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Assessing the impact of resource efficiency on selected case studies in Ireland

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In the EU, construction and the use of buildings account for 50% of final energy consumption, approximately 35% of greenhouse gas emissions, more than 50% of all extracted materials, 30% of water consumption by the population and 35% of total generated waste, annually. In Ireland, there has been a clear connection between construction output, construction and demolition production and energy use. During this time of economic recovery, there is a unique opportunity to decouple this connection and rethink the built environment to one that embraces material cycles that have net positive environmental benefits. This study used an action research methodology to benchmark the effectiveness of implementing a series of resource efficiency measures during the construction phase of four case studies with a small-to-medium enterprise building contractor. The implementation of these measures in the case studies produced cost savings of €14 567.70 representing 0.48% of the total project value (€3 050 032). The total energy savings were estimated to be 11 373.09 kWh and it was estimated that 176.751 t of materials were prevented from being placed in site skips. The total reduction in carbon dioxide (CO₂) emissions from the implemented measures was 52.263 t.

1. Introduction

In the European Union (EU), the construction and operation of buildings are estimated to account for 40% of final energy consumption, 35% of greenhouse gas (GHG) emissions, more than 50% of all extracted materials (approximately 3 billion t in the EU), 30% of water consumption by the population and 35% of total generated waste, annually (EC, 2014a). Construction and demolition waste (C&DW) production in Ireland has seen remarkable fluctuations over the past 10 years, hitting a peak of 17.8 Mt in 2007 followed by a dramatic decline to just over 3 Mt in 2011 and an increase to the most recent estimate of 4.7 Mt in 2017 (EPA, 2020). This trend has reflected the unsustainable economic growth and decline over this period and has clearly highlighted the direct correlation between construction output and increased environmental impacts. Despite these recent lower estimates, C&DW continues to be one of the largest waste streams in Ireland, almost 68% greater than municipal waste, the value for which in 2017 was 2.8 Mt (EPA, 2020). It is clear from these figures that this mode of consumption and waste production is not sustainable in the long term and so, in this time of continued economic recovery, there is an opportunity to move towards a more efficient use of resources that will also reduce the environmental pressures associated with the different phases of the building life cycle. EU policy and legislation has highlighted the need of moving towards a more resource-efficient society through a series of regulatory and strategic documents focusing on: the sustainable use of natural resources; sustainable competitiveness; energy efficiency and performance; the

prevention and recycling of waste; resource efficiency (RE) and the circular economy (CE). The European Commission (EC) communication *On Resource Efficiency Opportunities in the Building Sector* (EC, 2014b) recognised the importance of design and material choice decisions in the transition towards a more resource-efficient and low carbon dioxide sector and has called for reliable indicators on: total energy and water use in buildings (including embodied and operational energy and water); material use and the associated embodied environmental impacts; C&DW management; the recyclability, reusability and recycled content of materials; the durability and deconstruction of buildings and their material constituents (EC, 2017).

In Ireland, the national strategy, *Towards a Resource Efficient Ireland* (EPA, 2014), has identified RE and waste prevention as two of the key drivers to the vision of a future CE. Over the past 15 years in Ireland, a series of key legislative, policy actions and guidelines have focused on minimising waste production, reducing water use during occupation, improving energy performance and reducing GHG emissions. This has had mixed results with considerable improvements witnessed in the specification of improved energy performance in buildings focusing on the operational phase through the implementation of the Energy Performance of Buildings Directive (EU, 2010a) and subsequent revisions to the Technical Guidance Documents. Efforts to decouple waste production from construction output have been less successful as there is still a clear relationship between the two as evidenced by a

comparison of C&DW data with the construction production index published by the Central Statistics Office (CSO) (Table 1). Since 1995 there have been 14 national waste reports published by Ireland's Environmental Protection Agency, which show that the rising quantities of C&DW decreased from a peak in 2007 to a low of 3 Mt in 2011. (Note that the 2014 data are as presented in the *Ireland's Environment – An Assessment 2016* (EPA, 2016) report and the 2017 data are as presented in the *National Waste Statistics Summary Report 2020* (EPA, 2020).) This is reflective of the economic downturn and its effect on the construction sector during this period; however, the data for 2014 and 2017 once again show an increase in C&DW volumes of over 56% since 2011, which is matched by an increase in the construction production index of 74.5%.

A key challenge will be to decouple C&DW production from construction output as mentioned above. Therefore, this study aims to identify opportunities to reduce waste production during the construction phase of the selected case studies along with energy and water consumption. This addresses a gap in construction-related energy research to date as it focuses on an aspect of the initial embodied energy use arising out of construction site activities (Guo *et al.*, 2019) and builds on previous construction waste management studies (Cahill, 2007;

Gottsche and Kelly, 2018; Gottsche *et al.*, 2016; Grimes, 2005; Kelly, 2006; Kelly and Dowd, 2014, 2015) within an RE approach – that is, the combination of energy, waste and water reduction initiatives. The use of an RE site audit tool aimed at highlighting opportunities to reduce construction-phase environmental impacts that have been commonly assumed or ignored by practitioners to date (Gustavsson *et al.*, 2010; Iddon and Firth, 2013; Ueda *et al.*, 2019). Waste and Resources Action Programme (Wrap) in the UK has identified RE as the single most effective response to addressing the risks from resource scarcity (Wrap, 2015).

2. RE-related legislation and policy in Europe and Ireland

The EU has adopted more than 200 pieces of environmental legislation since the 1970s, while over the past decade the sustainable use of natural resources has received increasing attention in EU policy to address environmental, climate, economic efficiency and security of supply objectives. It is a central element in the 2050 vision for Europe, as laid down in the 7th Environment Action Programme (7th EAP) *Living Well, Within the Limits of our Planet* (EC, 2013). However, it was not until 2010 that RE was explicitly put on the EU policy agenda with the adoption of the *Europe 2020* strategy (EC,

Table 1. C&DW volumes compared with construction production index (Ireland 1990–2019)

Year	Total C&DW	Increase/decrease % in C&D waste	Value of production index in construction (CSO data)	Increase/decrease % in construction production index: %
2019	No waste report published to date		172.1	+10.8
2018	No waste report published to date		155.3	+16.8
2017	4 700 000	+42	133.0	+17.3
2016	No waste report published		113.4	+13.4
2015	No waste report published		100.0	+8.7
2014	3 310 000	+10.2%	92.0	+9.4
2013	No waste report published		84.1	+12.1
2012	No C&DW data in report		75.0	–1.6
2011	3 003 691	–13.3	76.2	–18.8
2010	3 464 683	–32	93.8	–28.9
2009	5 093 666	–62.3	132.0	–37.8
2008	13 500 000	–24	212.4	–26.8
2007	17 791 745	+5.8	290.2	–9.2
2006	16 819 904	+13	319.8	+9.9
2005	14 931 486	+123	290.9	+15
2004	11 167 599	+206	252.8	+19.8
2003	No C&DW data in report		211.0	+11.8
2002	No C&DW data in report		188.7	+6.8
2001	3 651 411	+35	176.6	+13.3
2000	No waste report published		155.9	N/A
1999	No waste report published		No data available from CSO	N/A
1998	2 704 958	+78	No data available from CSO	N/A
1997	No waste report published		No data available from CSO	N/A
1996	No waste report published		No data available from CSO	N/A
1995	1 520 000	–40	No data available from CSO	N/A
1990	2 500 000	N/A	No data available from CSO	N/A

2010) and its flagship initiative for a resource-efficient Europe (EC, 2011a, 2011b) that defined the political goal of ‘allowing the economy to create more with less, delivering greater value with less input, using resources in a sustainable way and minimising their impacts on the environment’ (EC, 2011a, 2011b). The flagship initiative set out to create a framework for policies to support the shift towards a resource-efficient and low carbon dioxide economy. The *Roadmap to a Resource Efficient Europe* (EC, 2011a, 2011b) of the same year proposed that buildings should be renovated and constructed with greater RE that would require policies looking at a wide range of environmental impacts across the entire life cycle (EC, 2011a, 2011b). A key challenge in this respect is to decouple environmental pressures and impacts from economic development. The 2012 *Strategy for the Sustainable Competitiveness of the Construction Sector and its Enterprises* (EC, 2012) reiterated that RE is among the main challenges that the sector faces in the period up to 2020 (EC, 2012).

Europe 2020 (EC, 2010) is the EU’s growth strategy to 2020, and the aim of the strategy is to make the EU’s economy a smart, sustainable and inclusive economy. The strategy aims to reduce GHG emissions by 20% compared with those in 1990, increase the share of renewable energy in final energy consumption to 20% and achieve a 20% increase in energy efficiency. In 2014, the EC also agreed on the 2030 climate and energy policy framework for the EU setting an ambitious economy-wide domestic target of at least 40% GHG emission reduction for 2030 (EC, 2014a). The Paris Agreement 2015 (COP21) vindicated the EU’s approach, when 195 countries adopted the first-ever universal, legally binding global climate deal (UN, 2015). While there are several instruments that have an impact on buildings and construction products such as the Energy Performance of Buildings Directive (EU, 2010a), the Energy Efficiency Directive (EU, 2012), the Construction Products Regulation (EU, 2011), the *EU Emissions Trading System* (EC, 2015c), the Industrial Emissions Directive (EU, 2010b), the Waste Framework Directives (WFDs; EU, 2008, 2018) and the Landfill Directive (EC, 1999), they focus on different resources and parts of the life cycle and for the time being they are not designed to provide an overall life-cycle approach (LCA). Therefore, one of the priority objectives of the 2013 7th EAP is to turn the EU into a resource-efficient, green and competitive low carbon dioxide economy (EC, 2013). One solution proposed to achieve this has been the concept of the CE and its application to the built environment that has gained considerable industry and policy support internationally and at the EU level over the past few years. The long-term vision of the 7th EAP is for a CE where nothing is wasted and where natural resources are managed sustainably (EC, 2013). To ‘close the loop’ and develop a CE the EU’s circular economy package (EC, 2015a) consists of an action plan with a list of follow-up initiatives and corresponding timelines,

and four new legislative proposals on waste. The CE is an essential contribution to the efforts of EU to develop a sustainable, low carbon dioxide, resource-efficient and competitive economy. The *EU Action Plan for the Circular Economy* (EC, 2015a) addresses five main areas: production (including product design and production processes); consumption (including labelling, reuse, repair, planned obsolescence and public procurement); waste management (including extended producer responsibility, recycling and harmonisation of methodologies); supporting markets for secondary raw materials and horizontal measures (including innovation, investment and monitoring). Key drivers include: the *EU Action Plan for the Circular Economy* (EC, 2015a) that proposes a restoratively designed economy to keep products, components and materials at their highest value at all times (EMF, 2015); the EC communication *On Resource Efficiency Opportunities in the Building Sector* (EC, 2014b) that calls for more resource-efficient design, planning, manufacturing and construction; the *EU Construction and Demolition Waste Management Protocol* (EC, 2016) that highlights the need of increasing confidence in C&DW management processes and C&D recycled materials; and the *Guidelines for the Waste Audits before Demolition and Renovation Works of Buildings* (EC, 2018).

The new WFD (EU, 2018) was approved by the EU in July 2018 and was transposed into Irish Law in July 2020. It requires EU member states to improve their waste management systems, to improve the efficiency of resource use and to ensure that waste is valued as a resource (EP, 2018). A large proportion of Ireland’s RE policy legislation is based on EU initiatives and directives and these directives are then transposed into Irish Law through legislation and policies of Ireland. The Irish government has implemented a number of policy and legislative documents dating back to 1996 with the implementation of the Waste Management Act (WMA) (ISB, 1996). The main objectives of the WMA were to improve performance of prevention and recovery of waste and to set out a regulatory framework in response to EU and national requirements (ISB, 1996). The 1996 WMA was subsequently amended by the WMA 2001 (ISB, 2001) and the Protection of the Environment Act 2003 (ISB, 2003). These Acts are the legislative basis for all waste management (WM) issues in Ireland. The WFD 2008 (EU, 2008) was entered into Irish Law in March 2011 and sets out the concepts and definitions relating to WM, such as the definitions of waste, recycling and recovery. It also explains when waste ceases to be waste and becomes a secondary raw material (so-called end-of-waste criteria), and how to distinguish between waste and by-products (EU, 2008). Also articles 28(1) and 29(1) of the WFD emphasise that waste management plans and waste prevention should be established in accordance with the waste hierarchy (EU, 2008). Ireland’s RE strategy was published in 2014 in the *Towards a Resource Efficient Ireland: A National Strategy to*

2020 document (EPA, 2014). While the document does not contain specific targets for the construction sector, the overarching objective is to implement EU and national policy on RE to break the link between economic growth and environmental impact. More specifically, it aims to reduce wasteful consumption of material, water and energy resources by changing behaviours, and enhance competitiveness and reduce business costs through the implementation of RE and the CE (EPA, 2014). There is currently no specific construction industry RE legislation in place in Ireland as RE is distributed among the other sectors' policies such as environment, energy and waste. The government's *Construction 2020: Strategy for a Renewed Construction Sector* (DHPLG, 2014) provides the basis for rebuilding a sustainable (in the economic sense) construction sector that has the capacity to build the houses and infrastructure that a society needs, and making its full contribution to economic recovery (EC, 2015b). The document does not mention the sustainable management of C&DW. The focus now must be on the actual WM and minimisation if these legislative improvements are to be maintained and national targets for C&DW recovery are to be achieved. In order to achieve the targets, set out in the policy and legislation, a radical change in attitudes, design considerations and on-site WM is needed.

Waste prevention, energy management and water management within the construction sector will play a central role in enhancing RE and creating a CE that enables society to maximise the economic return on scarce resources (EC, 2020). Europe and Ireland can gain many social and economic benefits from treating waste as a resource with the EC estimating that the implementation of CE models will create 580 000 jobs in the EU alone and save EU companies €600 billion (EP, 2018). The CE is expected to boost the EU's competitiveness by protecting businesses against scarcity of resources and volatile prices, helping to create new jobs and business opportunities and innovative, more efficient ways of producing and consuming. At the same time, it will save energy and help avoid the irreversible damages caused by using resources at a rate that exceeds the Earth's capacity to renew them in terms of climate and biodiversity, air, soil and water pollution (EC, 2020).

3. Literature review

Over the last 20 years, the concept of sustainability has been growing in importance and it has currently become the basis of most socio-economic activities and developments in the built environment (Edum-Fotwe and Price, 2009; Kelly *et al.*, 2019). However, the implementation of RE strategies to reduce GHG emissions and improve competitiveness has not yet been sufficiently tested by research. Collaborative research is needed to assess the merits of different RE strategies (Bleichwitz, 2011; EPA, 2019).

The construction industry is aware that it has an important role to play in minimising waste production (Gálvez-Martos *et al.*, 2018; Osmani, 2012) because materials and resources are vital in terms of supporting the industry (Kabirifar *et al.*, 2020; Knoeri *et al.*, 2011). The trend of previous peer-reviewed C&DW research to date has focused on general C&DW management (Tam, 2008), recycling, waste reduction techniques (Poon, 2007), generation, reuse and human factors through case studies, surveys, reviews and experiments (Yuan and Shen, 2011) and the identification of best practice for the management of C&DW (Gálvez-Martos *et al.*, 2018). Additional studies have also focused on modern approaches to waste minimisation such as the use of building information modelling (BIM) (Liu *et al.*, 2015; Lu *et al.*, 2017; Xu *et al.*, 2019). Despite this level of research, several authors have noted that the practical implementation of C&DW management strategies has been far from effective (Ajayi *et al.*, 2015, 2016; Gálvez-Martos *et al.*, 2018; Kofoworola and Gheewala, 2009; Lingard *et al.*, 2000; Osmani *et al.*, 2006; Tam, 2008; Yuan and Shen, 2011). At a project-level scale, Cheshire (2016), the Ellen MacArthur Foundation (EMF, 2015) and Wrap in the UK (Wrap, 2015) have provided a series of case studies that demonstrate how RE and circularity strategies can be embedded into the construction process by using low embodied, low toxicity, recycled and resource-efficient materials and components; improving energy performance; designing for deconstruction; designing out waste and using performance-related services – that is, fixtures and fittings. While a large volume of research has been carried out on the management and reduction of C&DW there is still a lack of research on the actual implementation of waste strategies in construction projects during the construction phase. To identify waste reduction opportunities (and RE opportunities), it is essential that the different phases of a building's life cycle are explored that includes a considerable amount of waste produced and the energy and water used during the construction process. When projected on to a building's life cycle, the research therefore concentrated on several life cycle phases including the construction, fit-out and retrofit phases.

Literature about energy reduction initiatives in other areas such as the manufacturing industry is extensive (Blackhurst *et al.*, 2011; Cheng *et al.*, 2020; Hallinan *et al.*, 2012; Mujtaba *et al.*, 2012; Woroniak and Piotrowska, 2014) but the literature in relation to energy usage on construction sites, during the construction phase, is lacking (Acquaye and Duffy, 2010; Davies *et al.*, 2014, 2015; Guo *et al.*, 2019; Hong *et al.*, 2015). With regards to energy, to date, all national estimates have referred to operational energy, for example energy usage in the residential sector (SEAI, 2015), with some studies focusing on the embodied energy used during the pre-construction phases only (Acquaye and Duffy, 2010; Fenner *et al.*, 2020; Goggins *et al.*, 2010; Hong *et al.*, 2016). Previous research has reflected

the legislative and policy approach to energy efficiency by focusing primarily on design and operational energy opportunities with less of an emphasis on embodied energy, particularly related to on-site construction activities (Bilec *et al.*, 2006; Davies *et al.*, 2015; Guo *et al.*, 2019). Energy use during the material, transportation and construction phases up to project practical completion is known as initial embodied energy. Previous research has focused on sections of this initial embodied energy, such as Dixit *et al.* (2015) who analysed the embodied energy of construction materials, Salcido *et al.* (2016) who compared the embodied energy of alternate materials for a construction project and Davies *et al.* (2015) who assessed the initial embodied energy associated with material extraction, transportation and construction phases. However, although it is important to consider this overall LCA in initial embodied energy it is also important to analyse the construction phase as a standalone element of the project life cycle, as the overall initial embodied impact has been deemed to be greater than the operational impact at the end of a building's 25-year lifespan (Davies *et al.*, 2015). The construction phase does offer more readily available 'live' data in the form of fuel receipts (petrol and diesel), metered energy use (gas and electricity) and plant/material registers that can address the perceived lack of quantifiable construction-phase embodied energy benchmarks (Bilec *et al.*, 2006; Davies *et al.*, 2013, 2014; Li *et al.*, 2010; Paganin *et al.*, 2017). This study focused on the enabling works, assembly processes and the installation work during the construction phase of four case study buildings to evaluate the impact of selected energy, waste and water reduction measures in terms of cost, energy savings (in kWh) and carbon dioxide (CO₂) emissions.

Water consumed directly by the construction industry has largely not been considered (Choudhuri, 2015; McCormack *et al.*, 2007). While water used to operate buildings is a significant component of worldwide water consumption, this is not the only form of water consumed throughout a building's life cycle (Akadiri *et al.*, 2012; Choudhuri, 2015). Water is also consumed in the extraction, production, manufacturing and delivery of materials and products to site, and the actual on-site construction process. The research carried out on water usage in the construction sector to date has largely focused on water quality monitoring during civil engineering and construction projects (Amado, 2013; Belayutham *et al.*, 2016a; Belayutham *et al.*, 2016b; Cocchiglia *et al.*, 2012; Houser and Pruess, 2009; Ooshaksaraie, 2011), while the impact of construction and civil engineering projects on water bodies has also been assessed (Raposo *et al.*, 2010; Rybka *et al.*, 2016). Stephan and Crawford (2014) found that studies typically consider only operational water that excludes the embodied water of a construction project. Additional research has also focused on elements of the embodied water in buildings with McCormack *et al.* (2007), Han *et al.* (2016) and Meng *et al.*

(2016) assessing the water embodied in building materials while Crawford and Pullen (2011) and Stephan and Crawford (2014) focused on an analysis of the life cycle of water in residential buildings. However, this embodied water does not feature significantly within the literature. Therefore, this study will also address this gap in the research by analysing the usage of water on construction sites and investigate the methods that can be used to reduce this usage.

Research has previously been undertaken on the various individual facets of RE as detailed above – that is, waste, energy and water; however, this previous research has focused on individual strands of RE whereas this study uses a more holistic approach to include these strands in one research project. Therefore, this study will address the research gap that exists for analysing the implementation of RE measures during construction and investigate the impact of reduction measures that can be undertaken during the construction phase of a project. This study therefore represents the first comprehensive attempt to provide quantitative guidance regarding the implementation of RE strategies within the Irish construction industry.

4. Methodology

This study employed a case study methodological approach in collaboration with a small-to-medium enterprise building contractor based in the West of Ireland. The study consisted of four case study projects that were undertaken over a 2-year period; these four case study projects ranged in value from €95 000 to €1.6 million and ranged from 199.5 to 401.3 m² in floor area. During the research, 85 site visits were carried out along with the completion of 69 RE audits. Details of the case studies are presented in Table 2.

The contractor provided a suitable sample due to its fundamental role during the construction phase (Davies *et al.*, 2014) and its willingness to examine current on-site practices to facilitate pragmatic action research (AR). This involved active participation by the researcher during the construction phase to explore the setting with a view to advancing understanding of the research area (Cousin, 2005; Fellows and Liu, 2012; Taggart *et al.*, 2014) that in this case was RE on site. The following series of activities were undertaken to identify 'actionable' interventions (Altrichter *et al.*, 2002; Baskerville, 1999; Brownlee *et al.*, 2019; Coughlan and Coughlan, 2002; Huxham and Vangen, 2003): site visits; on-site observations; site meetings with management; informal dialogue with site personnel; auditing and benchmarking energy and water use and waste production. This approach was framed by the cyclical model proposed by Susman and Evered (1978), who outlined the following key stages: diagnosing the issue or problem; developing an action plan to address the problem or improve

Table 2. Summary of case study projects

Case study number and name	Project type	Floor area: m ²	Value	Project length: months
Case study 1 Block M	Demolition and landscaping	199.5	€95 000	1
Case study 2 CF unit	New build healthcare	223.8	€590 000	9
Case study 3 Podiatry unit	New build healthcare	401.3	€1 600 000	9
Case study 4 HDU	Demolition and fit out	212	€765 000	3.5

the situation; implementation of the plan; evaluating the impact and specifying learning from this process (Figure 1).

The cyclical nature of the AR process provided the flexibility required to accommodate the construction project setting for the research and supported the necessity to divide the project into individual case study projects, where each complete cycle would inform the implementation of RE strategies in subsequent projects. This reflective process of progressive problem solving was carried out using a ‘Lessons Learned’ report that was presented to the case study contractor following the completion of each case study. This also enabled the research to systematically build on the problem solution and move towards a more holistic understanding, a key characteristic of AR (Coghlan and Brannick, 2005). This required the establishment of a client-system infrastructure (Chein, 1948; Susman and Evered, 1978) to facilitate a close collaborative working environment that encouraged deep participant involvement (Nielsen and Nielsen, 2006).

Several existing auditing tools were used during the project phases including the Sustainable Energy Authority of Ireland (SEAI) Energy Tracker tool; SEAI Register of Opportunities tool; SEAI Significant Energy Users tool (all available from the

SEAI website (SEAI, 2020)) and the Galway Mayo Institute of Technology Construction and Demolition Waste Audit book (not currently publicly available). The use of these tools informed the development of an RE auditing tool that was used on a weekly basis to benchmark RE practices on the selected case studies and allowed for the tracking of energy, waste and water usage data. This tool, in turn, informed the preparation of the RE plans that were implemented in the site. The initiatives were carefully monitored and evaluated to determine their effectiveness; identify any limitations or barriers and produce a set of key performance indicators (KPIs) for RE.

5. Results and discussion

This study sets out to explore the use of quick-win RE interventions during the construction phase and identified a series of RE initiatives that, when implemented, reduced the environmental impact of on-site activities and making significant cost savings. In addition, recommendations were made on how to improve RE practice on site that suggested further savings. It was clear from the analysis of RE on the case studies that opportunities exist to move the focus higher up the waste hierarchy towards reuse and prevention and that energy management can also be significantly improved. To address this, the following waste prevention, energy and water reduction practices were implemented: materials’ optimisation; waste segregation and benchmarking; appropriate materials’ management and logistics; use of minimal packaging; facilitating material take-back schemes, reuse of materials on site, night-time energy management, lighting controls and the installation of a water tap and tool-washing area. Results suggest that the case study contractor was open to most of these initiatives with the largest cost savings for the main contractor made in relation to waste segregation, reuse of materials, material and packaging take-back schemes and night-time energy management. A total of 74 RE initiatives were implemented on the four case study sites that included 49 waste management initiatives (Table 3), 11 energy management initiatives (Table 4) and 14 water management initiatives (Table 5) as shown in Tables 3–5.

Figure 1. AR cycle (source: Susman and Evered (1978))

The total cost savings, energy savings (kWh), waste reduction estimates (t), diversion from landfill levels and the carbon

Table 3. Waste management initiatives implemented in the case study projects

Waste management initiatives implemented	Block M	CF unit	Podiatry	HDU
Identification of waste causes, quantities and composition throughout the project	✓	✓	✓	✓
RE audits incorporating waste management on site	✓	✓	✓	✓
Pre-demolition audit to identify recycling and reuse opportunities within the existing structure	✓	N/A	×	×
Source segregation of waste produced on site with correct skip signage in place at all times	✓	×	✓	×
Use of a segregated timber waste skip	✓	×	✓	×
Use of a segregated metal waste skip	✓	×	×	×
Use of a segregated bin for office and canteen waste	N/A	×	✓	✓
Timber pallets segregated on site and returned to suppliers through a take-back scheme	×	✓	✓	✓
Timber cable drums segregated on site and returned to suppliers through a take-back scheme	N/A	✓	✓	✓
Removal of landscaping/building materials prior to construction works that were incorporated into the final design	×	✓	✓	✓
Sand and stone delivered in canvas bags to site to reduce material wastage through poor storage	N/A	✓	✓	✓
Hoarding and hoarding posts removed and stored for reuse in future projects	N/A	✓	✓	✓
Use of material optimisation when ordering materials – for example, metal stud wall system, plasterboard and ceiling tiles	N/A	✓	✓	✓
Setting up of central cutting and storage areas for plasterboard and carpentry trades	N/A	✓	✓	✓
Selection of a waste management contractor with a high diversion from landfill rate	✓	✓	✓	✓
Festoon lighting system removed correctly and stored for use in future projects	N/A	×	✓	✓
Timber shuttering kept for reuse in subsequent projects	N/A	×	✓	×
Minimal use of 'floor guard' protection materials when nearing project completion	N/A	×	✓	✓
Specification of off-site-manufactured components such as sink splash backs, doors and door frames	N/A	✓	✓	✓

Table 4. Energy management initiatives implemented in the case study projects

Energy management initiatives implemented	Block M	CF unit	Podiatry	HDU
Identification of energy usage and causes of energy wastage throughout the project	×	×	×	✓
RE audits incorporating energy management on site	✓	✓	✓	✓
Site lighting switched off at the close of each working day to reduce night-time energy use	N/A	✓	✓	✓
Transformer boxes on site switched off at night-time, weekends and holidays	N/A	×	✓	N/A
Temporary lighting switched off on site during daylight hours	N/A	×	✓	×
External security lighting fitted with photocell technology	N/A	×	×	✓

Table 5. Water management initiatives implemented in the case study projects

Water management initiatives implemented	Block M	CF unit	Podiatry	HDU
Identification of causes of water wastage throughout the project	✓	✓	✓	✓
RE audits incorporating water management on site	✓	✓	✓	✓
Installation of a tap system to minimise water wastage	N/A	✓	✓	✓
Use of a tool-washing bin system for wet trades	N/A	✓	✓	✓

dioxide savings (t) are outlined in Table 6 for the four case study projects.

The total cost savings arising out of implemented waste management initiatives were estimated to be €14 567.70 over the four case studies, which represented 0.48% of the total project value (€3 050 032) and 15.9% of a theoretical profit margin of 3% (€91 500.96). As well as reducing costs, a well-managed approach provided quantifiable evidence that can be used to demonstrate cost savings and a responsible approach

to resource use. The implemented measures reduced the energy usage in the case study projects by a total of 11 373.09 kWh, reduced the waste production by 176.751 t and reduced carbon dioxide emissions by 34.941 t. The implementation of RE initiatives was achievable and cost savings were made in many areas of RE. Addressing RE shortcomings provided the case study contractor with additional profit, reduced carbon dioxide emissions in the projects and had the added benefit of helping the contractor to become more competitive within the industry (reduced overheads). The financial position of the

Table 6. Implemented RE measures in site – results

KPI	Block M	CF unit	Podiatry	HDU
Project value: €	95 000	590 000	1 600 000	765 032
Cost savings: €	680.36	1961.16	8834.61	3091.57
Savings on project value: %	0.72	0.33	0.55	0.40
Saving per m ² floor area: €	N/A	8.76	22.01	14.58
Energy savings: kWh	N/A	1908.06	6028.59	3436.44
Waste reduction: t	N/A	4.69	164.03	8.031
Diversion from landfill: t	99.7	90	90	90
Carbon dioxide emission reduction (t) from energy savings	N/A	1.215	3.84	1.189
Carbon dioxide emission reduction (t) from waste reduction	N/A	3.067	6.449	4.987
Carbon dioxide emission reduction (t) from waste diversion from landfill	1.48	1.648	6.191	4.925

construction industry in Ireland is not what it used to be, with many contractors working to low-profit margins (SCSI/PwC, 2019) and thus all the RE incentives proposed were balanced against additional implementation costs. All the initiatives implemented were quick-win options with low to no implementation costs. This is a similar finding to a Wrap study in 2015 which found that a structured approach to resource management planning will deliver significant reductions in resource use, often with little or no capital investment (Wrap, 2015).

The evaluation of RE initiatives in terms of profit margins, energy savings (kWh) and carbon dioxide emission reduction differs from previous studies (Cole, 1999; Davies *et al.*, 2013, 2014, 2015; Guo *et al.*, 2019; Gustavsson *et al.*, 2010; Hong *et al.*, 2015; Ramesh *et al.*, 2010) that attempted to benchmark construction-phase energy use to identify its contribution to the overall building life cycle energy use. For the purposes of this study and to encourage further co-operation and collaboration of industry, it was vital to clearly demonstrate the financial implications of implemented RE initiatives on site. This pragmatic approach aimed at influencing change by providing situated knowledge that would enable and empower project participants to exploit opportunities in RE improvement. Furthermore, RE fits well within wider business improvement initiatives, linking with the introduction of BIM, supply chain management and lean construction. By re-examining where resources are wasted, it is often possible to identify better ways of working that deliver cost, environmental, quality and other project benefits.

Although it is recognised that these results cannot be extrapolated across the construction sector due to differences in on-site management practices, data collection and reporting structures (Davies *et al.*, 2013), it is important to highlight that the measures of RE improvement that were implemented on site are easily repeatable across the sector. This actionable knowledge is highly relevant to the Irish construction sector in the current economic environment, including the impact of Covid-19 on the sector, as it provides an opportunity

to increase profit margins while also reducing negative environmental impacts.

6. Conclusions and recommendations

The implementation of RE measures in the four selected case studies produced cost savings of €14 567.70 representing 0.48% of the total project value (€3 050 032) and 15.9% of an estimated overall profit margin of 3% (€91 500.96). The total energy savings were estimated to be 11 373.09 kWh by switching off lighting, reducing night-time energy use and installing photocells. In addition, it was estimated that 176.751 t of materials were prevented from being placed in site skips through waste segregation, material optimisation measures, supplier take-back schemes, reuse of materials and appropriate materials management on site. The water management initiatives included the installation of a tap system and the use of tool-washing systems on site. The total reduction in carbon dioxide emissions from the implemented measures was 52.263 t, measured using the SEAI carbon calculator tools (SEAI, 2020), the Wrap Carbon Calculator for C&DW and the Wrap Water Monitoring Tool (both available from the Wrap website (Wrap, 2020)). The detailed review of RE practices in the four selected case studies has highlighted the need for further research in the following areas.

- Auditing should continue on other case studies to identify current best practice and identify opportunities to improve RE performance during the construction phase. This will enable the development of a set of industry KPIs that can be used by organisations when they want to benchmark their on-site performance.
- The case studies outlined herein along with other identified case studies should inform the development of an industry toolkit containing practical, research-informed and evidence-based factsheets for industry stakeholders involved in the construction process.
- Further research is required to explore the concept of RE using an LCA – that is, from initial design to operation and final end-use. This fits within the CE model where greater engagement at all stages in the supply chain would

enable the identification of material loop opportunities considering embodied elements (energy, carbon, waste and water), as well as operational and final end-use elements.

- Waste prevention and the development of supply chain material loops should be embedded in an overall RE design approach to provide a holistic template that will produce low (embodied and operational) energy buildings that produce little or no waste and use water efficiently through all stages in their life cycle.

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REFERENCES

- Acquaye AA and Duffy AP (2010) Input-output analysis of Irish construction sector greenhouse gas emissions. *Building and Environment* **45**(3): 784–791.
- Ajayi SO, Oyedele LO, Bilal M *et al.* (2015) Waste effectiveness of the construction industry: understanding the impediments and requisites for improvements. *Resources, Conservation and Recycling* **102**: 101–112.
- Ajayi SO, Oyedele LO, Bilal M *et al.* (2016) Reducing waste to landfill: a need for cultural change in the UK construction industry. *Journal of Building Engineering* **5**: 185–193.
- Akadir PO, Chinyio EA and Olomolaiye PO (2012) Design of a sustainable building: a conceptual framework for implementing sustainability in the building sector. *Buildings* **2**(2): 126–152.
- Altrichter H, Kimis S and McTaggart R (2002) The concept of action research. *The Learning Organisation* **9**(3): 125–131.
- Amado MP (2013) Sustainable construction: water use in residential buildings in Portugal. *International Journal of Sustainable Construction Engineering Technology* **4**(2): 14–22.
- Baskerville R (1999) Investigating information systems with action research. *Communications of the Association of Information Systems* **2**(19): 7–17.
- Belayutham S, González VA and Yiu TW (2016a) The dynamics of proximal and distal factors in construction site water pollution. *Journal of Cleaner Production* **113**: 54–65.
- Belayutham S, González VA and Yiu TK (2016b) A cleaner production-pollution prevention-based framework for construction site induced water pollution. *Journal of Cleaner Production* **135**: 1363–1378.
- Bilec M, Ries R, Matthews HS and Sharrard AL (2006) Example of a hybrid life-cycle assessment of construction processes. *Journal of Infrastructure Systems* **12**(4): 207–215.
- Blackhurst M, Azevedo IL, Matthews HS and Hendrickson CT (2011) Designing building energy efficiency programs for greenhouse gas reductions. *Energy Policy* **39**(9): 5269–5279.
- Beischwitz R (2011) Resource efficiency – five governance challenges toward a green economy. *Journal of Industrial Ecology* **15**(5): 644–646.
- Brownlee SA, Whitson PJ and Ibrahim AM (2019) Measuring and improving the design quality of operating rooms. *Surgical Infections* **20**(2): 102–106.
- Cahill O (2007) *An Analysis of the use of Photogrammetric Sorting to Audit Construction and Demolition Waste Production on Site*. MSc (Research) thesis, Department of Building and Civil Engineering, Galway-Mayo Institute of Technology.
- Chein I (1948) Behaviour theory and the behaviour of attitudes. *Psychological Review* **55**(3): 175–188.
- Cheng M, Shao Z, Gao F *et al.* (2020) The effect of research and development on the energy conservation potential of China's manufacturing industry: the case of east region. *Journal of Cleaner Production* **258**: 120558.
- Cheshire D (2016) *Building Revolutions: Applying the Circular Economy to the Built Environment*. RIBA Publishing, London, UK. See <https://bit.ly/32v3LUC> (accessed 25/08/2020).
- Choudhuri IR (2015) Assessment of embodied water of construction: case study of a four-star rated hotel in New Delhi, India. *International Journal of Emerging Engineering Research and Technology* **3**(8): 195–199.
- Cocchiglia L, Kelly-Quinn M, Bruen M, O'Sullivan J and Purcell P (2012) Water quality monitoring during the construction of the M3 motorway in Ireland. *Water and Environment Journal* **26**(2): 175–183.
- Coghlan D and Brannick T (2005) *Doing Action Research in Your own Organization*, 2nd edn. Sage Publications, London, UK.
- Cole R (1999) Energy and greenhouse gas emissions associated with the construction of alternative structural systems. *Building and Environment* **34**(3): 335–348.
- Coughlan P and Coghlan D (2002) Action research for operations management. *International Journal of Operations and Production Management* **22**(2): 220–240.
- Cousin G (2005) Case study research. *Journal of Geography in Higher Education* **29**(3): 421–427.
- Crawford R and Pullen S (2011) Life cycle water analysis of a residential building and its occupants. *Building Research and Information* **39**(6): 589–602.
- Davies PJ, Emmitt S and Firth SK (2013) On-site energy management challenges and opportunities: a contractor's perspective. *Building Research and Information* **41**(4): 450–468.
- Davies PJ, Emmitt S and Firth SK (2014) Challenges for capturing and assessing initial embodied energy: a contractor's perspective. *Construction Management and Economics* **32**(3): 290–308.
- Davies PJ, Emmitt S and Firth SK (2015) Delivering improved initial embodied energy efficiency during construction. *Sustainable Cities and Society* **14**: 267–279.
- DHPLG (Department of Housing, Planning and Local Government) (2014) *Construction 2020: Strategy for a Renewed Construction Sector*. Government Publications, Dublin, Ireland. See <https://bit.ly/34wdPiy> (accessed 24/08/2020).
- Dixit MK, Culp CH and Fernandez-Solis JL (2015) Embodied energy of construction materials: integrating human and capital energy into an IO-based hybrid model. *Environmental Science and Technology* **49**(3): 1936–1945.
- EC (European Community) (1999) Council Directive 1999/31/EC of 26 April 1999 on the Landfill of Waste. *Official Journal of the European Communities* **L182**/1.
- EC (European Commission) (2010) *Europe 2020: a European Strategy for Smart, Sustainable and Inclusive Growth*. European Commission, Brussels, Belgium. See <https://bit.ly/31omDoX> (accessed 24/08/2020).
- EC (2011a) *A Resource-Efficient Europe – Flagship Initiative under the Europe 2020 Strategy*. European Commission, Brussels, Belgium. See <https://bit.ly/2Er6Lc6> (accessed 24/08/2020).

- EC (2011b) *Roadmap to a Resource Efficient Europe*. European Commission, Brussels, Belgium. See <https://bit.ly/3lgsT9Q> (accessed 24/08/2020).
- EC (2012) *Strategy for the Sustainable Competitiveness of the Construction Sector and its Enterprises*. European Commission, Brussels, Belgium. See <https://bit.ly/3ja4KQw> (accessed 24/08/2020).
- EC (2013) *Living Well, Within the Limits of our Planet: 7th EAP — The New General Union Environment Action Programme to 2020*. Publications Office of the European Union, Luxembourg. See <https://ec.europa.eu/environment/pubs/pdf/factsheets/7eap/en.pdf> (accessed 21/08/2020).
- EC (2014a) *A Policy Framework for Climate and Energy in the Period from 2020 to 2030*. European Commission, Brussels, Belgium. See <https://bit.ly/34svbgj> (accessed 24/08/2020).
- EC (2014b) *On Resource Efficiency Opportunities in the Building Sector*. European Commission, Brussels, Belgium. See <https://ec.europa.eu/environment/eussd/pdf/SustainableBuildingsCommunication.pdf> (accessed 25/08/2020).
- EC (2015a) *Closing the Loop – An EU Action Plan for the Circular Economy*. European Commission, Brussels, Belgium. See <https://bit.ly/3hrsCP5> (accessed 24/08/2020).
- EC (2015b) *Construction and Demolition Waste Management in Ireland*. Deloitte, Belfast, UK. See <https://bit.ly/31fgE5y> (accessed 21/08/2020).
- EC (2015c) *EU Emissions Trading System (EU ETS)*. European Commission, Brussels, Belgium. See https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf (accessed 24/08/2020).
- EC (2016) *EU Construction and Demolition Waste Management Protocol*. European Commission, Brussels, Belgium. See <https://bit.ly/31eDhHp> (accessed 21/08/2020).
- EC (2017) *Level(s) – A Common EU Framework of Core Sustainability Indicators for Office and Residential Buildings*. Publications Office of the European Union, Luxembourg. See <https://bit.ly/3fQAbrx> (accessed 13/08/2020).
- EC (2018) *Guidelines for the Waste Audits before Demolition and Renovation Works of Buildings*. European Commission, Brussels, Belgium. See <https://bit.ly/3gm8vAC> (accessed 21/08/2020).
- EC (2020) *A New Circular Economy Action Plan for a Cleaner and more Competitive Europe*. European Commission, Brussels, Belgium. See <https://bit.ly/2PMelk3> (accessed 13/08/2020).
- Edum-Fotwe FT and Price ADF (2009) A social ontology for appraising sustainability of construction projects and developments. *International Journal of Project Management* **27**(4): 313–322.
- EMF (Ellen MacArthur Foundation) (2015) *Towards a Circular Economy: Business Rationale for an Accelerated Transition*. Ellen MacArthur Foundation, Isle of Wight, UK. See <https://bit.ly/3l6Q6LO> (accessed 21/08/2020).
- EP (European Parliament) (2018) *Circular Economy: Definition, Importance and Benefits*. European Parliament, Brussels, Belgium. See <https://bit.ly/30XOIbX> (accessed 13/08/2020).
- EPA (Environmental Protection Agency) (2014) *Towards a Resource Efficient Ireland: A National Strategy to 2020*. Environmental Protection Agency, Wexford, Ireland. See <https://bit.ly/33VaaKU> (accessed 13/08/2020).
- EPA (2016) *Ireland's Environment – An Assessment 2016*. Environmental Protection Agency, Wexford, Ireland. See http://www.epa.ie/pubs/reports/indicators/SoE_Report_2016.pdf (accessed 13/08/2020).
- EPA (2019) *Resource Efficiency in Priority Irish Business Sectors*. Environmental Protection Agency, Wexford, Ireland. See http://www.epa.ie/pubs/reports/research/waste/Research_Report_271.pdf (accessed 24/08/2020).
- EPA (2020) *National Waste Statistics Summary Report 2020*. Environmental Protection Agency, Wexford, Ireland. See <https://bit.ly/30T70ph> (accessed 13/08/2020).
- EU (European Union) (2008) Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain Directives. *Official Journal of the European Union* **L312/3**. See <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN> (accessed 21/08/2020).
- EU (2010a) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings. *Official Journal of the European Union* **L153/13**. See <https://bit.ly/3hpyInb> (accessed 24/08/2020).
- EU (2010b) Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control). *Official Journal of the European Union* **L334/17**. See <https://bit.ly/2Eccq6d> (accessed 24/08/2020).
- EU (2011) Regulation (EU) No. 305/2011 of the European Parliament and of the Council of 9 March 2011 Laying Down Harmonised Conditions for the Marketing of Construction Products and Repealing Council Directive 89/106/EEC. *Official Journal of the European Union* **L88/5**. See <https://bit.ly/3llioCz> (accessed 24/08/2020).
- EU (2012) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC. *Official Journal of the European Union* **L315/1**. See <https://bit.ly/34sd8qx> (accessed 24/08/2020).
- EU (2018) Directive (EU) 2018/851 of the European Parliament and of the Council of 20 May 2018 amending Directive 2008/98/EC on waste. *Official Journal of the European Union* **L150/109**. See <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0851&from=EN> (accessed 21/08/2020).
- Fellows R and Liu A (2012) *Research Methods in Construction*, 3rd edn. Blackwell Publishing, London, UK.
- Fenner AE, Kibert CJ, Li J et al. (2020) Embodied, operation, and commuting emissions: a case study comparing the carbon hotspots of an educational building. *Journal of Cleaner Production* **268**, N.PAG.
- Gálvez-Martos JL, Styles D, Schoenberger H and Zeschmar-Lahl B (2018) Construction and Demolition Waste Best Management Practice in Europe. *Resources, Conservation and Recycling* **136**: 166–178.
- Goggins J, Keane T and Kelly A (2010) The assessment of embodied energy in typical reinforced concrete building structures in Ireland. *Energy and Buildings* **42**(5): 735–744.
- Göttsche J and Kelly M (2018) Assessing the impact of construction waste reduction on selected projects in Ireland. *Proceedings of the Institution of Civil Engineers – Waste and Resource Management* **171**(3): 71–81, <https://doi.org/10.1680/jwarm.17.00034>.
- Göttsche J, Kelly M and Taggart M (2016) Assessing the impact of energy management initiatives on the energy usage during the construction phase of an educational building project in Ireland. *Construction Management and Economics* **34**(1): 46–60.
- Grimes D (2005) *The Assessment of Construction and Demolition Waste Arising on Selected Case Study Construction Projects in the Galway Region*. MSc (Research) thesis, Department of Building and Civil Engineering, Galway-Mayo Institute of Technology, Galway, Ireland.
- Guo S Z, Hu Y, Hong J, Wu X and Tang M (2019) Embodied energy use in the global construction industry. *Applied Energy* **256**: 113838.
- Gustavsson L, Joelsson A and Sathre R (2010) Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. *Energy and Buildings* **42**(2): 230–242.

- Hallinan K, Enns H, Ritchey S *et al.* (2012) Energy information augmented community-based energy reduction. *Sustainability* **4**(7): 1371–1396.
- Han MY, Chen GQ, Meng J *et al.* (2016) Virtual water accounting for a building construction engineering project with nine sub-projects: a case in E-town, Beijing. *Journal of Cleaner Production* **112**(5): 4691–4700.
- Hong J, Shen GQ, Feng Y, Lau WS and Mao C (2015) Greenhouse gas emissions during the construction phase of a building: a case study in China. *Journal of Cleaner Production* **103**(1): 249–259.
- Hong J, Shen GQ, Guo S, Xue F and Zheng W (2016) Energy use embodied in China's construction industry: a multi-regional input–output analysis. *Renewable and Sustainable Energy Reviews* **53**: 1303–1311.
- Houser DL and Pruess H (2009) The effects of construction on water quality: a case study of the culverting of Abram Creek. *Environmental Monitoring and Assessment* **155**(1–4): 431–442.
- Huxham C and Vangen S (2003) Researching organizational practice through action research: case studies and design choices. *Organizational Research Methods* **6**(3): 83–403.
- Iddon CR and Firth SK (2013) Embodied and operational energy for new-build housing: a case study of construction methods in the UK. *Energy and Buildings* **67**(1): 479–488.
- ISB (Irish Statute Book) (1996) *Waste Management Act 1996*. Government Publications, Dublin, Ireland. See <http://www.irishstatutebook.ie/1996/en/act/pub/0010/print.html> (accessed 21/08/2020).
- ISB (2001) *Waste Management (Amendment) Act 2001*. Government Publications, Dublin, Ireland. See <http://www.irishstatutebook.ie/eli/2001/act/36/enacted/en/html> (accessed 24/08/2020).
- ISB (2003) *Protection of the Environment Act 2003*. Government Publications, Dublin, Ireland. See <http://www.irishstatutebook.ie/eli/2003/act/27/enacted/en/html> (accessed 24/08/2020).
- Kabirifar K, Mojtahedi M, Wang C and Tam VWY (2020) Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: a review. *Journal of Cleaner Production* **263**, <https://doi.org/10.1016/j.jclepro.2020.121265>.
- Kelly M (2006) *The Development of an Audit Methodology to Generate Construction Waste Production Indicators for the Irish Construction Industry*. DPhil thesis, Department of Building and Civil Engineering at the Galway-Mayo Institute of Technology, Galway, Ireland.
- Kelly M and Dowd D (2014) *A Review of Design and Construction Waste Management Practices on Selected Case Studies – Lessons Learned, EPA STRIVE Programme Final Report*. Environmental Protection Agency, Wexford, Ireland. See <https://www.epa.ie/pubs/reports/research/waste/research-report-146-for-web.pdf> (accessed 13/08/2020).
- Kelly M and Dowd D (2015) *A Review of Design and Construction Waste Management Practices on Selected Case Studies: Lessons Learned, EPA Report 146*. Environmental Protection Agency, Wexford, Ireland. See <https://www.epa.ie/pubs/reports/research/waste/research-report-146-for-web.pdf> (accessed 25/08/2020).
- Kelly M, Burke K and Göttsche J (2019) Exploring material circularity opportunities for a construction-SME on small-scale projects in Ireland. *IOP Conference Series: Earth and Environmental Science* **225**: 012066.
- Knoeri C, Binder CR and Althuas HJ (2011) Decision on recycling: construction stakeholders' decisions regarding recycled mineral construction materials. *Resources, Conservation and Recycling* **55**(11): 1039–1050.
- Kofoworola OF and Gheewala SH (2009) Estimation of construction waste generation and management in Thailand. *Waste Management* **29**(2): 731–738.
- Li X, Zhu Y and Zhang Z (2010) An LCA-based environment impact assessment model for construction processes. *Building and Environment* **45**(3): 766–775.
- Lingard H, Graham P and Smithers G (2000) Employee perceptions of solid waste management systems in a large Australian contracting organisation: implications for company policy implementation. *Construction Management and Economics* **16**(1): 383–393.
- Liu Z, Osmani M, Demian P and Baldwin A (2015) A BIM-aided construction waste minimisation framework. *Automation in Construction* **59**(1): 1–23.
- Lu W, Webster C, Chen K, Zhang X and Chen X (2017) Computational building information modelling for construction waste management: moving from rhetoric to reality. *Renewable and Sustainable Energy Reviews* **68**: 587–595.
- McCormack MS, Treloar GJ, Palmowski L and Crawford RH (2007) Modelling direct and indirect water consumption associated with construction. *Building Research Information* **35**(2): 156–162.
- Meng F, Liu G, Yang Z *et al.* (2016) Structural analysis of embodied greenhouse gas emissions from key urban materials: a case study of Xiamen City, China. *Journal of Cleaner Production* **6**(1): 132–149.
- Mujtaba IM, Edreder EA and Emtir M (2012) Significant thermal energy reduction in lactic acid production process. *Applied Energy* **89**(1): 74–80.
- Neilsen GH and Neilsen D (2006) Response of high-density apple orchards on coarse textured soil to form of potassium applied by fertigation's. *Canadian Journal of Soil Science* **86**(4): 749–755.
- Ooshaksaraie L (2011) An expert system applied in construction water quality monitoring. *American Journal of Environmental Sciences* **7**(1): 75–81.
- Osmani M (2012) Construction waste minimization in the UK: current pressures for change and approaches. *Social and Behavioural Sciences* **40**(1): 37–40.
- Osmani M, Glass J and Price A (2006) Architect and contractor attitudes to waste minimisation. *Proceedings of the Institution of Civil Engineers – Waste and Resource Management* **159**(2): 65–72, <https://doi.org/10.1680/warm.2006.159.2.65>.
- Paganin G, Angelotti A, Ducoli C *et al.* (2017) Energy performance of an exhibition hall in a life cycle perspective: embodied energy, operational energy and retrofit strategies. *Energy Efficiency* **10**(6): 1343–1364.
- Poon CS (2007) Management of construction and demolition waste. *Waste Management* **27**(2): 159–160.
- Ramesh T, Prakash R and Shukla KK (2010) Life cycle energy analysis of buildings, an overview. *Energy and Buildings* **42**(10): 1592–1600.
- Raposo JR, Molinero J and Dafonte J (2010) Quantitative evaluation of hydrogeological impact produced by tunnel construction using water balance models. *Engineering Geology* **116**(3–4): 323–332.
- Rybka I, Bondar-Nowakowska E and Połowski M (2016) Causes and effects of adverse events during water supply and sewerage system constructions. *Archives of Civil Engineering* **62**(1): 173–184.
- Salcido JC, Raheem AA and Ravi S (2016) Comparison of embodied energy and environmental impact of alternative materials used in

- reticulated dome construction. *Building and Environment* **96**(1): 22–34.
- SCSI/PwC (Society of Chartered Surveyors Ireland/ PricewaterhouseCoopers) (2019) *Construction Market Monitor 2019*. Society of Chartered Surveyors, Dublin, Ireland. See <https://www.pwc.ie/publications/2019/scsi-pwc-construction-market-monitor-2019.pdf> (accessed 13/08/2020).
- SEAI (Sustainable Energy Authority of Ireland) (2020) See <https://www.seai.ie> (accessed 13/10/2020).
- Stephan A and Crawford R (2014) A comprehensive life cycle water analysis framework for residential buildings. *Building Research and Information* **42**(6): 685–695.
- Susman G and Evered R (1978) An assessment of the scientific merits of action research. *Administrative Science Quarterly* **23**(4): 582–603.
- Taggart M, Dosela L and Rooke J (2014) The role of the supply chain in the elimination and reduction of construction rework and defects: an action research approach. *Construction Management and Economics* **32**(7/8): 829–842.
- Tam VVY (2008) On the effectiveness in implementing a waste-management-plan method in construction. *Waste Management* **28**(6): 1072–1080.
- Ueda T, Roberts ES, Norton A *et al.* (2019) A life cycle assessment of the construction phase of eleven micro-hydropower installations in the UK. *Journal of Cleaner Production* **218**: 1–9.
- UN (United Nations) (2015) *Paris Agreement*. United Nations, Paris, France. See <https://bit.ly/34yN1OV> (accessed 24/08/2020).
- Woroniak G and Piotrowska JW (2014) Effects of pollution reduction and energy consumption reduction in small churches in Drohiczyn community. *Energy and Buildings* **72**(1): 51–61.
- Wrap (Waste and Resources Action Programme) (2015) *The Business Case for Resource Efficiency: Contractors*. Waste and Resources Action Programme, Banbury, England. See <https://bit.ly/2CLH4T1> (accessed 21/08/2020).
- Wrap (2020) See <https://wrap.org.uk/> (accessed 07/10/2020).
- Xu J, Shi Y, Xie Y and Zhao S (2019) A BIM-based construction and demolition waste information management system for greenhouse gas quantification and reduction. *Journal of Cleaner Production* **229**: 308–324.
- Yuan H and Shen L (2011) Trend of research on construction and demolition waste management. *Waste Management* **31**(4): 670–679.

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