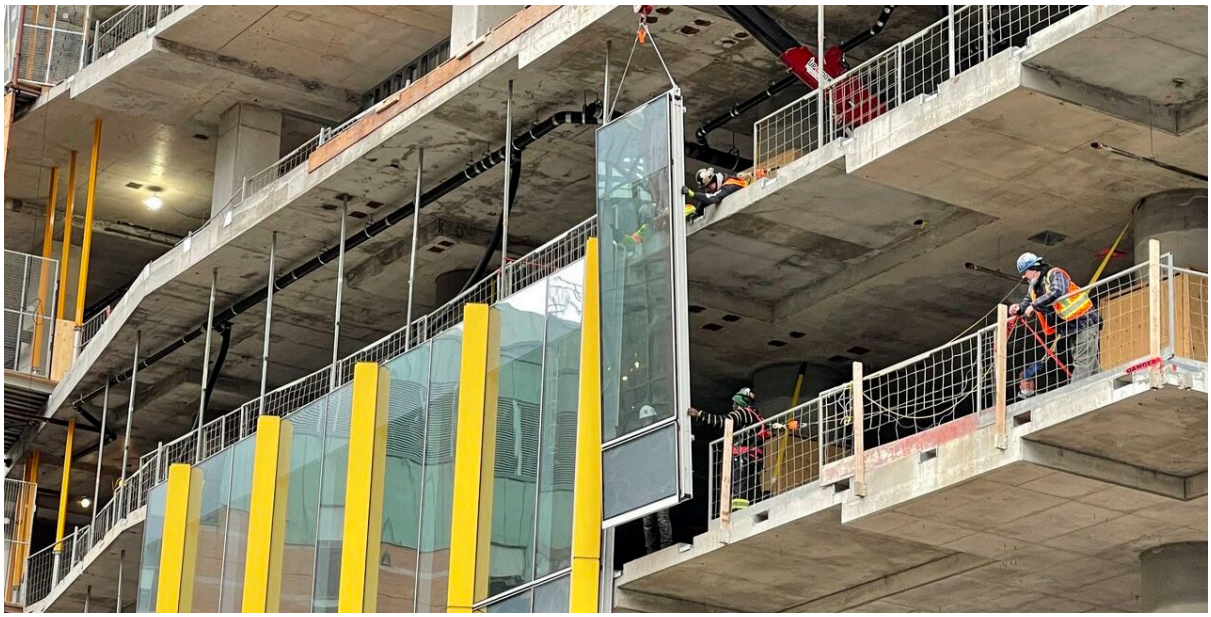


Figure 80. Do we think about disassembly when assembling a curtain wall? (Urban Toronto, 2022)

Economic Hurdles

Despite the increasing demand for reused curtain wall components, the salvaged market for aluminium and glass, such as through companies like AL13 Recycling and eCullet, is still evolving and faces challenges in fully capturing the potential of these materials. While aluminium from curtain walls is theoretically 100% recyclable, the reality is that only 75-85% recovered(CDRA n.d)due to contamination and separation challenges. The market for recycled glass(OWM 2019), specifically from curtain walls (also known as cullet), is constrained by contamination from sealants and coatings, as well as transportation costs. The facade industry faces significant challenges related to sealants and coatings, including toxicity, limited recycling options, and potential environmental harm throughout their lifecycle.

It highlights the need for continued innovation and investment in recycling technologies and infrastructure to fully realise the potential of these valuable resources and minimize waste in the facade industry. Many stakeholders in Canada's construction industry lack awareness of the potential benefits and challenges of circular strategies for curtain walls, perpetuating the belief that second-hand products are inherently less valuable. Also, the costs associated with deconstruction, transportation, storage, refurbishment, and reinstallation of the wall assemblies taken out from the PSC Building can be significant, sometimes surpassing the cost of new materials. The costs of storage and transportation increased further. It's unclear who will bear these costs. As a result, there is a limitation in the old, unitised curtain walls for reusability and a chance to look for better options like window-wall components and stick curtain walls depicting better performances, disassembly possibilities, and higher circular practice for the coming future.

Logistical Challenges

When designing the disassembly for future window wall components or stick curtain walls for potential reuse in the future, it is crucial to carefully manage the handling processes, which are more complex than simply discarding or recycling materials. The primary logistical challenges in this phase involve storage, transportation, and inventory management. The storage and transportation of components of old large unitised curtain walls, such as those found in the PSC Building, add challenges in today's context. Limited space in Toronto worsens the logistical complexities, pushing up costs and demanding complex coordination efforts. Repurposing existing elements further complicates the process, putting

extensive storage facilities during refurbishment or waiting for a proper recipient project. The volume of materials involved makes exact inventory management systems and processes a task with difficulties. Moreover, ensuring the safe dismantling, transportation, and handling of recovered curtain wall components requires rigid safety protocols and specialised expertise, adding significant complexity to an already demanding work.

Connection Challenges

The reuse of unitised curtain walls can be hindered by the complexity of assembly and joining techniques, particularly concerning bolts, extrusions, screws, adhesives, and sealants. These components often present challenges for disassembly and reuse, limiting the potential for circularity. For example:

Bolts: Pricier bolts may be durable during the first life cycle of curtain walls but cannot be reused more than once due to complications during the removal phase.

Nails: While nails enable faster construction, they are inexpensive and hard to remove, often causing damage during extraction.

Extrusions and Screws: The reusability of curtain wall frame extrusions with tapped screw channels poses a situation in the quest for circularity. These channels, planned for self-tapping screws, are often essential to the extrusion's structure, making their reuse after disassembly complex. The frequent insertion and removal of screws can lead to wear and tear, potentially compromising the integrity of the threads and the extrusion itself. While some manufacturers are exploring creative solutions such as removable or replaceable inserts within the channels, the widespread reuse of extrusions with tapped screw channels remains a technological challenge in the industry.

Adhesives and Sealants: Despite coming in a range of strengths, their potential for recycling and reuse is limited. They are sometimes impossible to separate, and techniques like gluing and welding make non-destructive disassembly unfeasible. Due to their shorter lifespan compared to other components, eventual replacement will be necessary. Sealants are difficult to disconnect from their components and are often cut out.

In conclusion, the complexity of assembly and joining techniques slows down the design for disassembly (DfD) process, leading to high labour costs for the construction and demolition of buildings. These challenges highlight the difficulties associated with reusing unitised curtain walls, suggesting that alternative facade systems, such as window wall components or stick curtain walls, may offer more promising opportunities for circularity. These systems often have simpler assembly and disassembly processes, making them more conducive to reuse and recycling. Additionally, they may have improved performance characteristics and be better suited to modern construction standards. While these alternatives may require careful consideration and evaluation to ensure their suitability for specific projects, they present a viable path toward achieving a more circular construction industry.

7.3 The *Action* Plan

The Action Plan for an envelope such as Aluminium unitised curtain walls aims to address possible challenges that may appear after 30 years or at the end of its first lifecycle (see Chapter 3.2.2) in healthcare infrastructures in Toronto, like the Patient Support Centre. The adapted Action Plan (Teeuwen 2023, 72-81) abstracts regenerative possibilities through strategic possibilities for the building envelope when upgrades to components and materials are needed. This method towards a more circular approach is in four levels: Refuse, Panel-based, Component-based, and End-of-life (Table 12). As shown in Illustration 48, the eight strategies are also aligned with case studies in Chapter 6, encompass:

Refuse/Prevention level	Panel-based level	Component-based level	End-of-life level
Strategy 1: In-place upgrade	Strategy 2: Panel Reuse Strategy 3: Panel Refurbishment Strategy 4: Panel Re-manufacturing	Strategy 5: Component Reuse Strategy 6: Component Refurbishment	Strategy 7: Recycling Strategy 8: Waste

Table 12. Eight strategies for the Patient Support Centre(Created by Author, 2024)

In Chapter 2, the Forensic Analysis of the SickKids' Patient Support Centre observed that wall assemblies from W2-W7 share similar features with unitised curtain walls commonly found in the Canadian facade industry. Due to the absence of noteworthy differences in these typologies, the same wall assembly, 'W5', will be utilised. As in Illustration 49, with 953 W5 assemblies sharing basic construction principles and materials (aluminium, glass, and unitised curtain wall systems) with the remaining 3,599 wall assemblies, it is reasonable to assume that solutions developed for the W5 assemblies could potentially be applied to the other types as well. While transformations may be necessary to account for variations in size and design, the basic principles behind strategies like energy efficiency improvements or component reuse will remain relevant across the different wall assemblies.

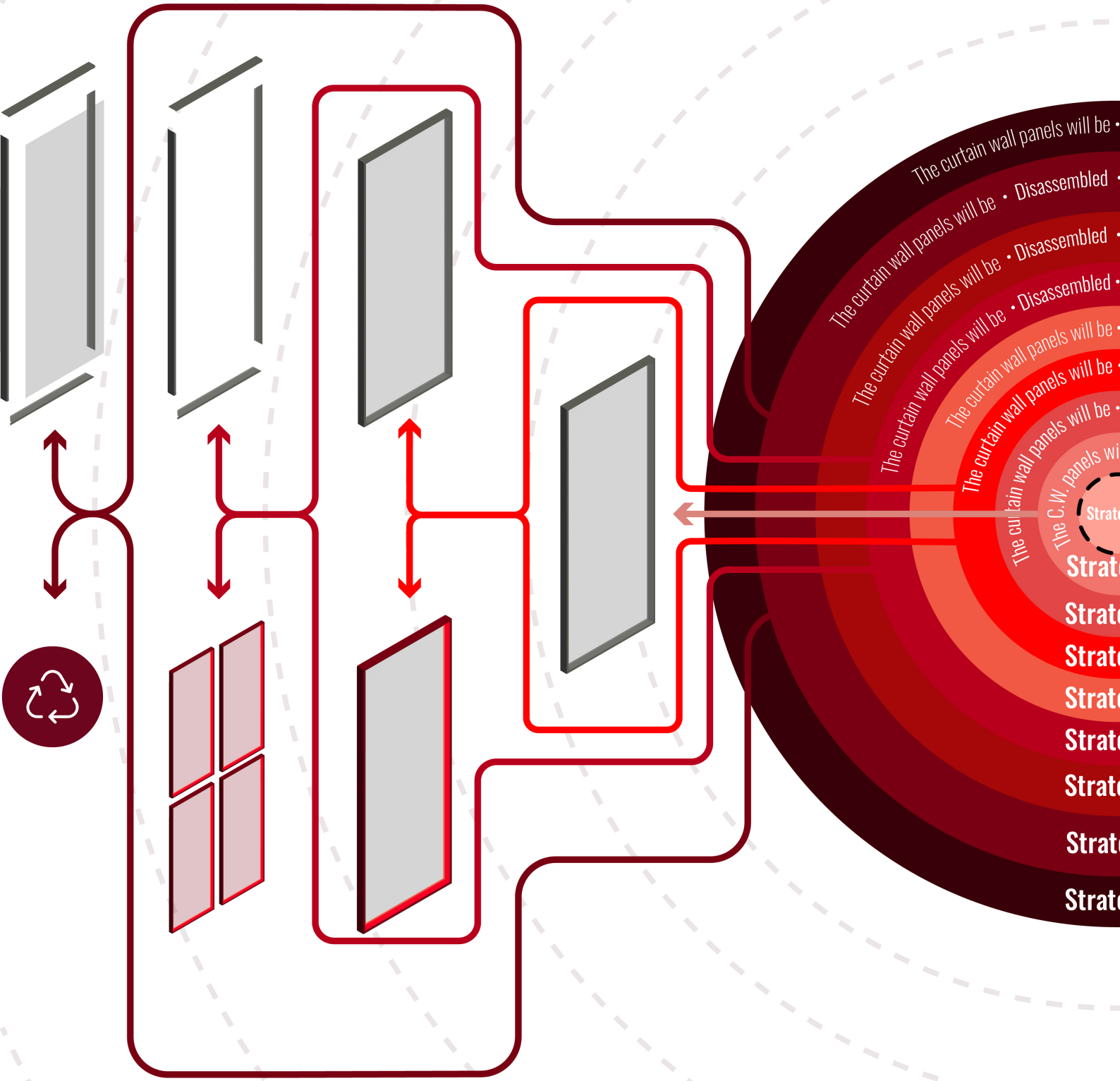
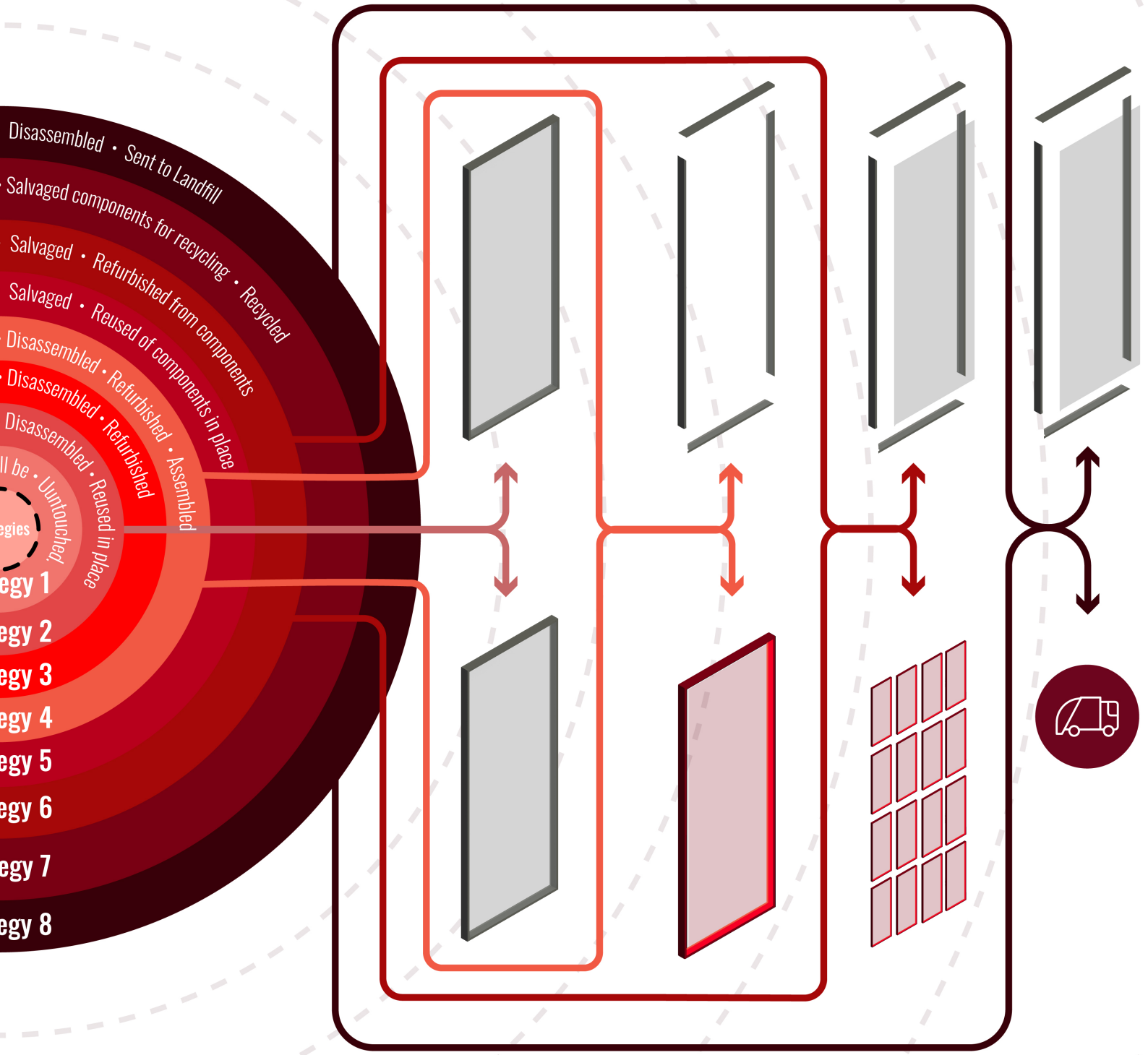


Illustration 51. Visual representation of eight strategies o



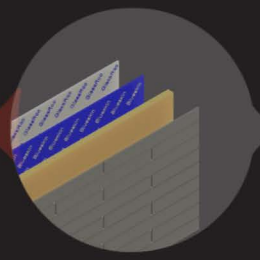
n PSC Building's curtain walls (Created by Author, 2024)

W1

Aluminium panels

2468

+



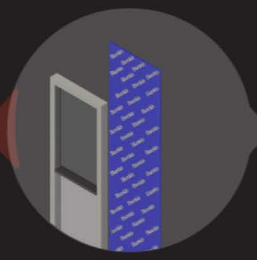


W2

Alu. Curtain wall 1

276

+



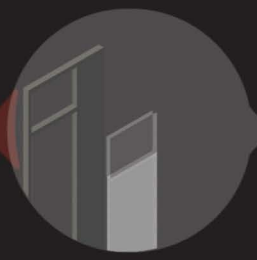


W3

Alu. Curtain wall 2

100

+



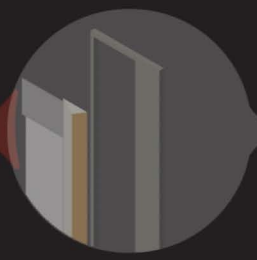


W4

Alu. Curtain wall 3

495

+

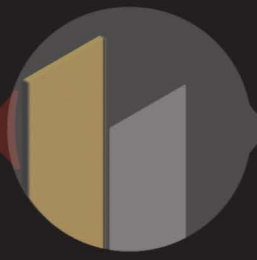




W6

Alu. Curtain wall 5

260





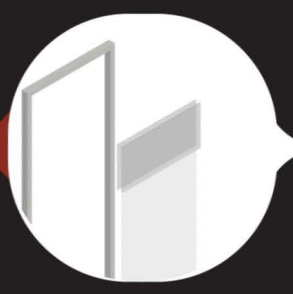
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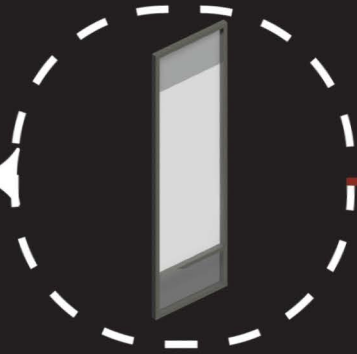
have similar construction techniques as ‘W5

W5

Alu. Curtain wall 4

953





953

panels of ‘W5’ were considered for DfD principle.

7.3.1 Refuse Level

As summarised in the 10R Framework by Metabolic (featured in Chapter 5's Value Hill), the "Refuse" or ‘Prevention’ level represents the initial phase in the hierarchy of circular economy strategies. At this level, the focus is on minimising waste generation from unitised curtain walls and similar components by rethinking consumption patterns and their design. This strategy involves critically evaluating the necessity of products and services related to curtain walls, advocating for a transition to sustainable alternatives, and designing them with durability, repairability, and recyclability in mind. The primary goal of the "Refuse" level is to minimise the inflow of waste into the system, thereby reducing the environmental and resource limitations associated with waste management and disposal. However, the "Refuse" level may not be the most effective strategy for unitised curtain walls due to the challenges. These challenges include the complex construction and limited flexibility of unitised curtain walls, which can hinder their disassembly and reuse. Alternative options to consider include window wall components, which are generally more flexible in design and can be constructed with a greater focus on deconstruction. This can facilitate their reuse or recycling, contributing to a more circular economy approach.

7.3.1.1 Strategy 1: *In-place* upgrade

The objective is to effectively remove curtain wall W5 while keeping it intact, making the most of the product and minimizing disruptions to interior spaces. This can be accomplished through careful planning and detailed implementation, ensuring that the removal process is conducted in a deliberate and methodical manner (as demonstrated in the BMO tower). Techniques such as temporary weatherproofing, protective barriers, and phased removal can be employed to maintain the building envelope's integrity and protect the interior from the elements during the upgrade (B2-B3 stage). Additionally, coordinating the work schedule with building occupants can help minimize disruptions to their daily activities. While in-place upgrades can be a viable option for certain scenarios, they may not always be suitable for unitised curtain walls. The complex construction and limited flexibility of these systems can make it difficult to remove them without causing damage or disrupting the building's structural integrity. Alternative strategies, such as panel-based approaches, may be more effective for achieving circularity in curtain wall systems.

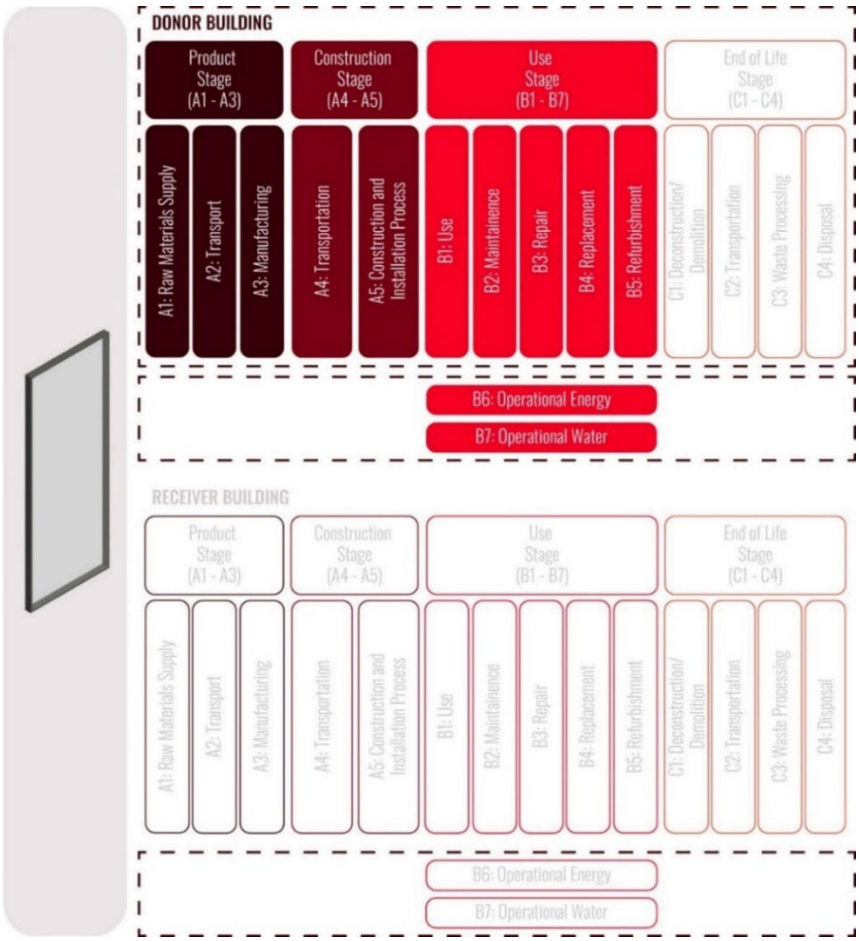


Illustration 53. Life cycle stages involved in a potential "In-place upgrade" (Created by Author, 2024)

7.3.2 Panel-based Level

In panel-based systems, unitised curtain wall elements are designed for easy installation and maximum material reuse. However, due to their fixed dimensions and configurations, challenges related to performance, appearance, and size constraints can arise, making replacement more complex. Despite these limitations, these strategies offer advantages over material disposal, such as resource conservation and waste reduction. For example, in a building like the PSC (used here as an illustrative example), unitised panels could be disassembled and reused in a new location with modifications, offering a downcycled but sustainable option. Also, new panel-based systems (Window walls) may be more amenable to circularity strategies with their modular design can facilitate easier disassembly and reuse, reducing the need for complete replacement.

7.3.2.1 Strategy 2: Panel *Reuse*

Reusing W5 curtain wall panels without intervention is often ineffective due to the challenges it presents that have reached the end of their service life or damaged without some form of intervention. As shown in Illustration 51, disassembling the W5 unitised curtain wall panel may not be feasible. However, if it were a window wall component with better Design for Disassembly (DfD) techniques, it would have been easier to disassemble it from the donor building (C1), transport it (C2), and reintegrate it into the receiver building (A4-A5). Nevertheless, these activities add costs related to labor, equipment, and transportation, which can be offset by avoiding expenses associated with raw material extraction (A1), processing (A2), and new manufacturing (A3). Additionally, reusing window walls over the W5 panel can lower disposal costs (C4) by diverting waste from landfills. The overall cost-effectiveness depends on various factors such as transportation distances and the condition of the reused panel. However, the potential for substantial savings in material and production costs makes this approach a financially viable option for window walls over curtain wall reuse. Alternative strategies, such as panel

refurbishment or remanufacturing, may be more effective in achieving circularity for unitised curtain walls.

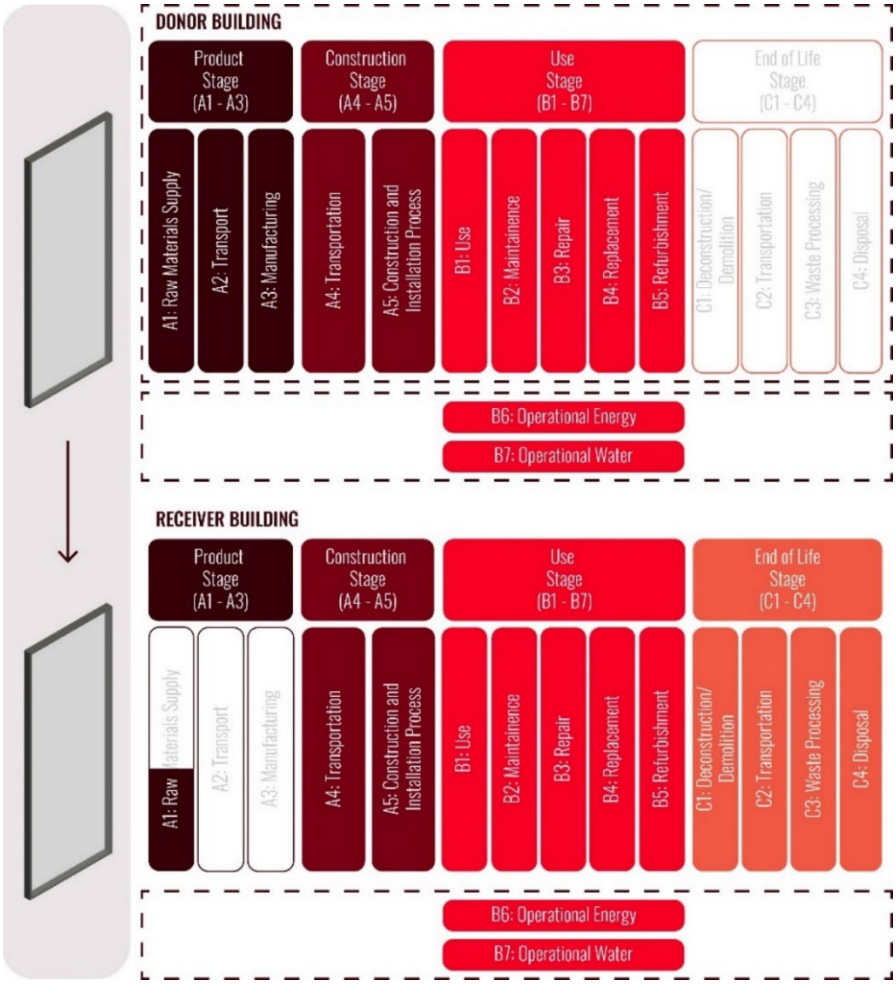


Illustration 54. Life cycle stages involved in a potential "Panel Refurbishment" (Author, 2024)

7.3.2.2 Strategy 3: Panel *Refurbishment*

When considering refurbishing the W5 curtain wall panels, it is important to note that disassembly might not be feasible due to complex construction or the limitations of DfD practices. However, this strategy can be easily applied to multi-wall components such as window walls, which offer more flexibility. Although this approach may not significantly alter the panel's appearance, it allows for specific upgrades. Improvements to the insulative properties of the IGU of window walls can be achieved by replacing the gaskets and spacers and further enhanced by adding gas filling or an extra pane. Another option is to clean and polish the glazing to restore its appearance, although this may slightly affect glass strength. While panel refurbishment may not always be feasible or cost-effective for unitised curtain walls due to their complexity and the potential for damage during refurbishment, window wall assemblies can be dismantled easily from the donor building and transported to the nearest production facility for refurbishment in Toronto. Once restored and updated, the assemblies can be constructed onto the receiver building irrespective of the location. It is essential to note that the restoration and update process of the older wall assembly may generate a higher carbon footprint than simply reusing the components as is. This is due to the energy and resources required for refurbishment, which can be minimized by prioritizing local production facilities and optimizing transportation routes. In some cases, alternative strategies, such as panel remanufacturing, may be more suitable for achieving circularity.

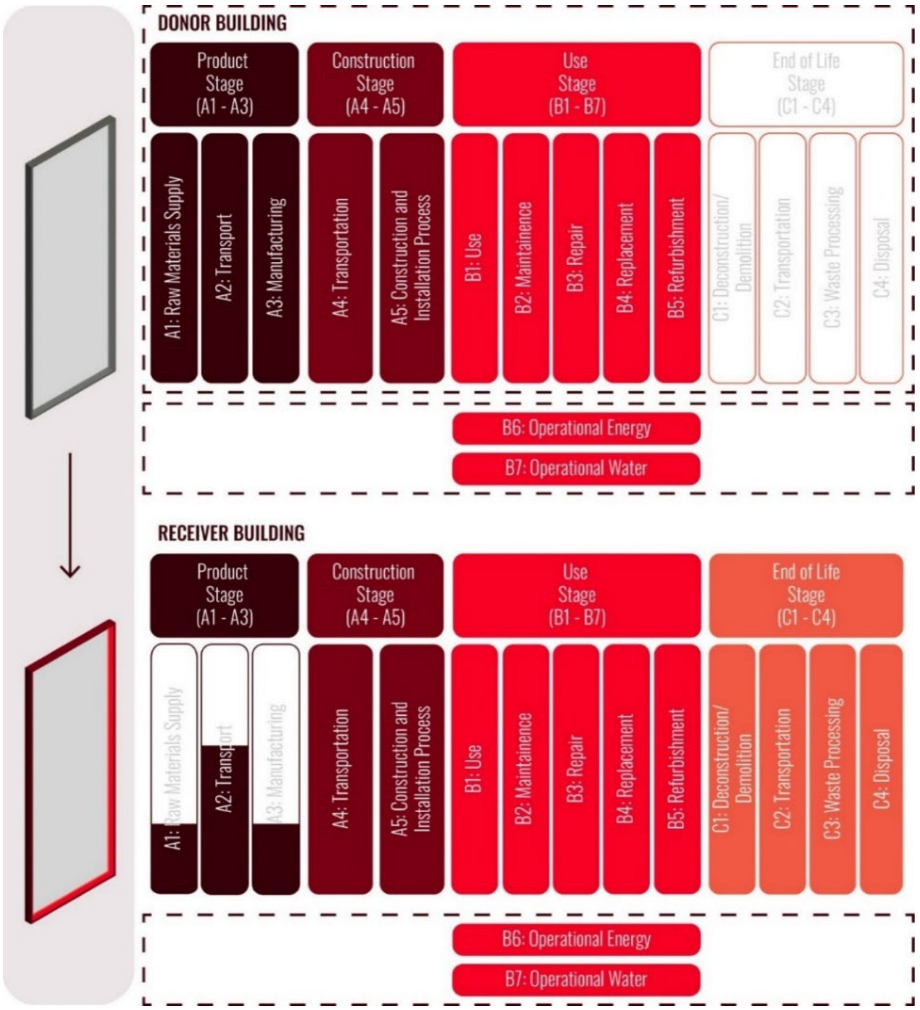


Illustration 55. Life cycle stages involved in a potential "Panel Refurbishment" (Author, 2024)

7.3.2.3 Strategy 4: Panel *Re-manufacturing*

This approach(Illustration 53), commonly used in today's construction industry, involves the components of wall assembly W5 and reusing them in new curtain walls or similar components through remanufacturing. During disassembly (C1), specific components like clear glazing or aluminium extrusions in framing(W5) will be separated. While this approach extends the lifespan of building components and reduces waste in the construction sector, the remanufacturing process requires additional effort and resources, potentially increasing the carbon footprint due to deconstruction, transportation (C2), and remanufacturing (A3) activities, such as resizing aluminium extrusions, replacing sealants, and filling holes with aluminium paste. However, the potential benefits of reduced raw material extraction (A1), transportation (A2), and waste diversion can offset these costs and contribute to a more sustainable construction practice, making it a valuable strategy despite the compromises. Replacing the sealant will present challenges as it must be cut out or removed from the attached components. Additionally, resizing the aluminium increases its application, and insulation inside the framing enhances thermal properties. Filling holes within the framing with aluminium paste is possible, but screw ducts may be damaged during complete disassembly. Despite these considerations, this strategy offers a valuable way to extend the lifespan of building components and reduce waste in the construction sector.

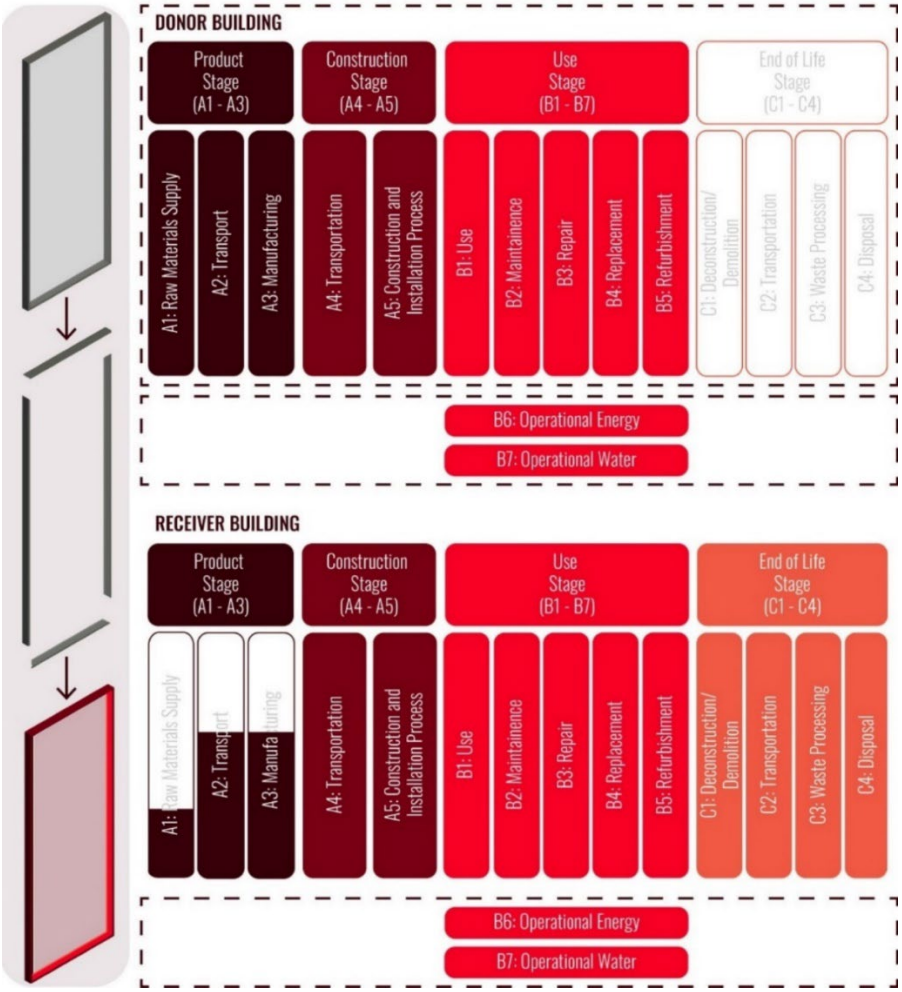


Illustration 5. Life cycle stages involved in "Panel Re-manufacturing"(Author 2024)

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7.3.3 Component-based Level

In component-based construction, the unitised curtain wall W5 elements will offer the potential for enhanced performance and aesthetic improvements, including the flexibility for large-scale replacements and size adjustments. However, this adaptability in the PSC Building will come with trade-offs. As shown in Table 13, these trade-offs of component-based reuse could be understood by an example of W5 curtain wall assembly of PSC building of dimension 4Mx1.5m.

Trade-off 1: Fit vs Redesign	Trade-off 2: Resource Savings vs. Added inputs	Trade-off 3: Customisation vs. Standardisation
The new building features a window opening that measures 3m x 2m. While it is possible to adjust your current W5 panels to fit this opening,	Reusing the W5 unit helps save the resources needed to manufacture a new one from scratch. However, there are some considerations to consider:	With W5, a restriction to a specific size and configuration limits the design options for the new building's facade, so options to consider:

doing so comes with the following considerations: - Specialized Tools: Cutting the glass requires professional equipment and expertise. - Material Waste: Trimming the aluminum frame results in scrap metal, and the excess glass is likely to be unusable. Time Investment: This modification process is labor-intensive and will extend the project timeline.	- New Materials: Requirement of new gaskets, sealants, or even smaller infill panels to fill gaps if the new opening doesn't match exactly. - Refurbishment Energy: Cleaning, repairs, and modification work all require energy. - Potential for Loss: If a glass panel breaks during handling or modification, the embodied energy gets wasted, and a replacement needs to be required.	- Modularisation: Design the facade around a grid that fits the W5's size, creating a repetitive but potentially visually interesting pattern. - Combine: Various salvaged W5 units can create a more varied facade while increasing complexity. - Sacrifice: Specific look can be compromised using existing W5 units.

Table 13. Trade-offs of 'Component-based reuse' (Created by Author, 2024)

Nevertheless, as component-based approaches become more prevalent, procedures are expected to become more standardised and streamlined in healthcare and other infrastructures, leading to innovative disassembly techniques that will ultimately lower costs and shorten project timelines.

7.3.3.1 Strategy 5: Component *Reuse*

In this strategy(Illustration 54), the W5 components will first be disassembled and converted into individual components, such as aluminium extrusions, float glass, and insulating materials, which will be used in different panels or functions. This approach will offer flexibility, allowing for combination with previous strategies, such as repurposing a large component replaced in Strategy 3. However, this flexibility may result in increased activity in production facilities, potentially raising demand for raw materials and waste generation. Careful management and optimisation of these processes will be crucial to mitigating these potential drawbacks and maximizing the net benefits of this approach. The complex nature of these adaptations may also lead to a higher exposure to breakage. For example, the aluminium framing will offer considerable potential for reuse, but changing its finish while altering its appearance will be a demanding task that might impact the thickness and strength of the material. Nonetheless, as these component-based strategies become more widespread, the work will become standardized and simplified, paving the way for innovative dismantling techniques, driving lower costs, and reducing project timelines.

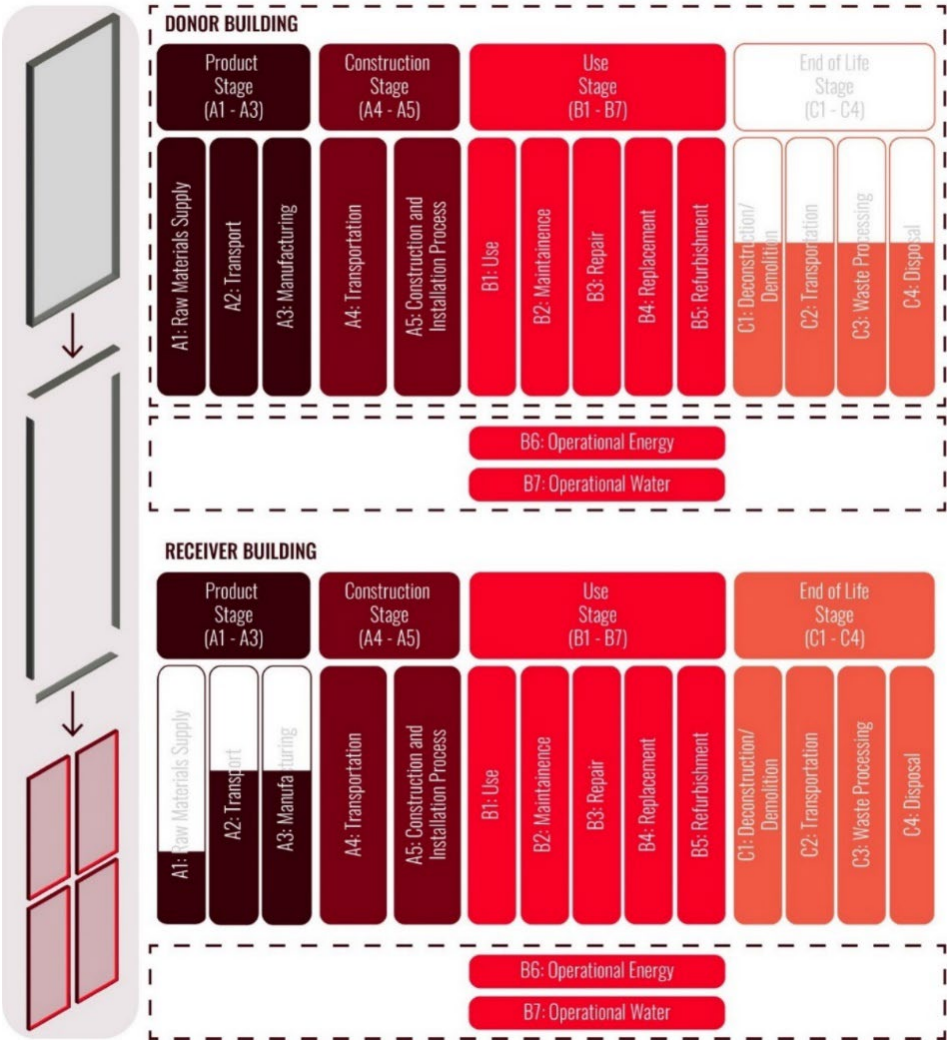


Illustration 57. Life cycle stages involved in a potential "Component Reuse" (Author, 2024)

7.3.3.2 Strategy 6: Component *Refurbishment*

This strategy will closely resemble Strategy 5, with most steps remaining the same, but the focus will be more on visual improvements with adjustable size constraints. The process will involve dismantling materials from the PSC Building, transporting them to the production hall, disassembling the W5 assembly, and refurbishing and mounting components into a new configuration. Transportation to the receiver building would be approached similarly. However, as shown in Illustration 55, the manufacturing or construction of the reused panels could be associated with a high carbon footprint. Changing transparent elements into opaque parts can reduce internal solar gains while limiting the panel's appearance. For instance, by replacing glass with spandrel or shadow box elements, the WWR can be reduced, potentially improving the building's energy efficiency and reducing internal solar gain. Moreover, replacing glass with spandrel can enhance the R-value, or thermal resistance. Spandrel glass typically has a higher R-value than clear glass due to its opaque nature and insulation properties. This modification can improve the energy efficiency of the building by reducing heat transfer through the curtain wall. As a result, aesthetic flexibility and environmental impact can be balanced, allowing visual customization while utilizing existing materials.

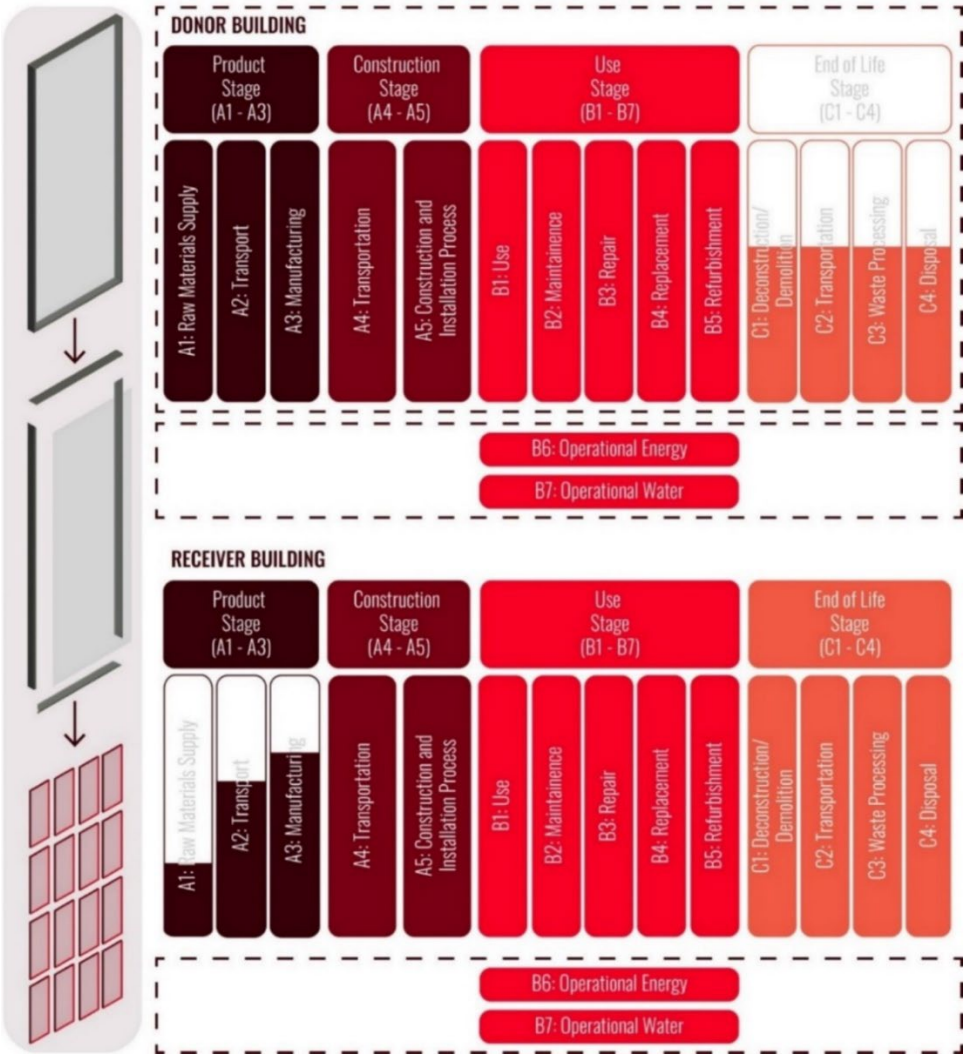


Illustration 58. Life cycle stages involved in a potential "Component Refurbishment" (Author, 2024)

7.3.4 End-of-Life Level

The final two strategies at the end-of-life stage are currently the most general in Canada. However, it is projected that these options will become less common over the next 30 years due to evolving waste management practices. These two strategies involve Recycling and Wastage. In the case of recycling, materials are completely broken down and then reprocessed using various methods to create new materials, which may be of either lower or equal quality. In the case of curtain walls, recycled aluminium, often sourced from mixed alloys, may show variations in composition and contain impurities that can weaken its structural integrity and corrosion resistance. Also, recycled glass may have inconsistencies in colour and clarity due to the blending of different glass types, and it may contain defects that could compromise its strength and durability. These quality considerations can pose challenges for using recycled aluminium and glass in high-performance curtain wall systems where specific material properties are crucial. However, this process requires a substantial amount of energy. The last strategy involves wastage, which is a scenario to be minimised.

7.3.4.1 Strategy 7: *Recycling*

As discussed in Chapter 5 of Value Hill, recycling is a common practice when removing curtain walls from buildings in Toronto or elsewhere in Canada. The focus of this recycling effort is predominantly on materials such as steel, aluminium, and glass. While aluminium and glass are often recycled and reused in the facade industry at the same or higher-grade quality, this strategy(Illustration 56) is still advantageous considering today's circumstances. For the W5 unitised curtain wall, recycling strategies can be implemented in different ways for different materials. High-value recycling involves materials like aluminium, steel, and glass, which can be recycled into new materials of the same quality. With this method, old scrap materials can be used in the same manner as before. High-value recycling is feasible for float glazing and cullet with no impurities, although this is not always the case with construction waste. Following the dismantling and removal of W5 from the PSC Building, the materials will be transported to a nearby recycling facility in Toronto for high-value recycling. Subsequently, the recycled materials will undergo all necessary stages before being transferred to the receiving building.

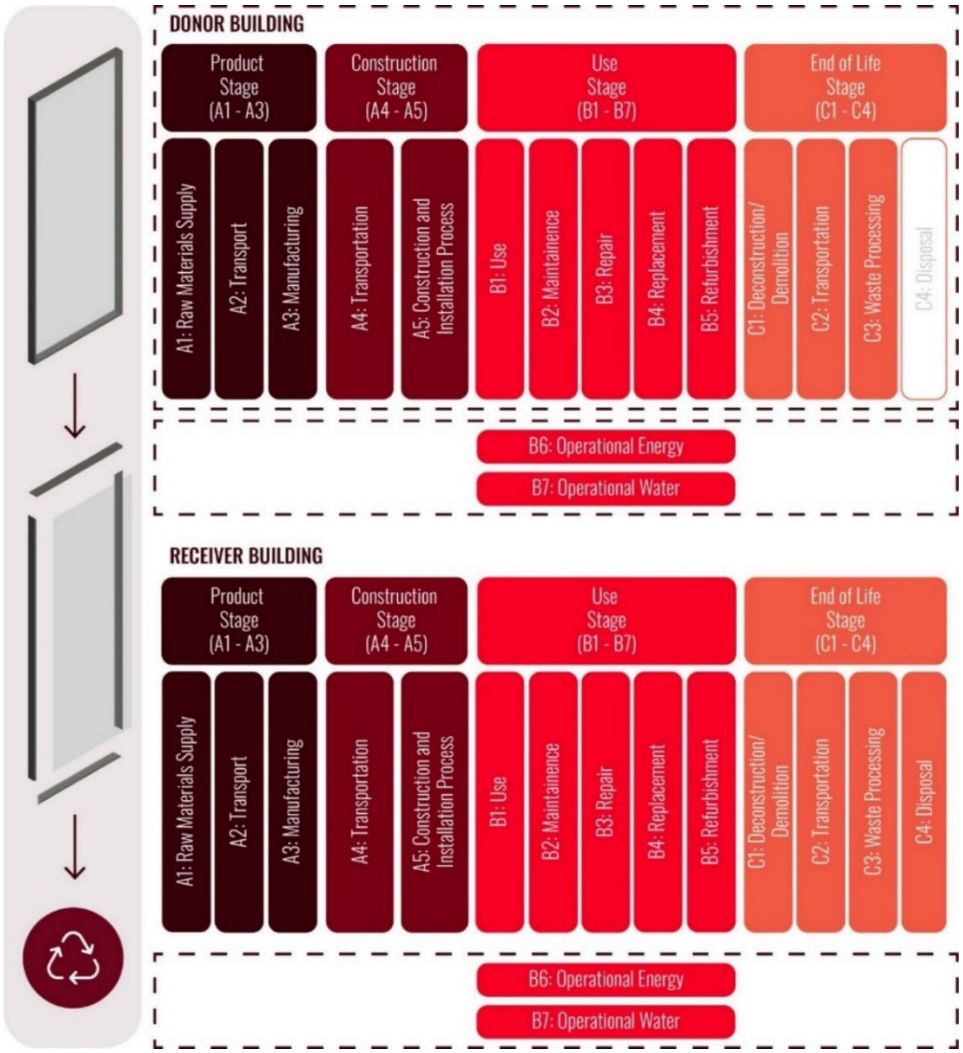


Illustration 59. Life cycle stages involved in a potential strategy of "Recycling" (Author, 2024)

7.3.4.2 Strategy 8: *Waste*

The final strategy(Figure 57), and perhaps the least desirable option for this thesis, involves directly disposing of materials in a landfill on the outskirts of Toronto. This linear approach, even 30 years from now, especially given the changing environmental landscape, would be ill-advised for the facade industry. This strategy involves the simple yet environmentally harmful process of disassembling assemblies like W5 from the PSC Building, transporting them to a waste management facility, and ultimately depositing them in a landfill.

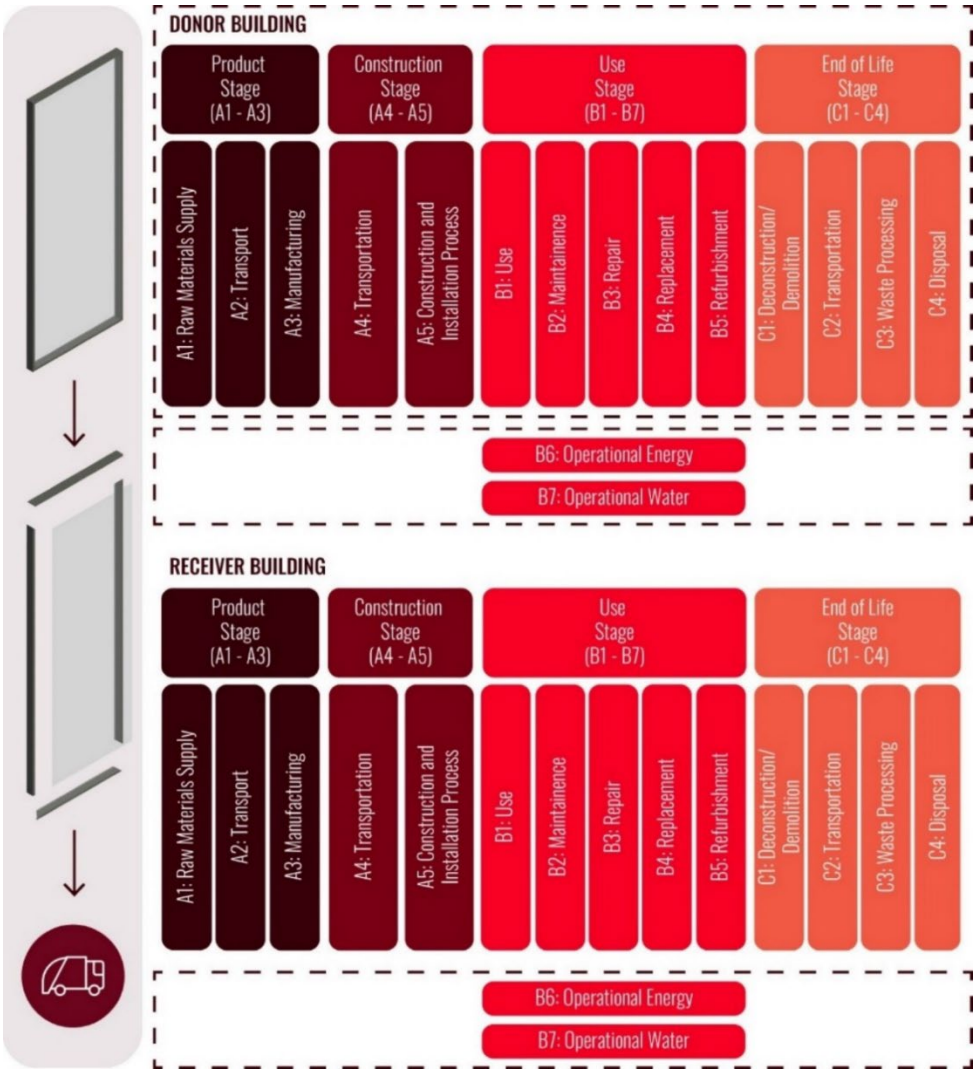


Illustration 60. Life cycle stages involved in a potential strategy of "Wastage" (Author, 2024)

7.4 *Circular* Impact

7.4.1 Idea I

The current approach to increasing the embodied carbon footprint of various types of curtain wall envelopes, as detailed in Chapters 2 and 3, highlights the non-donor mindset that has emerged among stakeholders in the construction industry. To address this mindset, it is crucial to adopt a donor and receiver mentality when considering the future upgrades to the envelope of healthcare infrastructure such as the Patient Support Centre (PSC) in Toronto, Canada, and similar facilities over the next three decades. Embracing such a mentality can help minimise carbon emissions to the greatest extent possible within the current limitations. By promoting the reuse of materials and avoiding unnecessary waste at the end of the first life cycle, future window wall components or stick curtain walls can be designed with better assembly or Design for Disassembly (DfD) techniques. However, due to challenges related to reuse, performance, non-standardization, and complex construction techniques, unitised curtain wall assemblies may only be partially circular. In Chapter 5, the concept of a circular loop is examined, illuminating the role of life cycle stages in both the PSC (donor) Building and a hypothetical receiver building in mitigating carbon emissions through fair material reuse. This approach can be explored through case studies such as Koningskade and The Natural Pavilion, where the components might not directly reuse the materials. However, they provide valuable insights into the practical applications of the DfD framework, potential challenges of reusing the curtain wall assemblies, and more benefits in looking at its alternatives. In Illustration 58, two life cycles are examined: one for the PSC Building and another for a receiver building in Toronto. By 2053, three decades after completion, the donor building will need to decide on various wall assemblies, as certain components will have reached the end of their service life. This decision marks the beginning of the embodied carbon savings process. According to standard LCA, this occurs after the 'B' Module (Use stage), with the 'C' Module serving as the decision point for the end-of-life impact of the unitised curtain walls. With a circular mindset, stakeholders in the donor building could send materials to the receiver building, initiating its A' module.

In Illustration 59, instead of using virgin materials like Alumina and Bauxite for new Aluminium frames and floating glass, an optimal scenario occurs on the receiver's end before involvement in the 'B' Module. In this adaptation (Teeuwen 2023, 76), the unitised curtain walls of the donor building can be directly refurbished and utilised rather than directly getting reused according to 'Strategy 2', thereby avoiding stages C1, C2, C3, and C4 from donor building, and stages A2 and A3 can be eliminated in the receiving building. The extraction of virgin materials can be classified as A1, constituting a dismantling impact. Furthermore, on the receiver's end, stages A4 and A5 will account for the transportation and construction of the reused materials sourced from the Patient Support Centre. Therefore, the embodied carbon impact is mitigated from A1 to A3 in the receiving project, and waste generation is minimised in the donor building.

7.4.2 Idea II

The second idea is a more realistic approach, currently created by donating curtain wall materials in best to worst scenarios. In this case, some situations remain the same. Three decades from now, when the Patient Support Centre is ready to renew the facade by considering a new window wall component and the old curtain wall facade with the end-of-life of its components and materials, it will act as a donor with no receiver building, yet the assemblies will still be in the process of a second life cycle. The study has selected wall assembly ‘W4’ to highlight that the strategies noted in Chapter 7.3 apply to all types of united curtain wall assemblies or comparable ones in PSC buildings and other related buildings. Talking about W4, the assembly is a composition of varied components and materials, such as aluminium extrusion, composite panels, IGU and opaque glasses, insulation materials, EPDM gaskets, and gaskets, making it a fitting case by maximising the building circularity by remanufacturing, refurbishing or recycling it for future use. This idea describes the analysis of all components of varied materials to be utilised from best to worst scenario, visually and in an Excel sheet. Below are the five scenarios in connection with the "Action Plan.", shown before.

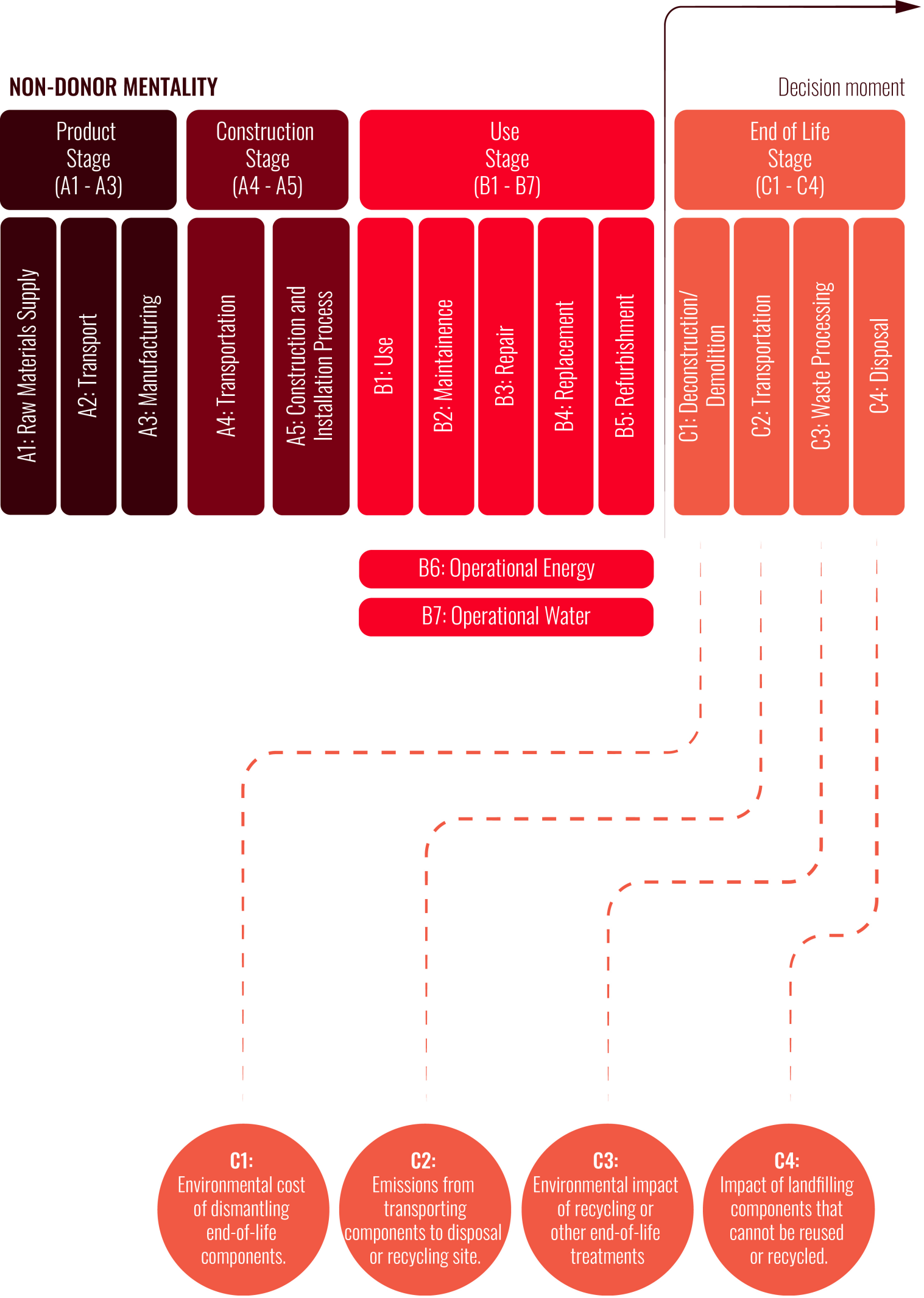
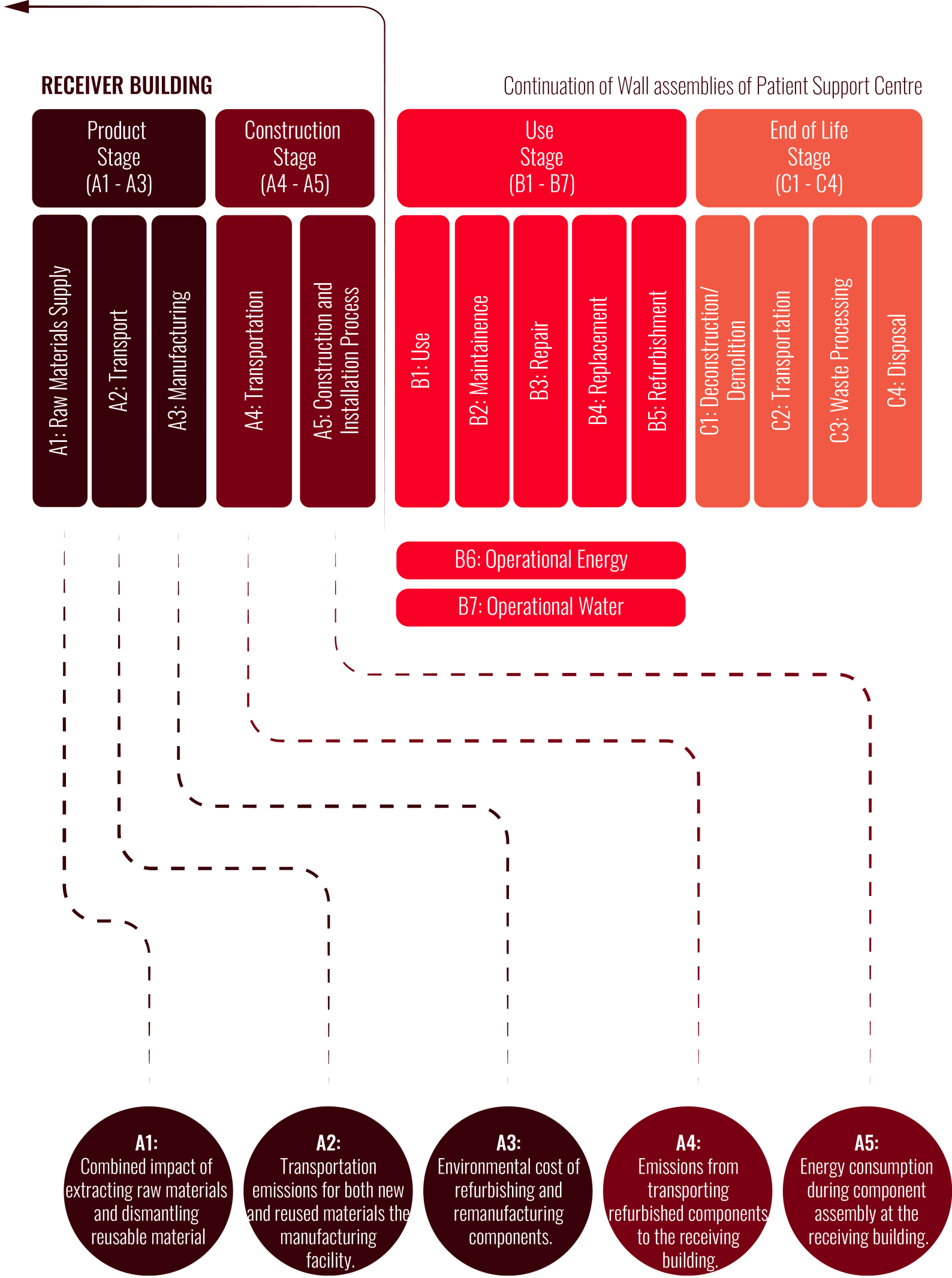


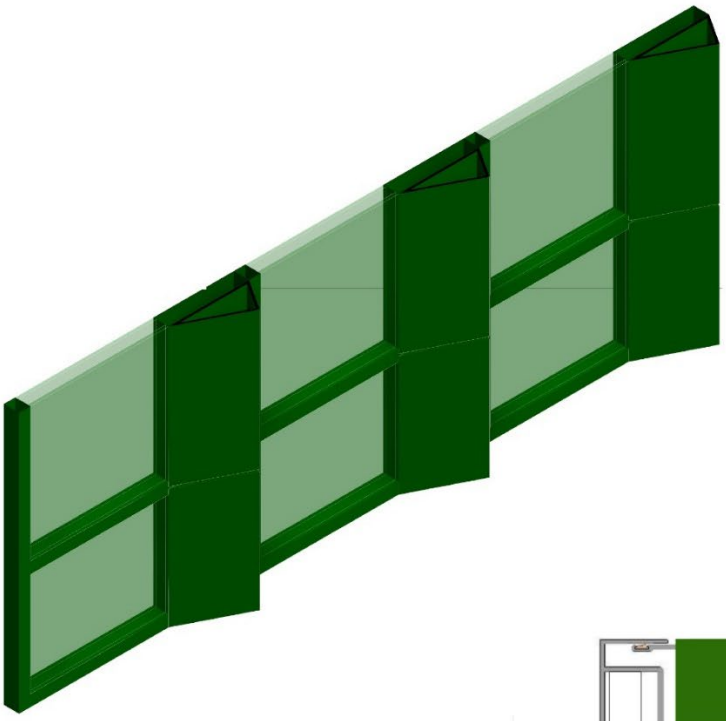
 Illustration 52. Calculation of the 'W5' assembly and its r

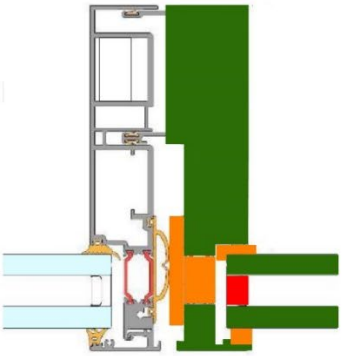


relation to other curtain walls. (Created by Author, 2024)

Scenario 1: In Illustration 59, it is clear that Scenario 1 shows the highest level of circularity, with the most "Material Recovered" and "Material Returned." When combined with the unitised curtain wall 'W4', this scenario, in intersection with Strategy 1: In-place upgrade, Strategy 2: Panel Reuse, and Strategy 5: Component Reuse, suggests that all the advantages of this system could be leveraged to maximise material reuse during the Dfd(Design for Disassembly) process of the Patient Support Centre. This scenario seems to be the best option for lowering the embodied carbon footprint by reusing materials such as Aluminium Mullions and Panels, IGUs, and Opaque assemblies, incinerating rather than disposing of plastic materials and recycling stainless steel bolts, nuts, and screws.

3D View of W-04 - Circularity Scenario 1 for CW's components





Detail of curtain wall W-04's components showing EOL process

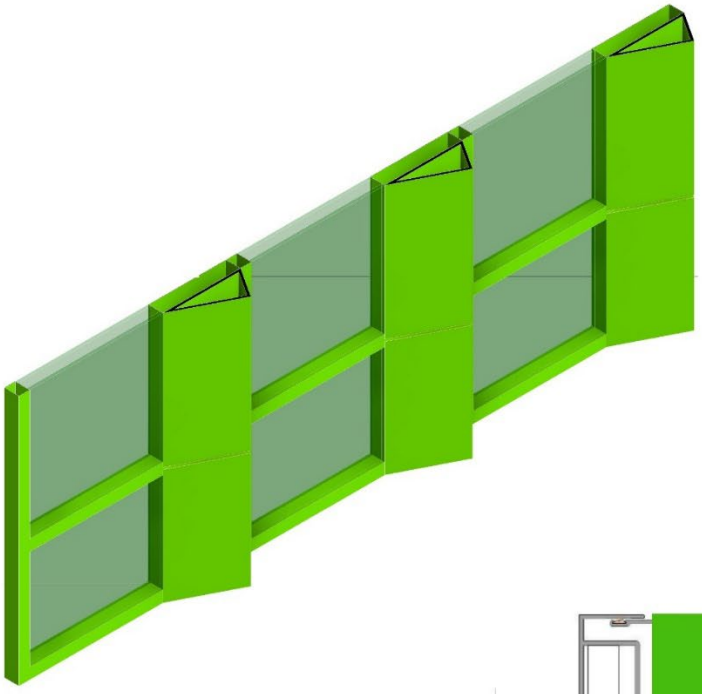
Unitised curtain wall - W04	Service life	Recycled(%)	Reused(%)	Wastage(%)	DfD	DfA	EOL	Process
Scenario 1: Majorly influenced by Strategy 1, 2, and 5								
Aluminium Mullions	**30**	-	90	10	**X**	-		Reuse as Material
Aluminium Composite panels	**30**	-	90	10	**X**	-		Reuse as Material
Insulated Glass Units(IGU)	30	20	75	5	**X**	-		Reuse as Material
Opaque assembly	30	20	50	30	**X**	-		Reuse as Material
EPDM Gaskets	30	-	-	7.5	**X**	-		Use as energy
Thermal Break	30	-	-	10	**X**	-		Use as energy
Ceramic fibre Insulation	30	-	-	30	**X**	-		Use as energy
Chemical sealant, Adhesives, & Tapes	15	-	-	100	**X**	-		Disposal
S.S: Bolts, Nuts, Washers, & Screws	30	90	-	10	**X**	-		Recycling

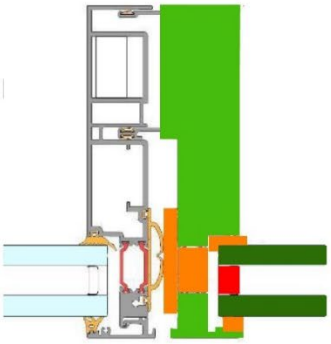
Building material circularity inputs for W-04. Cells in purple are modified.

Illustration 62. Circularity scenario 1 (Created by Author, 2024)

Scenario 2: In Illustration 60, Scenario 2 demonstrates the circularity principle for W4 assembly, highlighting the reusability of materials such as IGU and opaque glass assemblies with recycling aluminium mullions and composite panels. This strategy aligns with Strategies 5 and 6, which focus on component reuse and refurbishment, necessitating the disassembly, cleaning, refinishing, and reassembly of the building elements of the unitised curtain wall assembly to extend their service life for another cycle. This scenario will also focus on the incineration of old materials for energy production rather than their disposal. Key progress to further improve the circularity of this scenario would involve using durable materials designed for disassembly, easily accessible from inside the building, or another cost-effective method to reduce service costs.

3D View of W-04 - Circularity Scenario 2 for CW's components





Detail of curtain wall W-04's components showing EOL process

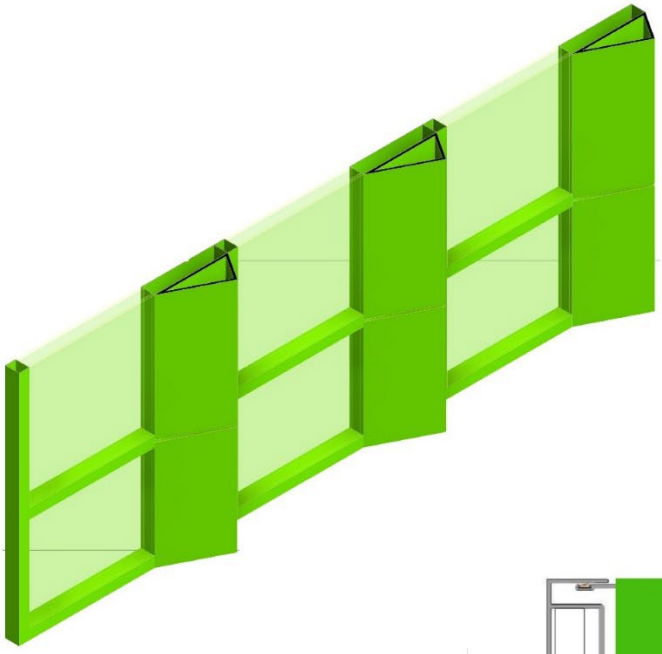
Unitised curtain wall - W04	Service life	Recycled(%)	Reused(%)	Wastage(%)	DfD	DfA	EOL	Process
Scenario 2: Majorly influenced by Strategy 5 and 6								
Aluminium Mullions	60	85	-	15	-	X		Recycling
Aluminium Composite panels	30	85	-	15	-	X		Recycling
Insulated Glass Units(IGU)	30	20	75	5	X	-		Reuse as Material*
Opaque assembly	30	20	50	30	X	-		Reuse as Material*
EPDM Gaskets	30	-	-	7.5	X	-		Use as energy
Thermal Break	30	-	-	10	X	-		Use as energy
Ceramic fibre Insulation	30	-	-	30	X	-		Use as energy
Chemical sealant, Adhesives, & Tapes	15	-	-	100	X	-		Disposal
S.S: Bolts, Nuts, Washers, & Screws	30	90	-	10	X	-		Recycling

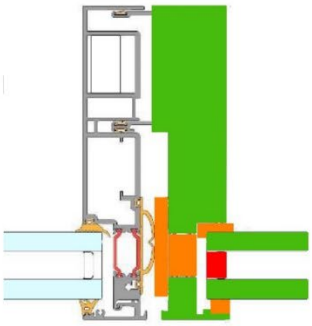
Building material circularity inputs for W-04. Cells in purple are modified.

Illustration 63. Circularity scenario 2 (Created by Author, 2024)

Scenario 3: In Illustration 61, Scenario 3 presents a baseline for material circularity. The goal is to return the maximum number of materials or redirect all other materials from landfills for end-of-life (EOL) outcomes, if possible. In this approach, mixed plastics such as EPDM gaskets, thermal breaks, and Insulation in the W4 curtain wall assembly can incinerated to produce energy and redirect them from the landfill stream. Although recycling is the preferred method (more than 60% in the table), and can recover energy through incineration, but is currently the best available means of disposal for plastics, which are difficult to recycle. Waste incineration can authorize the recovery of surplus heat, which can be utilised for hot water, steam, and electricity. As a result, Scenario 5 is related to Strategy 6: Component refurbishment and Strategy 7: Recycling. These strategies can be much better than the coming scenarios but are a safe, albeit not so carbon-negative, approach for curtain wall assemblies in the research site project.

3D View of W-04 - Circularity Scenario 3 for CW's components





Detail of curtain wall W-04's components showing EOL process

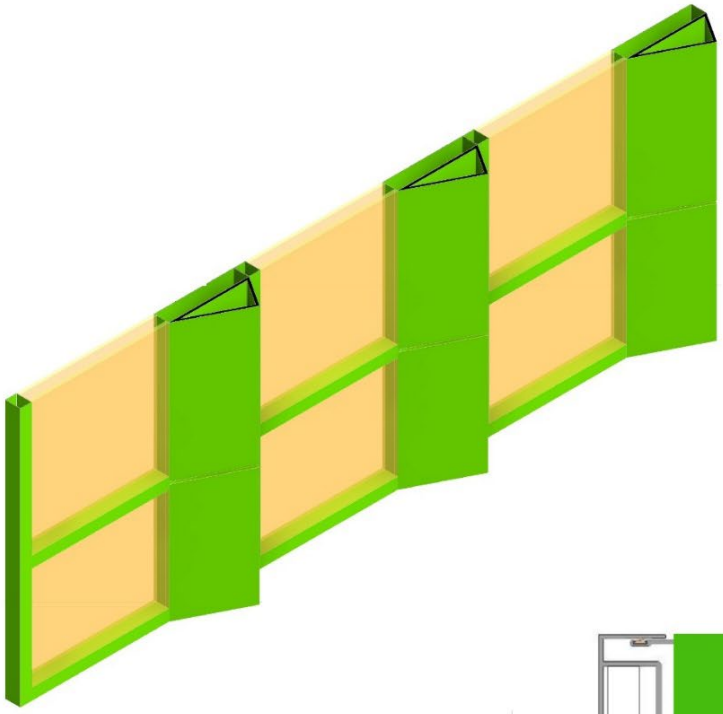
Unitised curtain wall - W04	Service life	Recycled(%)	Reused(%)	Wastage(%)	DfD	DfA	EOL	Process
Scenario 3: Majorly influenced by Strategy 6 and 7								
Aluminium Mullions	60	85	-	15	-	X		Recycling
Aluminium Composite panels	30	85	-	15	-	X		Recycling
Insulated Glass Units(IGU)	30	95	-	5	X	-		Recycling
Opaque assembly	30	70	-	30	X	-		Recycling
EPDM Gaskets	30	-	-	7.5	X	-		Use as energy*
Thermal Break	30	-	-	10	X	-		Use as energy*
Ceramic fibre Insulation	30	-	-	30	X	-		Use as energy*
Chemical sealant, Adhesives, & Tapes	15	-	-	100	X	-		Disposal
S.S: Bolts, Nuts, Washers, & Screws	30	90	-	10	X	-		Recycling

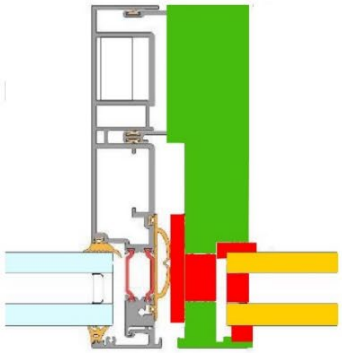
Building material circularity inputs for W-04. Cells in purple are modified.

Illustration 64. Circularity scenario3 (Created by Author, 2024)

Scenario 4: In Illustration 62, Scenario 4 is considered partially unfavorable for circularity in W4 due to a reduced focus on DfD (Design for Disassembly). This approach will not only hurt with a lower percentage recycling content for the aluminium members but will also cause the IGUs and opaque glass assemblies to be down-cycled based on their material type. On the other hand, allowance for these assemblies for disassembly and remanufacturing would potentially extend the components of the unitised curtain's service life to 60+ years, with the possibility of replacing the glazing and opaque panels. However, Scenario 4 still depends on disposal, with 50% of the materials like gaskets, thermal breaks, and insulation ending up in landfills. About Strategies 7 and 8 (Recycle and Waste), this concept fails to fully embrace the principle of circularity for donor buildings like the Patient Support Centre.

3D View of W-04 - Circularity Scenario 4 for CW's components





Detail of curtain wall W-04's components showing EOL process

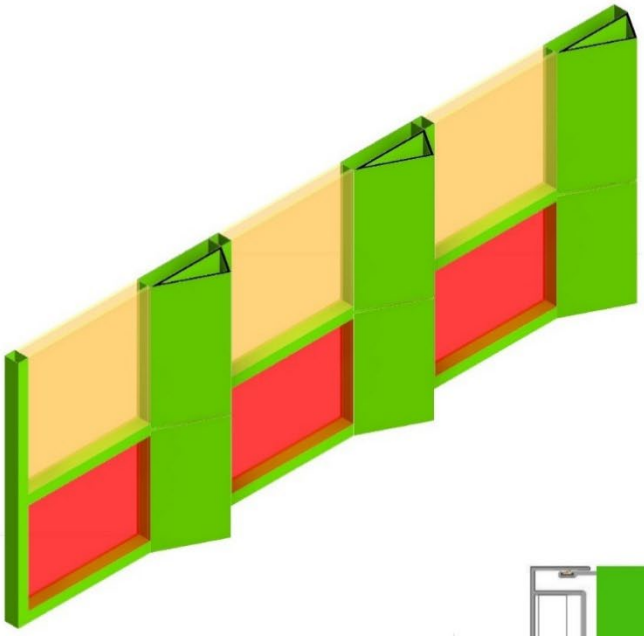
Unitised curtain wall - W04	Service life	Recycled(%)	Reused(%)	Wastage(%)	DfD	DfA	EOL	Process
Scenario 4: Majorly influenced by Strategy 7 and 8								
Aluminium Mullions	60	75	-	25	-	X		Recycling
Aluminium Composite panels	60	75	-	25	-	X		Recycling
Insulated Glass Units(IGU)	30	-	-	5	X	-		Downcycling
Opaque assembly	30	-	-	30	X	-		Downcycling
EPDM Gaskets	30	-	-	100	X	-		Disposal
Thermal Break	30	-	-	100	X	-		Disposal
Ceramic fibre Insulation	30	-	-	100	X	-		Disposal
Chemical sealant, Adhesives, & Tapes	15	-	-	100	X	-		Disposal
S.S: Bolts, Nuts, Washers, & Screws	30	-	-	100	X	-		Disposal

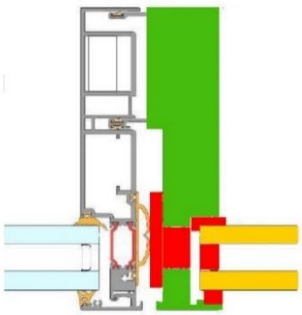
Building material circularity inputs for W-04. Cells in purple are modified.

Illustration 65. Circularity scenario 4 (Created by Author, 2024)

Scenario 5: In Illustration 63, Scenario 5 of 'W4' concerns recycling the aluminium extrusions and composite panels while the insulated glass unit (IGU) gets downcycled. The remaining CW assembly components, including sealants, thermal breaks, insulations, opaque glass assemblies, and other small members, are disposed of straight to landfills. This procedure is associated with the lowest circularity score due to the lack of end-of-life (EOL) processes for building materials(common in provinces such as Ontario until 2024). Downcycling: According to the table, the building glass might be recyclable (up to 75%), but it can rarely get recycled into new glass products at the end of its life. Instead, it will be typically crushed with other building materials, put into dumps, or salvaged. The IGU materials are "downcycled" because it is either impossible or not cost-effective to recycle them into similar products due to the wide range of float glass used in the industry. Further, technical issues such as IGUs being glued or welded make it very challenging to recycle them into similar products. As a result, this scenario aligns more with Strategy 8: Waste and partially with Strategy 7: Recycling as materials like IGU are downcycled into products like glass fibre, glass aggregate, asphalt, or foamed glass, a lower percentage of materials such as aluminium are recycled, and most of the materials get dumped.

3D View of W-04 - Circularity Scenario 5 for CW's components





Detail of curtain wall W-04's components showing EOL process

Unitised curtain wall - W04	Service life	Recycled(%)	Reused(%)	Wastage(%)	DfD	DfA	EOL	Process
Scenario 5: Majorly influenced by Strategy 8								
Aluminium Mullions	30	75	-	25	-	-		Recycling
Aluminium Composite panels	30	75	-	25	-	-		Recycling
Insulated Glass Units(IGU)	30	-	-	5	-	-		Downcycling*
Opaque assembly	30	-	-	100	-	-		Disposal
EPDM Gaskets	30	-	-	100	-	-		Disposal
Thermal Break	30	-	-	100	-	-		Disposal
Ceramic fibre Insulation	30	-	-	100	-	-		Disposal
Chemical sealant, Adhesives, & Tapes	15	-	-	100	-	-		Disposal
S.S: Bolts, Nuts, Washers, & Screws	30	-	-	100	-	-		Disposal

Building material circularity inputs for W-04. Cells in purple are modified.

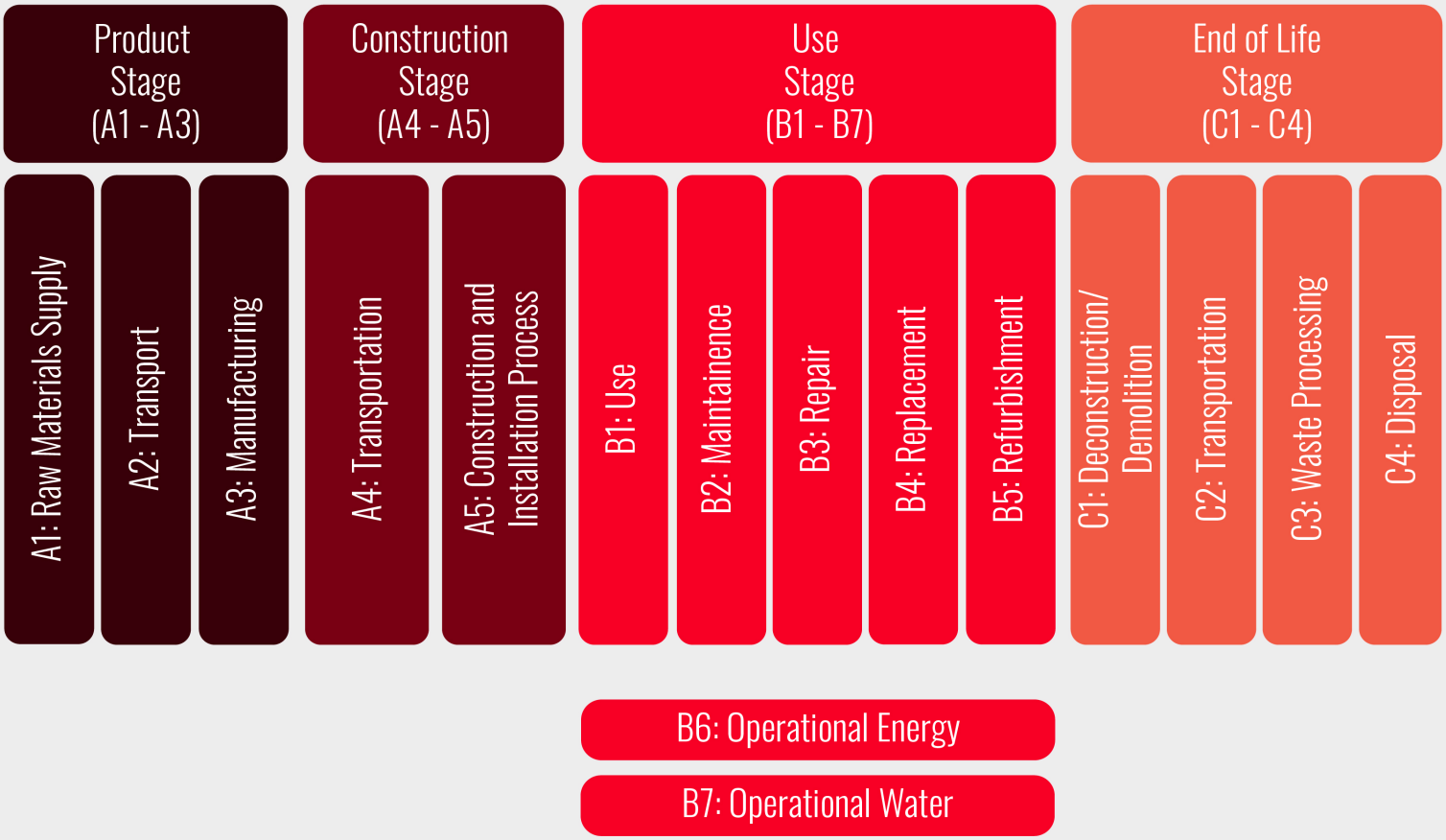
Illustration 66. Circularity scenario 5 (Created by Author, 2024)

7.5 The *Future* of Curtain Walls

Integrating a Design for Disassembly (DfD) approach into the facade industry represents a pivotal shift towards a circular economy, offering significant opportunities to reduce waste, conserve resources, and mitigate carbon emissions. This approach, particularly relevant for healthcare infrastructures like the Patient Support Centre (PSC) in Toronto, provides a comprehensive framework with eight distinct strategies, which the last four can apply to guide decision-making when unitised curtain walls reach their end-of-life phase. Whereas, if it were a case of stick curtain wall systems or window wall systems, due to their easier DfD applicability and less complex panel structures, all eight strategies, ranging from in-place upgrades and panel reuse to component remanufacturing and recycling, can offer a unique balance of environmental benefits, cost considerations, and practical feasibility.

The implementation of DfD principles can yield substantial carbon savings by avoiding the need for new material extraction and production, as well as minimizing waste disposal. In the case of the PSC, applying these strategies to its wall assemblies used in the project can significantly reduce the environmental impact of the building over its lifespan. This is achieved by strategically selecting the most appropriate strategy based on the condition and intended future use of the materials. However, the transition to a circular model is not without its challenges. In the case of unitised curtain walls, the limitations such as standardisation of assessment methods, economic viability, logistical complexities in handling and storing large components, and difficulties in disconnecting various connection points in curtain walls present obstacles that make it challenging to reuse these assemblies as panels. Instead, they can be reused, remanufactured, or refurbished as segregated components. Addressing these challenges requires collaborative efforts among stakeholders, including building owners, designers, manufacturers, and policymakers. Alternative options such as window-wall or stick curtain-wall systems should be explored, as they offer fewer limitations. By embracing the issues of unitised curtain walls and addressing the associated challenges for these alternatives, the facade industry can pave the way for a more sustainable future. Through careful examination, testing, and innovation, the industry can successfully transition from a linear "take-make-dispose" model to two branches. First, a lower circular approach, where the old, unitised curtain wall components can be utilized to the highest extent by remanufacturing or refurbishing its components, and second, the discontinuing of unitised curtain walls, window walls, or similar panel types can help in maximizing the value of resources and minimizing environmental impact. This shift will not only benefit individual projects like the PSC but also contribute to a broader transformation towards a more circular and sustainable built environment.

NON-DONOR MENTALITY



DONOR MENTALITY

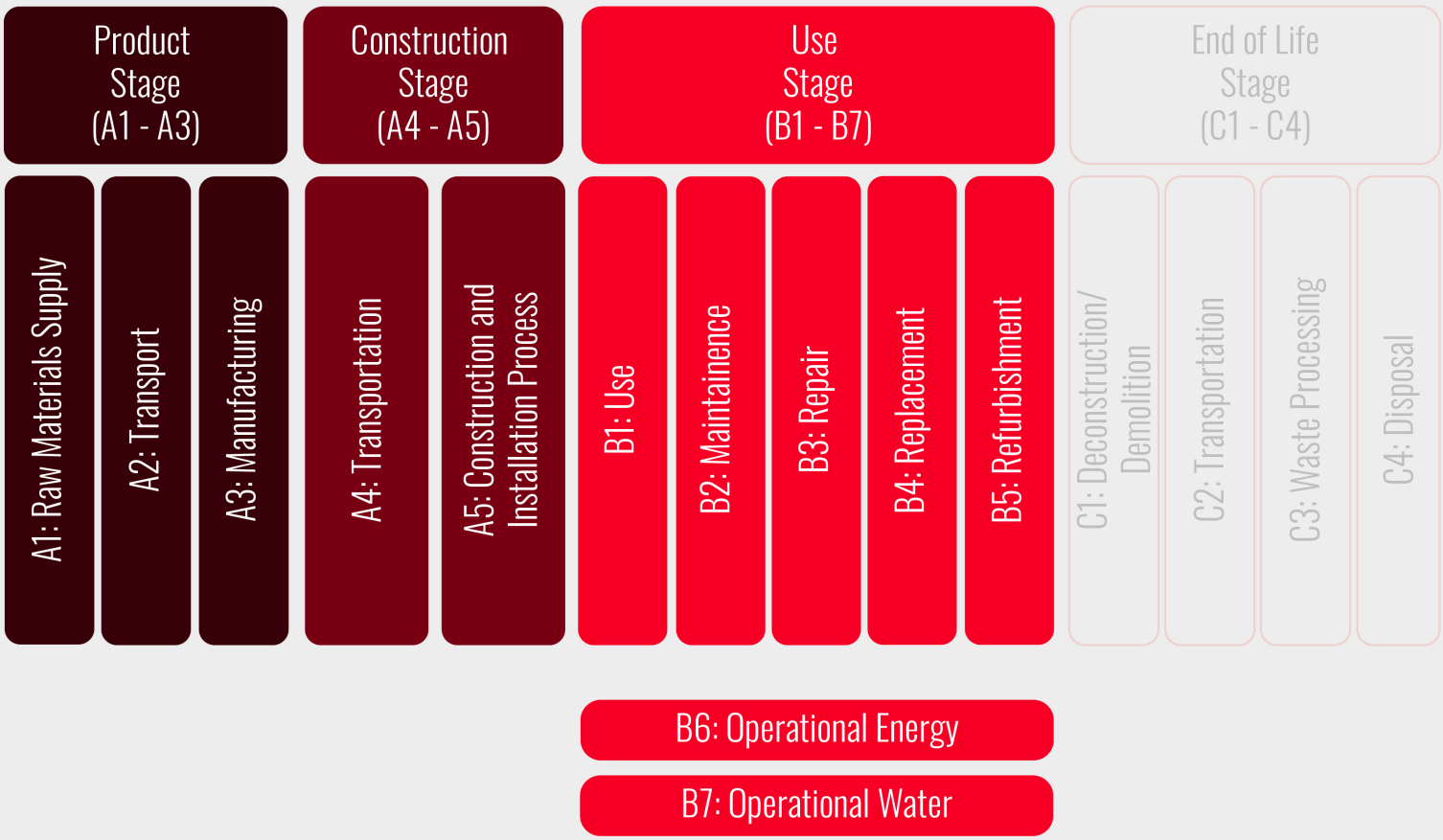
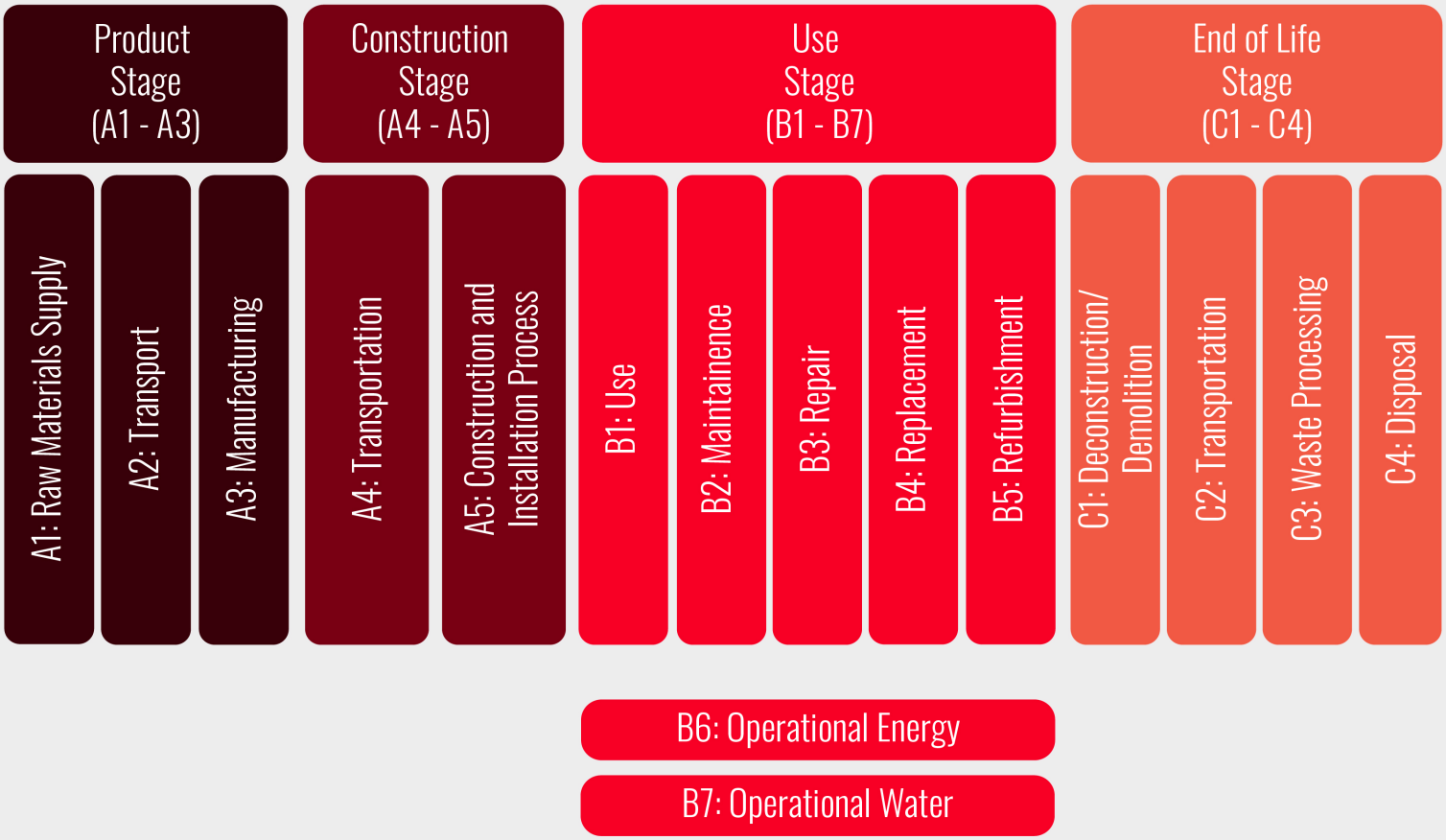
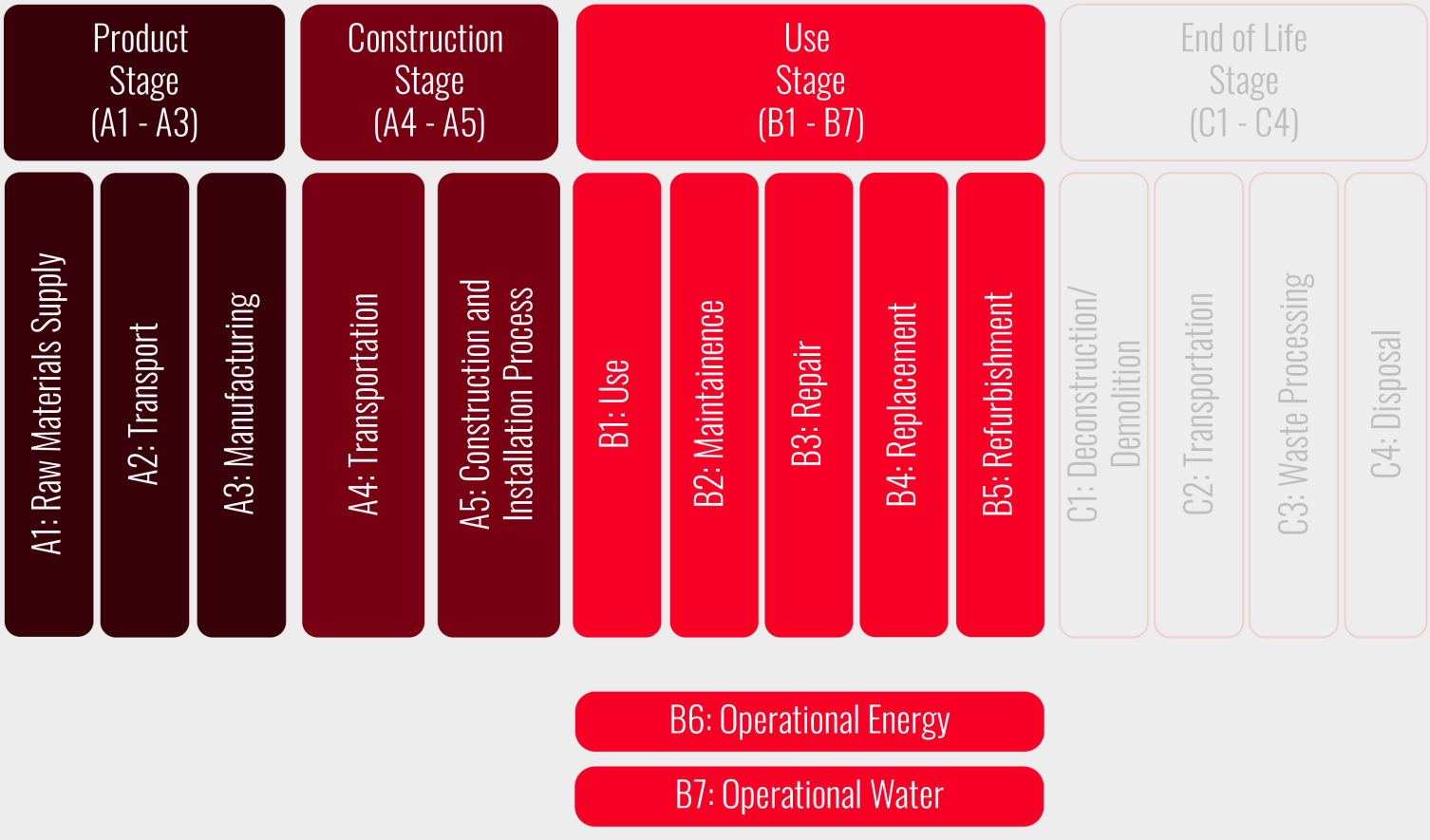


 Illustration 67. Life cycle stages regarding Koningskade 4 B

NON-DONOR MENTALITY



DONOR MENTALITY



8. Conclusion

" The

Circular Economy

is not just about doing

Less Bad,

it's about doing

More Good."

- William McDonough

The thesis sought to highlight the shift towards circular practices in the facade industry, prioritizing the end-of-service lifecycle of Aluminium Unitised Curtain walls in the Canadian context, with a particular emphasis on Toronto's healthcare infrastructure. The research revealed significant challenges inherent to curtain wall systems and emphasized the potential benefits of exploring alternative building envelope systems that are more conducive to adaptive reuse. These systems may be more likely to meet contemporary performance standards, offer a more efficient assembly/disassembly process, and better align with modern construction assembly goals and standards.

In exploring the circular framework, the research set out three primary objectives: 'Clarity,' 'Comparability,' and 'Practicality.' These objectives aimed to underscore the value of materials, the importance of retention, and the necessity of transitioning from a linear take-make-dispose culture to a model that emphasizes reuse, reduction, and remanufacturing. However, the complexity and limitations associated with the reuse criteria for unitised aluminium curtain walls required a critical evaluation of their suitability for circular applications.

The first pillar, 'Clarity,' addressed global and local construction practices, quantifying the carbon footprint and waste generation associated with issues such as housing shortages, climate change, and the depletion of virgin materials. The research focused on the healthcare infrastructure in Toronto, Canada, specifically examining the facades of buildings such as the Centre for Addiction and Mental Health (CAMH) and Toronto Western Hospital, identifying the recently completed SickKids' "Project Horizon," including The Patient Support Centre, as a key research site. The study involved analysing the assemblies, components, and materials of curtain walls and similar components in modern Canadian construction on OneClick LCA software to assess their embodied carbon footprint and potential for circularity. This investigation shed light on the assembly process and environmental impact of systems like a stick or unitised aluminium curtain walls and window walls while emphasizing the need for further exploration into their performance limitations and circularity challenges.

The second pillar of this thesis, 'Comparability,' acted as the central part of mass and interpersonal communications. In the one-to-many communication, stakeholders from the construction and other industries engaged in a wide range of circular loop ideas, diverging from traditional linear concepts. Influential voices, including Unilever, Metamorphosis, Philips, and the Ellen McArthur Foundation, highlighted the importance of addressing climate change within our industry and finding potential areas for adaptation. Theories such as Value Hill, Life Cycle Stages, and Circular Loop Obstacles, and engaging with diverse stakeholders, a thorough practical examination of the architectural realm unfolded through a series of productive conversations. Architects, Facade Consultants, Contractors, Clients, Material Processors, and others worldwide were interviewed across three key stages: Build Less! Build Intelligently! and Build for the Future! Respondent input highlighted the potential for circularity in facades, particularly through remanufacturing and refurbishment. However, the research also uncovered significant challenges hindering the widespread adoption of these practices, especially with unitised aluminium curtain walls. While there is potential for material reuse, factors such as legislation, supply chain dynamics, aesthetic considerations, and energy performance requirements pose obstacles. Comparative analysis of Canadian and international practices revealed a similar trend, with limited examples of successful circularity implementation in curtain walls. Despite these challenges, case studies and stakeholder feedback demonstrated the potential for circularity in the building envelope, emphasizing the need for innovative design strategies and policy support to overcome existing barriers.

Three reference studies—Citi Bank (UK), BMO Tower (Canada), and Koningskade-4 & The Natural Pavilion (Netherlands)—underwent embodied carbon footprint and building circularity assessments using OneClick LCA. The case studies offered valuable insights into the potential cost savings associated with circular facade strategies. However, it's important to note that while these examples demonstrated the benefits of reusing, reducing, and renewing, their relevance with assemblies like

unitised curtain walls was limited due to the unavailability of reusable methods caused by construction techniques and design constraints. Additionally, the research investigated the Design for Disassembly (DfD) in collaboration with industry stakeholders. While DfD holds promise for improving the circularity of building components, its practical implementation in the context of unitised curtain walls will require further investigation to overcome challenges related to material compatibility, disassembly processes, and reassembly constraints.

The third pillar of the project, Practicality, focused on applying circular economy principles to the healthcare sector. Specifically, the research explored the feasibility of Design for Disassembly (DfD) for the curtain wall assemblies of the Patient Support Centre. While DfD presented an opportunity to manage curtain wall components through strategies ranging from in-place upgrades to recycling, the complexity of unitised curtain walls posed considerable challenges. Identifying suitable recipients for reusing the components and predicting the long-term performance of these materials proved particularly difficult. Life cycle analysis was employed to evaluate the environmental and economic implications of various management strategies. Although the study demonstrated the potential of circular approaches, it underscored the need for further research to address the limitations of curtain wall systems. To achieve a truly circular lifecycle, it is important to address challenges such as disassembly, material compatibility, and the potential for downcycling rather than upcycling. Future research could focus on exploring alternative facade systems, specifically window wall components and stick curtain walls, that have greater potential for disassembly and reuse.

Moving forward: The importance of success stories and economic incentives

Motivating stakeholders, especially developers, to adopt circular practices will require more than just emphasizing environmental benefits. Therefore, to achieve broader approval for the facade industry, it will be significant to showcase a variety of successful case studies where circular approaches have resulted in substantial cost savings. Such variation will entail projects that have not only minimised environmental impact but also displayed financial advantages through reduced material costs, lower maintenance expenses, and potential tax incentives or grants for sustainable construction. By aligning circularity with economic benefits, the construction industry can build a compelling business case for sustainable approaches, setting the stage for a more circular tomorrow.

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Appendix

Discussion "no.": "Person's name"@ "Firm's name"(Country)
Keywords: Technical Challenges; Façade details + Construction; Life cycle + Circular Design; Decarbonisation + Embodied Carbon

Brief Introduction of thesis: To explore future possibilities of how to renew the facades of 20-40 story hospitals and similar buildings. On one side, the topic understands the ways to easily dismantle the existing curtain walls or window wall systems from 1970s buildings and think more than just recycling. At the other, it investigates how future facades that can be deconstructed easily, with materials being salvaged and reused for second life cycle.

1: How can we think building less?
2: How can we think building intelligently? and
3: How can we think building for the future?

Segment 1: Build less.
From my last few months investigating the construction industry of Canada, have made me realize two factors: -
1) Extracted materials like Aluminium and Glass from demolished buildings are never reintegrated or reused in new building skins. and
2) Even if we have increasing no. of suppliers of reclaimed and recycled building materials and components near us, we are using it very rarely.

So, from that, I was curious about the material selection process for a new curtain walls or similar components in multifaceted continental projects.
Is the main focus primarily on cost, energy efficiency, or some other factors too?

Segment 2: Build intelligently.
At global level, our industry produces 40% of carbon emissions, in which 11% is by embodied carbon, whereas provincially, Ontario produces 80% of embodied carbon. Moreover, being the largest consumers of virgin materials have made us to worsen up the situations.

Considering this, I am very eager to ask two important questions on it:

1) Is it a mindful choice to repurpose components from older buildings and employ existing materials for new innovative facades?

If not, are National codes, structural limitations, or any other factors steering us away from sustainable options?

2) Is it a good option to explore locally sourced materials, potentially not the most cost-effective route to decrease our embodied carbon footprint?

For example, due to bad energy grid and cost efficiency in nearby provinces like Alberta, the firms find it better to buy materials from Washinton DC. However, the situation remains the same in that province.

Segment 3: Build for the Future.
In today's world of unitized curtain walls and window-wall systems, unfortunately we've to discard components like EPDM gaskets, sealants, and opaque assemblies. Aluminum panels deserve a second life through recycling, yet our design flaws hinder disassembly. Curtain walls, connected with strong fixings and adhesives, resist proper dismantling.

And, as you've expertise in façade technicalities and construction, so do you think we should meticulously detail unitized curtain walls, in such a way, that it can be easily removable or replaceable for maintenance? Also available for future reuse and modifications?