Circular interventions during the demolition and enabling phase: An Irish Case Study

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ABSTRACT:
The global construction industry is the world's largest consumer of raw materials and creates an estimated third of the world's overall waste. A circular economy is one that aims to keep products, components and materials at their highest utility and value at all times. The Opera site development project in Limerick is being utilised as a Lighthouse Demonstrator Project for the Circular Built Environment. The site is a brownfield site located in the heart of Limerick City. The transformational commercial development which commenced in 2020 consists of office, retail, residential and public buildings on a 3.7-acre site. During the demolition and enabling phase of the project, a number of buildings were demolished. Prior to demolition, a pre-demolition audit was undertaken, and its purpose was to identify the type and quantities of the materials that would arise from the demolition works and possible opportunities to implement circular economy principles. This paper will conduct a case study on the Opera Square project located in Limerick, Ireland, and evaluate the circular economy interventions implemented during the demolition and enabling phase of the project. The study aims to assess the effectiveness of the interventions in achieving a diversion rate for construction and demolition material from landfill of 98%. The overall aim of this research project is to provide a suite of lessons learned which can be used to inform guidance factsheets for industry in relation to implementation of circular economy principles on construction projects.

KEY WORDS: Circular Economy, Lighthouse Demonstrator Project, Built Environment Case Study, Demolition, Reuse

1 INTRODUCTION

Climate change is a burning issue that affects our planet in various ways. It causes the sea level to rise, intensifies heat waves and worsens storms. The primary cause of climate change is the emission of greenhouse gases. The European Union has pledged to reduce greenhouse gas emissions by 55% by 2050 [1]. The construction industry must play a crucial role in achieving the EU's target of reducing greenhouse gas emissions by 55%. This is because the construction sector uses large amounts of resources, accounts for around 50% of all extracted materials, and the sector is also responsible for generating over 35% of the EU's total waste [2]. Greenhouse gas emissions from the manufacturing of construction products, as well as the construction and renovation of buildings, account for between 5-12% of total GHG emissions [2]. However, if we can improve material efficiency, it is possible to reduce up to 80% of these emissions [2]. Clients are becoming more focused in their capacity to shape sustainable design practices, adhere to sustainable financial models, and minimise costs. This is because environmental, social, and governance (ESG) concerns are crucial factors that impact global financial markets. In the real estate industry, these demands can influence investment strategies, rental and capital growth potential, and the vulnerability of assets to becoming obsolete [3].

The research presented in this paper focuses on the Circular Built Environment as part of an EPA-funded Green Enterprise project. It is a collaboration between the Irish Green Building Council (IGBC), the Build360 research group at Atlantic Technological University (ATU), the Southern Region Waste Management Office (SRWMO), and the Limerick Twenty Thirty (LTT) property development company. The project challenges the construction industry to look at waste not as a problem but as a resource to be reused in a circular economy to reduce the carbon footprint of the construction sector.

The aim of the research is to explore circular economy opportunities across the various phases of the Opera Square project in collaboration with the project stakeholders. The scope of this paper is 'Contract A' which covers the demolition and enabling works for the project.

It is hoped that the Opera Square project will serve as a lighthouse demonstrator project that will produce guidance applicable across the built environment sector in Ireland.

Some initiatives so far have included:

- conserving raw materials by identifying building and material extension-of-life opportunities via adaptive reuse and refurbishment.
- minimising the embodied carbon footprint by directly reusing existing historic buildings.
- reuse of existing materials and components with further work planned to explore material circularity options during the subsequent phases of the project.

2 WHAT IS THE CIRCULAR ECONOMY?

The concept of a circular economy (CE) has become a significant school of thought in sustainable economics [4]. It is defined as an industrial system that is intentionally designed to

be restorative or regenerative [5]. Since the start of 2020, the assets managed through public equity funds that have circular economy as the sole or partial focus have increased by six times, from USD 0.3 billion to over USD 2 billion [6]. Exploiting the circular economy can bring job creation, a more vibrant business environment, value creation through social entrepreneurship, and reduced carbon emissions. In five specific sectors alone (steel, aluminium, cement, plastic, and food), adopting a more circular approach could reduce annual greenhouse gas emissions by 9.3 billion tonnes of CO2eq in 2050 [6].

The Government of Ireland Climate Action Plan [7] emphasises the importance of the circular economy in helping Ireland meet its greenhouse gas reduction targets. The construction industry plays a crucial role in achieving these targets as embodied carbon emissions make up 14% of Ireland's national emissions [8].

But what is the circular economy? A circular economy is an economic system that aims to keep resources in use for as long as possible, by extracting the maximum value from them while in use, and then recovering and regenerating products and materials at the end of each service life. In this system, waste is minimised, and resources are reused, refurbished, repurposed and recycled in that order of decreasing prioritisation. By doing so, a circular economy aims to reduce resource scarcity and environmental degradation, whilst also minimising upfront and whole life carbon emissions [9]. In their research paper, Bailey et al. [10] describe the four principles on which the CE is built upon as:

- designing products with their entire life cycles in mind.
- maximising product life cycles.
- recycling materials from end-of-life products; and
- reusing materials across diverse industries and value chains.

In 2020, Benachio *et al*. [11] conducted a content analysis of 45 published articles in four stages. The first stage was the definition of CE for the construction industry. The second stage was the analysis of the stages of the life cycle included in the research; finding that research has focused primarily on the construction and operation stages of a building's life cycle, with fewer concepts incorporated in the project design, material manufacture, and end of life stages. The third stage was the analysis by research theme. Lastly, the fourth stage listed CE practices by life cycle stage. The research by Benachio *et al*. [11] highlighted only one article that considered all stages, and most considered only one stage. This shows that research in the CE is still focused on applying the concepts of CE in the built environment in only one life cycle stage at a time.

Irrespective of whether focussing on one lifecycle stage or across the whole project lifecycle, indicators are required to assess CE. Although, what should be measured is subject for debate as key performance indicators and numerical targets can be ambiguous and might lead to incorrect conclusions when determining success or otherwise of CE strategies [12] . This is compounded further when concept and definitions within the CE remains open to interpretations [13] e.g. reuse, recycle. Therefore, the principle of maintaining products, components and materials at their highest utility and value at all times should be used in determining appropriate indicators and targets.

The research by Salma [14] explores the potential for reusing concrete elements and materials from demolished buildings. The author presents the argument that reusing these elements could lead to a shift towards a more circular model in the construction industry. The study concludes that it is possible to change the linear life-cycle model to a cyclic one by applying Design for Disassembly (DfD) criteria to precast concrete systems and elements. The importance of incorporating circularity into the entire lifecycle of a building project is discussed and the authors state that this can be achieved more easily when there is early engagement in the concept stage of a project.

The EU has published numerous papers related to circular practices, which indicates the importance they place on achieving their environmental and climate objectives [11]. The EU's directives and regulations regarding national environmental and waste management policies target a bottom-up approach to tackle environmental sustainability challenges by implementing CE principles [15]. Although it is widely acknowledged that CE can contribute to environmental sustainability by attracting both business and policy-making communities to sustainability efforts, it needs scientific research to secure that the actual environmental impacts of CE work toward global net-sustainability [16]. Therefore, it is an imperative that we understand how best to implement CE principles in practice that fully considers sustainable development placing people at the forefront, with an emphasis on economic prosperity to live fulfilling lives in harmony with nature. The circular economy remains focused on technological solutions, driven by a promise of traditional economic growth [17] at levels which are not environmentally sustainable.

Ireland is making strides towards adopting a circular economy with the 2022 Whole of Government Circular Economy Strategy and the Circular Economy Bill [18]. However, the country's circularity material use rate was only 2% in 2020, indicating the need for further progress [19].

There is little substantive, evidence-based case studies dealing with CE principles in the built environment within the Irish jurisdiction [11]. The Opera site development project in Limerick is being utilised as a Lighthouse Demonstrator Project for the Circular Built Environment. This paper’s purpose is to provide an evidence-based case study from Project Opera.

3 LIMERICK TWENTY THIRTY

The document; Limerick 2030 Vision: An Economic and Spatial Plan for Limerick [20] is an economic and spatial framework for the redevelopment and growth of Limerick City Centre that was published in 2013. Key to the delivery of the plan is the development of a number of strategic sites by

Limerick Twenty Thirty (LTT). LTT is a Designated Activity Company (DAC) established by Limerick City and County Council (LCCC) in 2016 to undertake strategic property development on key strategic sites in Limerick that will act as anchors for enterprise and development for the Mid-West region. Project Opera has been identified as a strategic site. As such, a key objective of the project is to restore and regenerate a site within the city centre that has been vacant for decades into a modern-day world-class mixed-use development.

3.1 Project Opera

The Opera Square project is a brownfield site located in the heart of Limerick City Centre in the functional area of LCCC. The site, as indicated within the red boundary in Figure 1, occupies the majority of a city block bounded to the west by Patrick Street and Rutland Street, to the north by Bank Place, to the east by Michael Street, and to the south by Ellen Street. It contains various building structures dating from the 18th to the 20th century.

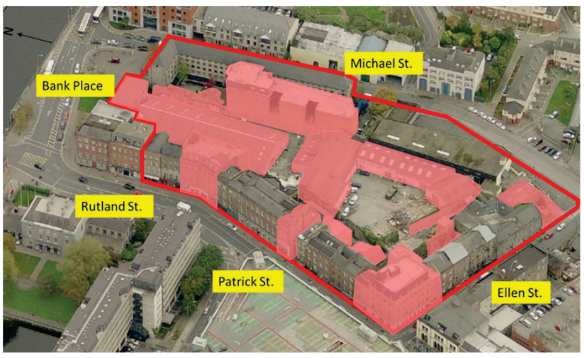

Figure 1 Opera Square project within the red boundary

The buildings with red infill in Figure 1 indicate twentieth-century buildings and later additions to the rear of existing heritage structures which are not designated as being of heritage value. These structures were demolished in Contract A (Demolition and Enabling Phase), as indicated in Figure 2. The project value is estimated at €300m, providing 500 construction jobs during development and 2,500 jobs during operation.

The development consists of specific parcels across five phases (A-E), which include One Opera Square, a 14,000m^2, 6-storey office, retail and restaurant; a hotel, which is 4,700m^2 and consists of 110 rooms and a restaurant; a new 4,410m2 City Library, living room, and café; Four Opera Square, a 2,580m^2, 5-storey office (flex space); Parcel 3B, which comprises six one-bedroom Georgian apartments and retail; a 14-storey landmark office building of 12,300m^2; the refurbishment of the Granary building (2,715m^2) constructed in 1870 into offices and a restaurant; an 8,000m^2 basement for 155 car spaces and 495 bike spaces; and a new public realm space for the City Centre of 5,700m^2, complete with a Mirror Pool.

Figure 2 Opera Square project end of Contract A (Demolition and Enabling Phase)

3.2 Contract A

The Contract A scope of work was outlined in a performance specification that was issued in May 2020 for tender for the demolition and enabling of the project site. The scope of work included various tasks such as surveys, site-setup, hoarding installation, traffic and pedestrian management, site-clearance, building stabilisation, demolition of structures, sewer construction, hazardous material investigation, and site grading. The aim of the work was to prepare the site for future phases of the project.

The specification highlighted the importance of preserving and storing special conservation pieces. The contractor was required to develop a project-specific Construction Environmental Management Plan (CEMP). The plan included a Construction and Demolition Waste Management Plan, an Environmental Emergency Preparedness and Response Plan (EEPRP), measures to ensure protection of surface waters during works, measures for the management of invasive species, and measures for the protection and management of bat species.

The section outlining Waste Management Requirements was particularly important as it placed a requirement to divert at least 75% of demolition construction waste from landfill. The contract documentation also referred to a pre-demolition audit, the first of its kind at this scale in Ireland, which was underway at the time of award. The pre-demolition audit was to confirm quantities of demolition waste and identify markets or potential uses for demolition waste before the demolition works commenced. The contractor was instructed to take account of the pre-demolition waste audit in the construction phase and fully participate in and cooperate with the project's research and educational elements. In October 2020, the pre-demolition audit was published, and John Sisk and Sons were successful in the competitive tender process and were awarded the first phase at the Opera Site: Contract A.

3.2.1 Pre-demolition Audit

The pre-demolition audit aimed to identify and evaluate the type and quantities of materials to be deconstructed and/or demolished. The audit also provided recommendations on their further handling. The audit process comprised two phases,

namely a desk study followed by field survey and was undertaken by RPS Group.

The desk study involved reviewing available information and documentation pertinent to the building, including the age of the building, design documents, documentation of use, a list of hazardous substances, the surroundings, and access. The study aimed to identify the construction date/period, dimensions, construction typology, composition, type of materials, location of machinery and installations, and details of hidden or difficult to access spaces. The audit-team also referred to design and planning documentation, particularly the asbestos demolition survey and heritage reports. The field survey involved a visual inspection of the site and buildings' and, where necessary, minor invasive works. The survey comprised a site visit to develop a material inventory; identifying, quantifying, and locating material types in each building such as floor coverings, electrical fitting, interior walls, false ceilings, to inform recommendations on reuse and recycling. In summary, and based on discussions with the lead auditor, 'the desk top study allowed the identification of quantities and the field survey determined material type'.

The audit aimed to determine materials quantities and type for reuse or recycling and to consider factors such as safety, time, economic feasibility, and market acceptance. The audit recognised that existing buildings were a material resource, and the utility and value of their components, elements, and materials should be maintained for as long as possible. The audit provided the necessary information to plan and manage demolition and disassembly work to deliver best practice approaches to resource recovery.

4 RESULTS

The data on the quantities of materials from the pre-demolition audit and the actual values recorded during the demolition and site clearance works are presented in Table 1. Some material categories identified at the pre-demolition stage were not segregated during the execution of the demolition and site clearance works and were recorded under the category of "General waste". The estimated amounts from the pre-demolition audit differ from the actual recorded material quantities for the Red Clay Brick and Natural Stone because some bricks were crushed with the concrete and block, and a large amount of natural stone was reused. Another reason for the difference is that the pre-demolition audit was based on preliminary data from the planning stage models, and the Recorded Material quantities are predominately from Smart Waste.

4.1 On-site reuse

The demolition on site was carried out systematically and involved the removal of several buildings and support areas. These included the existing industrial/warehouse/workspace buildings towards the centre of the site, office buildings, modern additions/extensions to the rear of the Granary Building (a Protected Structure), and to the rear of heritage structures fronting onto Rutland Street, Patrick Street, and Ellen Street. Additionally, the existing Ellen Street surface car park, as well (modern day buildings) as Nos. 6 and 7 Rutland

Table 1. Estimated and Actual Materials from Demolition Phase

All figures in tonnes (t)

Material Category	Pre-Demolition Audit Estimate	Recorded Materials
Concrete and Blocks	12,213	15,003[(a)]
Red Clay Brick	1,658	10[(b)]
Natural stone	2,202	889[(c)]
Metal	214	354
Bituminous Stone	195	200
Timber	177	200
Gypsum-based Material	111	nr
Asphalt / Bituminous	71.3	nr
ACM	46	156
Composite (glazing etc)	22	1.0
Clay / Ceramic Tiles	19	nr
Textiles	17	nr
Mineral fibre ceiling tiles	16	nr
Electrical (light fittings)	6.0	nr
Plastic	5.0	nr
Other Fittings	3.0	nr
Green waste	nr	5.0
General waste	nr	430
Total	16,973	17,248

Key
nr: not recorded
ACM: Asbestos Containing Material

(a)
On-site Reuse:

Concrete (In-situ)	7,503
Bricks (Engineering)	5,000
Blocks (Concrete)	2,500

(b)
Off-site Reuse:

Canal Harbour Building	8

On-site Reuse in future phase of project:

Georgian red brick	2

(c)
Off-site Reuse:

Annacotty	75
Herbertstown	75
Askeaton	50
Limerick City Build	650
Civil Trust	2

On-site Reuse in future phase of project:

Cobble stones	12
Limestone Door Case	25

NOTES
1) Smart Waste, a web-based platform, was predominantly used to quantify, report, and manage construction site waste.

Street, Nos. 6 and 7/8 Patrick Street, and No. 3 Ellen Street were also removed. The structure adjoining to the south of the former Town Hall was also removed in order to facilitate the widening of the existing east-west access route into the site. The process of demolition included soft stripping of the buildings, installation of an airtight dust bubble (where applicable) for asbestos removal, and the use of mechanical excavators for the demolition of the buildings. The material resulting from the demolition process, commonly referred to as the 'crushed' material, was composed of crushed concrete (in-situ), blocks (concrete), bricks (engineering), red brick, and some natural stone. This material was stockpiled on-site and underwent testing to confirm its adherence to the material grading requirements of the 6F2 fill material, as stipulated in Table 6/2 of the TII Specification for Road Works, Series 600-Earthworks [21]. As a result, it was deemed suitable for on-site reuse as a piling mat. By reusing 15,003 tonnes of this crushed material classified as 6F2, for the haulage road build-up and piling mat layer (Fig. 3) on the Opera project, a significant amount of construction and demolition waste was diverted from the landfill.

Figure 3 Piling mat formed using reused material from site

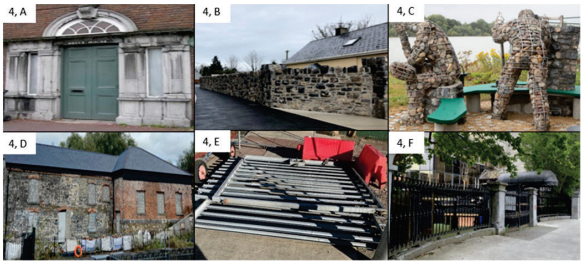

Figure 4 Examples of Reuse Materials

4.2 Reuse on site in future phase of project.

The cobble stones from passageway to Patrick St., and Rutland St., a historic Limestone door case to 6 Rutland Street (Fig. 4, A) and 3 pallets of old Georgian red brick which are palletised onsite for reuse in later phases of the Opera Square project are currently stored onsite for future reuse in the public realm and Library project.

4.3 Off-site Reuse

A total of 852 tonnes of natural stone, from Project Opera, have been reused across a range of projects throughout Limerick City and County, including in the following applications:

- construction of natural stone walls (Fig. 4, B),
- construction of a memorial for the Finucane Brothers (Fig. 4, C),
- Canal Harbour Building (Fig. 4, D) has also benefited from this initiative, with the LCCC Archaeology Department reuse of 2,000 red clay bricks from Opera Square project in the redevelopment of this building.

Additionally, the Limerick City Build regeneration project in Moyross has been able to use the stone in a stone mason training scheme. The regeneration project is for disadvantaged youths from underprivileged backgrounds. The successful reuse of this material has undoubtedly contributed to the sustainable development of the community.

Other examples of Off-site Reuse include:

- Palisade metal fencing panels reused by the Richmond Rugby Club (Fig. 4, E).
- Timber-framed internal division wall with glass panels
- Gates and stone pillars reused by Limerick Civic Trust (Fig. 4, F).

5 DISCUSSION

The on-site reuse of 15,003 tonnes of crushed material, classified as 6F2, including concrete, brick, red brick, and some natural stone, resulted in a significant amount of construction and demolition waste being diverted from the landfill. On-site reuse of this material eliminated the need for virgin aggregate for the piling mat. This opportunity for reuse of crushed materials resulted in a diversion rate of 87%, which surpassed the required diversion rate of at least 75% of demolition and construction waste from landfill as outlined in the Waste Management Requirements for the demolition and enabling phase. This achievement demonstrates a commitment to sustainable practices in the construction industry. The crushed material will ultimately be removed offsite once it has served the function of piling mat and has potential as a reuse material under an EPA-approved Article 28 End-of-Waste [22] procedure. Article 28 may be used when a waste has undergone a recycling or other recovery operation and is considered to have ceased to be waste. The tracking of this material will be investigated in future phase of this research project.

In addition to on-site reuse of the crushed material, providing an 87% diversion from landfill rate, the project achieved an overall diversion rate for construction and demolition material from landfill of 98 %. This was accomplished due to the following initiatives:

- 889 tonnes of natural stone reused off-site and stored on site for use in future phases of the Opera project.
- The recorded value for metal was 354 tonnes. This value includes the metal fencing panels that were delivered to a nearby sports club for reuse. The remaining metal waste generated on-site was segregated and sent for recycling. Although it is not clear if there was further reuse potential with this metal, it is assumed that the majority of the metal was recovered reinforcing steel from the demolished cast-in-situ reinforced concrete buildings and steel members from roof constructions consisting of beams, steel trusses and steel columns.
- 200 tonnes of bituminous stone material was recycled to create base material for new asphalt applications.

- 200 tonnes of timber were source-segregated on-site and sent off-site for recycling.

Overall, these initiatives contributed to an impressive diversion rate from landfill of 98 %.

There was no source segregation of the following materials. Instead, they were sent offsite in the General waste stream for further processing at an authorised facility:

- Asphalt / Bituminous roofing material
- Composites (glazing)
- Mineral fibre ceiling tiles
- Textiles (including carpet tiles)
- Plastic
- Electrical
- Clay / Ceramic Tiles

The asbestos-containing material (ACM) noted in Table 1 was disposed of as hazardous material.

6 CONCLUSIONS

LTT recognised the importance of sustainable practices and demonstrated their commitment to sustainability by integrating targets in the specification for Contract A works for diversion from landfill of construction and demolition waste at the pretender stage and commissioning a pre-demolition audit on Project Opera. Through their efforts, LTT and Project Opera was able to deliver real benefits in resource efficiency and sustainability. The recycling of materials such as concrete, brick, and stone for on-site reuse reduced the need to import virgin stone material for use as piling mat material, which in turn significantly reduced the number of truck movements required for the project.

The pre-demolition audit provided valuable data on the materials within the building's structure and fabric. The audit identified potential waste diversion opportunities for certain waste streams, including reuse, recycling, and estimated the diversion rates for these waste streams. The pre-demolition audit provided various alternatives for each material group or waste stream, and economically and environmentally beneficial on-site sorting activities were identified for storage, handling, separation, and other operations required to manage different waste streams. The optimal time to incorporate the level of potential detailed in a pre-demolition audit is during the concept stage. The pre-demolition audit was completed on the Opera Square project after the creation of the specification for Contract A works and after the tender process to appoint contractors to undertake the demolition works was underway.

Overall, the collaboration between Limerick Twenty Thirty, Southern Waste Management Region office and Limerick City and County Council's sustainable approach to the demolition on the Opera Square project demonstrates their commitment to protecting the environment and their community.

6.1 Key lessons from the project

- Key performance indicators (75% diversion from landfill in this project) and numerical targets can be ambiguous especially when the definition of reuse is not stipulated within contract documents.
- Clients are empowered to consider if selective demolition and similar methods to recover material assets are worth incorporating into tender documents at the concept stage in a project through the data made available in a pre-demolition audit, allowing contractors to appropriately cost their tender submission.
- The pre demolition audit provided recommendations on further handling of materials. However, it arrived too late in the process to allow for separate individual material recovery targets.
- The red brick was crushed and used as a piling mat; the material could have been extracted for reuse on other projects as it has architectural salvage value and low embodied carbon. However, removing the brick intact during the demolition process through selective demolition is costly and time-consuming and must be included in early-stage tender documents.
- Tracking of waste must be a client priority.

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7 WORKS CITED

[1] European Commission, "Commission welcomes completion of key ‘Fit for 55' legislation, putting EU on track to exceed 2030 targets," 9 October 2023. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4754. [Accessed 12 04 2024]

[2] European Commission, "Buildings and construction," 25 March 2024. [Online]. Available: https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en#:~:text=The%20construction%20sector%20is%20responsible%20for%20over%2035%25,estimated%20at%205-12%25%20of%20total%20national%20GHG%20emissions. [Accessed 12 04 2024]

[3] RICS, ESG data list for real estate valuations, World Built Environment Forum, London, 2024.

[4] Skene KR. Circles, spirals, pyramids and cubes: Why the circular economy cannot work. Sustain. Sci 13, 479–492.

[5] Ellen MacArthur Foundation.. Towards the circular economy. Journal of Industrial Ecology. 2013;2(1):23-44.

[6] Ellen MacArthur Foundation. Financing the circular economy: Capturing the opportunity. [Online]. Available: https://www.ellenmacarthurfoundation.org/financing-the-circular-economy-capturing-the-opportunity. [Accessed 12 04 2024]

[7] Department of the Environment, Climate and Communications , "Climate Action Plan 2023 CAP23 Changing Ireland for the Better," Government of Ireland, Dublin, 2022.

[8] IGBC, "Whole Life Carbon in Construction and the Built Environment in Ireland," Dublin, 2021.

[9] LETI, "Circular economy and carbon in the construction sector," 12 16 2021. [Online]. Available: https://www.leti.uk/opinionpieces. [Accessed 12 04 2024]

[10] Baily MN, Manyika J, Gupta S. US productivity growth: An optimistic perspective. International Productivity Monitor. 2013 Apr 1(25):3.

[11] Benachio GL, Freitas MD, Tavares SF. Circular economy in the construction industry: A systematic literature review. Journal of cleaner production. 2020 Jul 1;260:121046.

[12] Moraga G, Huysveld S, Mathieux F, Blengini GA, Alaerts L, Van Acker K, De Meester S, Dewulf J. Circular economy indicators: What do they measure?. Resources, Conservation and Recycling. 2019 Jul 1;146:452-61.

[13] Morseletto P. Targets for a circular economy. Resources, conservation and recycling. 2020 Feb 1;153:104553..

[14] Salama W. Design of concrete buildings for disassembly: An explorative review. International Journal of Sustainable Built Environment. 2017 Dec 1;6(2):617-35.

[15] Ghisellini P, Cialani C, Ulgiati S. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner production. 2016 Feb 15;114:11-32.

[16] Korhonen J, Honkasalo A, Seppälä J. Circular economy: the concept and its limitations. Ecological economics. 2018 Jan 1;143:37-46.

[17] Velenturf AP, Purnell P. Principles for a sustainable circular economy. Sustainable Production and Consumption. 2021 Jul 1;27:1437-57.

[18] Department of the Environment, Climate and Communications, "Whole of Government Circular Economy Strategy 2022-2023, Livig More, Using Less," Government of Ireland, Dublin, 2021.

[19] OECD, "The Circular Economy in Ireland, OECD Urban Studies," OECD Publishing, Paris https://doi.org/10.1787/7d25e0bb-en, 2022. [Accessed 12 04 2024]

[20] Limerick City and County Council, "Limerick 2030: An Economic and Spatial Plan for Limerick," Limerick, 2013.

[21] Transport Infrastructure Ireland, "Specification for Road Works, Series 600-Earthworks," Transport Infrastructure Ireland, Dublin, 2013.

[22] EPA, "End of Waste (Art. 28)," Environmental Protection Agency, [Online]. Available: https://www.epa.ie/our-services/licensing/waste/end-of-waste-art-28/. [Accessed 12 04 2024].