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A Review of Design and Construction Waste Management Practices on Selected Case Studies – Lessons Learned

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Environment, Community and Local Government

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by

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DISCLAIMER

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Construction and demolition waste (C&D W) is estimated to account for one third of all waste generated in the European Union (EU)[1]. Generation rates in Ireland have fluctuated considerably over the past decade from 3 million tonnes (Mt) in 2001[2] to nearly 18 Mt in 2007[3] and back down to just over 3 Mt in 2011[4], demonstrating a direct correlation to the equally unprecedented economic growth and decline during this time. There is an opportunity at this time of relatively low construction output and economic recovery to rethink and re-imagine the design and construction process to promote a more resource-efficient approach.

Waste management legislation and policy have evolved towards a focus on prioritising waste prevention and life-cycle thinking. This has, in turn, highlighted the key role of all construction stakeholders in contributing towards a more resource-efficient industry. The recent EU Communication on *Resource Efficiency Opportunities in the Building Sector*[5] has called for the development of reliable indicators for C&D W management, the use of recycled content, the reusability and recyclability of construction materials and products, and design for deconstruction (plus other resource efficiency strategies). To date, C&D W research in Ireland has focused on end-of-pipe solutions by investigating the development of processing infrastructure[6], the generation of waste production indicators[7,8] and the evaluation of different audit methodologies[8,9].

1. EC (European Commission), 2011. (COM(2011) 1067/1068) *EU Roadmap towards Resource Efficiency.* EC, Brussels, Belgium.
2. EPA (Environmental Protection Agency), 2003. *National Waste Database Report 2001.* EPA, Johnstown Castle Estate, Co. Wexford, Ireland.
3. EPA (Environmental Protection Agency), 2009. *National Waste Report 2007.* EPA, Johnstown Castle Estate, Co. Wexford, Ireland.
4. EPA (Environmental Protection Agency), 2013. *National Waste Report 2011.* EPA, Johnstown Castle Estate, Co. Wexford, Ireland.
5. European Commission (EC), 2014. (COM(2014)445) *Resource Efficiency Opportunities in the Building Sector.* EC, Brussels, Belgium.

This study has moved the focus towards the top of the waste hierarchy by investigating the implementation of waste reduction strategies during the design and construction phases of two selected case studies, through a close collaboration with Scott Tallon Walker Architects and John Sisk & Son.

The result of the work is summarised in the following report, which describes the design and construction reviews that produced a set of simple and transferable lessons learned for the construction sector. The waste management strategies implemented during the construction phase on one of the case studies was also benchmarked using a set of critical success factors adapted from Cha et al.[10].

The major output of the project was the development of a Waste Reduction Toolkit for Design Teams[11] comprising the following series of factsheets:

- Principles for Designing out Waste
- Procurement and Tendering for Waste Reduction
- Materials Optimisation and Standardisation

6. Kelly, M., 2002. *The Development of a Construction and Demolition Waste Recycling Facility in Galway – A Case Study.* Unpublished M.Sc. (Research) Thesis, Department of Building and Civil Engineering, GMIT, Galway, Ireland.
7. Grimes, D., 2005. *The Assessment of Construction and Demolition Waste Arising on Selected Case Study Construction Projects in the Galway Region.* Unpublished M.Sc. (Research) Thesis, Department of Building and Civil Engineering, GMIT, Galway, Ireland.
8. Kelly, M., 2006. *The Development of an Audit Methodology to Generate Construction Waste Production Indicators for the Irish Construction Industry.* Unpublished Ph.D. (Research) Thesis, Department of Building and Civil Engineering, GMIT, Galway, Ireland.
9. Cahill, O., 2007. *An Analysis of the Use of Photogrammetric Sorting to Audit Construction and Demolition Waste Production on Site.* Unpublished M.Sc. (Research) Thesis, Department of Building and Civil Engineering, GMIT, Galway, Ireland.
10. Cha, H.S.; Kim, J.; Han, J., 2009. Identifying and assessing influence factors on improving waste management performance for building construction projects. *Journal of Construction Engineering and Management* **135(7):** 647–656.

- Off-Site and Modern Methods of Construction
- C&D W Reuse and Recycling Opportunities
- Deconstruction and Flexibility

11. Kelly, M., 2015. *Construction and Demolition Waste Reduction Toolkit for Design Teams.* Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland.

1 Background and Objectives

1.1 Legislation and Policy Actions

Construction and demolition waste (C&D W) production has fluctuated dramatically over the past decade, reflecting the equally unprecedented economic growth and subsequent sharp decline in Ireland. The Environmental Protection Agency (EPA) has estimated that C&D W production rose from 3.7 million tonnes (Mt) in 2001 (EPA, 2003) to a peak of 17.8 Mt in 2007 (EPA, 2009), with a subsequent decline to just over 3 Mt in 2011 (EPA, 2013). Irrespective of these varying generation rates, C&D W has continuously been one of the largest contributing waste sources in Ireland.

The past decade has witnessed significant changes in the management of waste in Ireland, moving from an over-reliance on landfill towards a more sustainable system of waste treatment, resulting in higher levels of recycling and recovery. This modernisation of waste management practices in Ireland has been directly influenced by European Union (EU) legislation, policies and strategies, especially through the implementation of the Waste Management Act, 1996 (DoEHLG, 1996). This provided a legislative basis to focus on the improvement of waste management practice and infrastructure. Government policy has supported this transition starting with the *Changing Our Ways* policy document (DoEHLG, 1998a), which set out ambitious construction sector recycling targets of 50% by 2003 and 85% by 2013, grounded in the recognised hierarchy of prevention, minimisation, reuse/recycling, energy recovery and disposal. Subsequent legislation (DoEHLG, 1998b,c, 2000a, 2001a) supported this improvement in regulation and infrastructure. In 2000, thresholds were introduced in the Planning and Development Act 2000 (DoEHLG, 2000b) for the application of C&D W plans[1]. The industry responded with the development of the National Construction and Demolition Waste Council (NCDWC) in 2002 to provide a platform for a voluntary initiative to meet these targets[2]. A number of industry publications followed focusing on legislative responsibilities, site management strategies and the preparation of C&D W plans (CIF and FÁS, 2002; RPS-MCOS et al., 2004; DoEHLG, 2006). In 2002, the policy statement *Preventing and Recycling Waste: Delivering Change* (DoEHLG, 2002a) specifically focused on waste prevention and recycling, emphasising the importance of taking a hierarchical approach, with prevention[3] highlighted as the most desirable option. Further regulatory and producer responsibility legislation followed (DoEHLG, 2002b, 2003a,b). The *National Waste Prevention Programme* was introduced in 2004 through the *Waste Management: Taking Stock and Moving Forward* policy document (DoEHLG, 2004). This programme sought to address a finding from the EU Commission Communication *Towards a Thematic Strategy on Preventing and Recycling Waste* (COM(203)301 final) (EC, 2005b) that limited progress was made in "… *turning the objective of waste prevention into practice*". The subsequent publication *Best Practice Guidelines on the Preparation of Waste Management Plans for Construction and Demolition Projects* (DoEHLG, 2006) provided the construction sector with a series of recommendations for the development of C&D W management plans. Further regulatory legislation on licensing, permitting and registration of waste facilities and recovery operations (DoEHLG, 2007a,b, 2008a,b) was implemented, which significantly increased the processing infrastructure available to the construction industry.

The transposition of the revised EU Waste Framework Directive into Irish law in 2011 by the European Commission (Waste Framework Directive) Regulations 2011 (SI 126 of 2011) (EC, 2008a) aimed to move beyond waste management towards a more resource-efficient and sustainable materials

1. Section 34(4)(l) of the Planning and Development Act 2000 permits the attachment of conditions relating to C&D W management.
2. This voluntary initiative was promoted through a national C&D W roadshow in 2005.
3. Prevention was defined as "*...reducing the quantity and harmfulness to the environment of materials and the substances contained therein*".

management approach. The Directive is grounded in a number of EU resource use, consumption and waste management strategies[4] and **means that for the first time the waste hierarchy is legally established in a national statute and should apply as a priority**.

The most recent Irish waste management policy *A Resource Opportunity – Waste Management Policy in Ireland* (DoECLG, 2012a) supported the prioritisation of the waste hierarchy (Fig. 1.1) and identified specific producer responsibilities for construction and demolition projects (over certain thresholds) as a key area for exploration[5].

The Green Public Procurement (GPP) action plan, *Green Tenders* (DoECLG, 2012b), has recommended that design teams should include both a qualitative and a quantitative assessment, including a demonstration of environmental design experience and/or qualifications as part of the construction procurement process, and that all construction materials should be assessed for environmental impact, including embodied energy and carbon dioxide, resource use, responsible sourcing, construction waste, durability, recyclability and disposal. This is further supported by the publication *Green Procurement: Guidance for the Public Sector* (EPA, 2014a), which sets out core GPP criteria focusing on demonstrating technical and professional capability including the following waste reduction initiatives:

- The contractor should prepare an outline construction environmental plan, which will include a **C&D W management plan**;
- An environmental management **training plan** must be developed to cover waste minimisation, management and selective waste collection strategies; and
- **Secondary aggregate and recycled materials** should be specified in place of virgin materials.

This procurement approach aligns with the overarching 2020 vision outlined in the recent national strategy *Towards a Resource Efficient Ireland: A National Strategy to 2020* (EPA, 2014b), which highlighted the importance of resource efficiency and waste prevention to the vision of a future circular

4. *Thematic Strategy on the Sustainable Use of Natural Resources* (COM(2005)670) (EC, 2005a); *Thematic Strategy on the Prevention and Recycling of Waste* (COM(2005)0666) (EC, 2005b); *Raw Materials Initiative* (COM(2008)699) (EC, 2008b); *EU 2020 Strategy for Smart, Sustainable and Inclusive Growth* (COM(2010)2020) (EC, 2010); and the *EU Roadmap towards Resource Efficiency* (COM(2011)1067/1068) (EC, 2011).
5. No specific detail was provided but this is likely to refer to the introduction of compliance bonds on projects that exceeded the thresholds outlined in the *Best Practice Guidelines on the Preparation of Waste Management Plans for Construction and Demolition Projects* (DoEHLG, 2006).

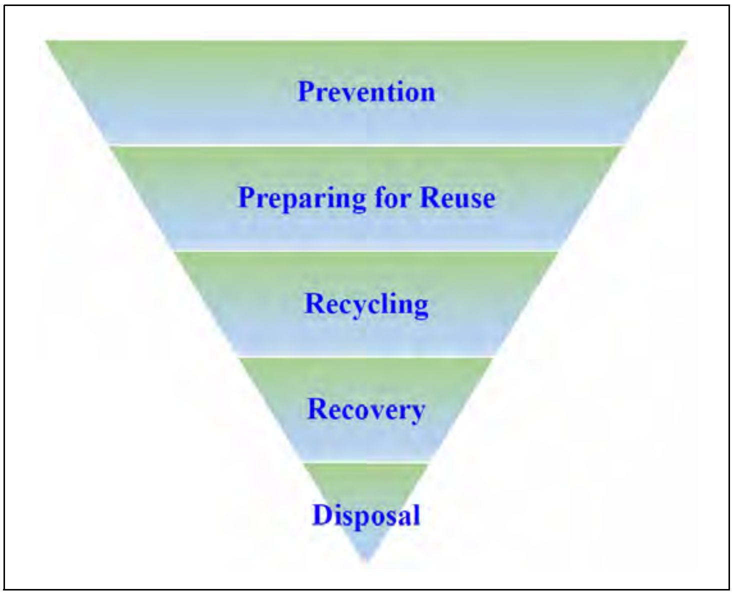

Figure 1.1. Waste management hierarchy as outlined in the Waste Framework Directive (EC, 2008a).

economy[6]. The recent EC Communication on *Resource Efficiency Opportunities in the Building Sector* (EC, 2014) has recognised the importance of design and material choice decisions and called for reliable indicators for C&D W management, recycled content in construction materials, recyclability and reusability of construction materials and products, and design for deconstruction.

6. Put simply, this is the reduction in our dependency on finite resources without compromising future development (EPA, 2014b).

This evolution in legislation and policy towards a more resource-efficient approach poses many challenges for the Irish construction sector. This study focused on the analysis of implemented waste reduction strategies during the design and construction phases of two selected case studies to develop a series of lessons learned that were applicable across the whole construction sector.

2 Research Approach and Results

2.1 Case Studies

The case study analysis was structured to evaluate waste reduction strategies implemented during the design and construction phases of two selected case studies. These 'live' case studies, the Human Biology Building (HBB) on the National University of Ireland, Galway (NUI Galway) Campus and the Mater Adult Hospital (MAH) extension to the Mater Misericordiae University Hospital in Dublin offered a unique insight into C&D W management approaches employed by design and construction teams.

The HBB was designed as a 8,200 m^2, four-storey cast in-situ reinforced concrete-frame educational building, with glass, stone and aluminium facades, a full height colonnade and a semi-basement accommodating three separate departments for anatomy, pharmacology and physiology on the NUI Galway Campus. The MAH extension was a 67,800 m^2, part five-storey, part nine-storey, public hospital built over a two-storey underground basement. The main structural frame was a cast in-situ reinforced concrete frame, with architectural concrete cladding and a modular glazing system making up the facade.

2.2 What is C&D W?

For the purposes of this study, the EPA definition of C&D W as "...*all waste that arises from construction and demolition activities including excavated soil from contaminated sites....listed in Chapter 17 of the European Waste Catalogue (EWC*[7]*)*" (EPA, 2012) will be used[8].

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7. The European Commission established the EWC to provide a common terminology to improve the collection and management of data on waste in Europe. This was published as the *European Waste Catalogue and Hazardous Waste List* by the EPA in 2002 (http://www.epa.ie/pubs/reports/waste/stats/epawastecataloguehazardlist2002pdf.html#.VMkY-dKsVQI).
8. It is worth noting, however, that the C&D W stream can overlap into other EWC chapters (Chapters 8, 15 and 20) (Llatas, 2011).

2.3 Origins and Causes

Tracing the origins and causes of C&D W is key to understanding how to prevent and minimise it. By far the most comprehensive analysis of the principal causes of waste was carried out by Skoyles on 280 building projects over a 20-year period (1963–1983) in the UK (Skoyles 1976a,b,c; Skoyles and Skoyles, 1987). This research defined the nature of C&D W into categories of natural, direct, indirect, substitution, production, operational, negligent and consequential waste. According to Skoyles and Skoyles (1987), within the direct and indirect waste strands lay a number of causes, including:

- Delivery waste;
- Site storage and internal site transit waste;
- Conversion waste;
- Cutting waste;
- Applications and residue waste;
- Waste due to the uneconomic use of plant;
- Management waste;
- Waste caused by other trades;
- Criminal waste;
- Waste due to wrong use;
- Materials wrongly specified;
- Learning waste;
- Substitution of materials;
- Builder's errors; and
- The use of excess quantities not allowable under the contract.

Several researchers have since classified the origins and causes of waste according to material types (Formorso et al., 2002; Pinto and Agopyan, 1994),

Table 2.1. Design, tendering and contract-related waste causes (adapted from Gamage, 2011).

- Design changes
- Poor design drawings and specification
- Lack of collaboration between project stakeholders
- Complicated design using composite materials
- Lack of knowledge on materials optimisation
- Poor contract documentation
- Contract and/or tendering strategy not suitable for effective waste reduction

Table 2.2. Construction-related waste causes (adapted from Gamage, 2011).

- Materials management and logistics, e.g. ordering, delivery and storage
- Poor materials specification
- Poor or unnecessary materials handling
- Poor or inappropriate storage
- Lack of on-site supervision and management
- No site waste management plan
- Poor communication on-site and a lack of clear responsibilities
- Poor workmanship, errors and rework
- Poor sequencing of work packages leading to damage by succeeding trades
- Lack of materials optimisation resulting in excessive off-cuts
- Inadequate, incorrect or excessive packaging
- Time pressure
- Site office/canteen waste

project activities (Gavilan and Bernold, 1994; Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000) and project life cycle (Osmani et al., 2008). Gamage (2011) summarised the main causes of waste relating to the design, tendering and contracts, and construction phases (Tables 2.1 and 2.2), collating previous work[9] by Keys et al. (2000), Tam et al. (2007a) and Osmani et al. (2008). The benchmarking of waste causes is a key element in measuring waste project performance and can inform the development of preventative strategies during the design and construction phases.

9. The previous work also included Gavilan and Bernold (1994), Bossink and Brouwers (1996) and Ekanayake and Ofori (2000), as listed above.

2.4 Designing Out C&D W

The design phases offer the best opportunities to prevent waste, as highlighted in the opportunity curve for material efficiency and waste reduction at each stage of a project (Fig. 2.1) (BSI, 2013).

As the design moves through the different stages, decisions are made that become fixed, with the cost of making any changes increasing. It should be noted

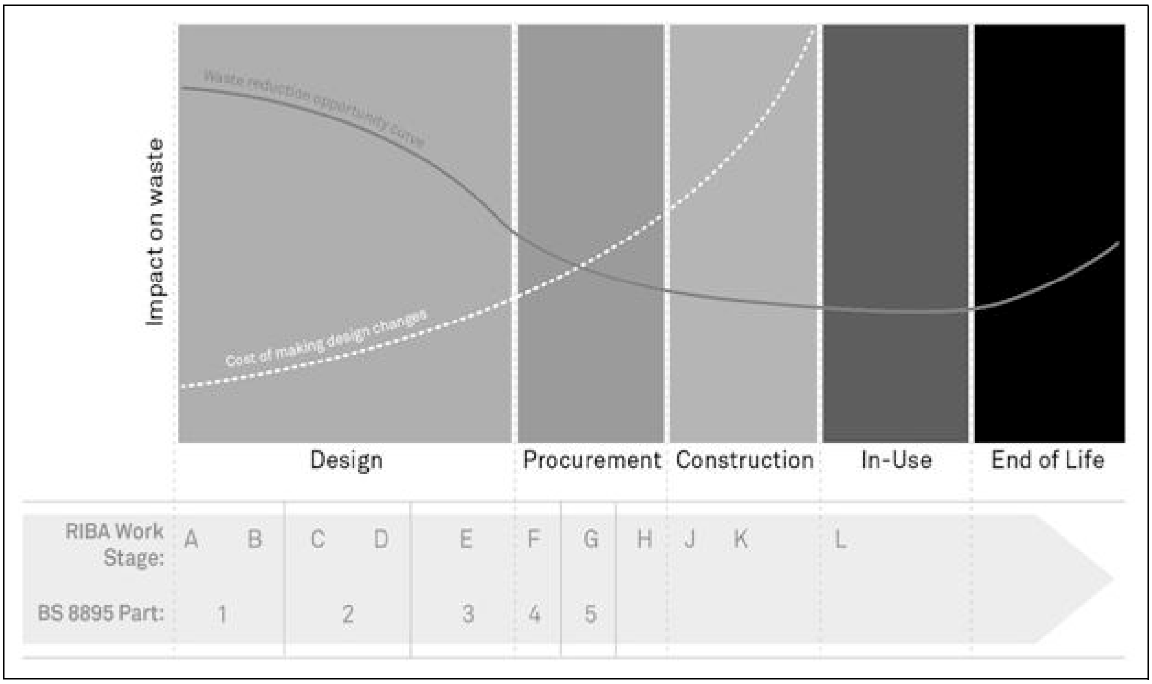


Figure 2.1. Indicative opportunity curve for material efficiency and waste reduction against each stage of a project (BSI, 2013). Permission to reproduce extracts from *BS 8895-1:2013 Designing for material efficiency in building projects* is granted by BSI. British Standards can be obtained in PDF or hard copy formats from the BSI online shop: www.bsigroup.com/shop or by contacting BSI Customer Services for hardcopies only: Tel: +44 (0)20 8996 9001, Email: cservices@bsigroup.com.

that opportunities still exist during the procurement, construction, operational and end-use phases but the maximum impact is made during the initial design and planning stages. The extent of the waste reduction potential has been highlighted by Innes (2004), who suggested that 33% of all on-site waste was due to a failure to implement waste reduction measures during the design stages. Osmani et al. (2008) supported the view that poor design contributed significantly to construction waste generation based on previous research carried out in this area (Bossink and Bouwers, 1996; Faniran and Caban, 1998; Ekanayake and Ofori, 2000; Chandrakanthi et al., 2002). This may be due, in part, to the awareness and attitudes of the design profession as highlighted by the observation of McDonald and Smithers (1996) "*...consultants involved in the design and procurement process are often unaware of the waste implications of their design approaches. Similarly, they are often unaware of the environmental and cost implications of building waste. Relatively few designers adopt an identifiable design waste minimisation strategy, and waste reduction in the design stage is carried out as a by-product of the total cost*".

This is supported by the finding of Poon et al. (2004a) that designers attached relatively little importance to waste reduction potential when selecting materials for a project. This is further reinforced by Osmani et al. (2006), who identified that architects did not view waste as a priority as they believed that it was rarely generated during the design stages despite a notable body of literature (Coventry and Guthrie, 1998; Greenwood et al., 2003; Poon et al., 2004a; Baldwin et al., 2006) identifying the architectural profession as having a key role to play in construction waste reduction. Interestingly, Osmani et al. (2008) found that architects expressed a willingness to design out waste if this was incentivised by the clients through an enhanced fee. The respondents viewed this as an additional cost, as reducing waste was not viewed as a core activity in the design process.

2.5 Waste Management Attitudes of Irish Architects

A survey of waste management attitudes and perceptions of Irish architects was undertaken in 2009[10], which focused on environmental policies, attitudes and sources of information, responsibilities, waste causes, implemented strategies, barriers and incentives. The main findings were as follows:

- Eight per cent of respondents had ISO 14001 certification, with 29% having an environmental policy and 42% having a waste management policy.
- Seventy-five per cent of respondents viewed C&D W as an inevitable by-product of designing for the built environment.
- Fifty-one per cent of respondents recognised waste as a priority in the design process.
- Eighty-one per cent cited '*self-study and personal research*' as their main sources of information, highlighting a gap in professional training provided. This '*lack of knowledge and training*' is also highlighted as a main barrier.
- There is a recognition that shared responsibility is a key component to effective waste management on a project, with the client, architect and main contractor (if involved early) sharing almost equal responsibility during the design phase. Interestingly, during the construction phase, the respondents also view an equal sharing of responsibility between the main contractor, subcontractors and building suppliers, with some input from the client and architect.
- The two major design-phase waste causes identified were '*general design changes*' and '*last-minute changes due to client's requirements*', supporting the findings outlined in Table 2.1.
- The three major construction-phase waste causes identified were '*poor site management*', '*unskilled and untrained labour*' and '*improper storage space and methods*', supporting the findings outlined in Table 2.2.
- There was a lack of waste reduction strategies employed, with high percentages never employing any, e.g. 72% of respondents never set any waste management goals.
- Respondents employed waste reduction principles, such as off-site construction (37% 'frequently') and materials optimisation (37% 'frequently'), in the design process.
- The main barriers identified were cost (67% 'major barrier'), no commitment from client (61% 'major barrier'), and lack of knowledge and training (58% 'major barrier').
- The main incentives identified were financial rewards (78% 'major incentive') and government policies and legislation (54% 'major incentive').

This survey highlighted a lack of waste management policy direction and training in the architectural sector in Ireland[11] but, encouragingly, all the main construction stakeholders (clients, architects, main contractors, subcontractors, suppliers) were seen to have a role to play in effective waste management. The main waste causes identified during the design and construction phases were design changes and poor site management, with C&D W viewed as an inevitable by-product of the construction process. This, in addition to the perceived barriers of cost and lack of client commitment, may explain the absence of any consistent implementation of waste management strategies during the design process and on-site.

The understanding of architects' attitudes towards waste management helps to identify potential

10. An online questionnaire was disseminated to 200 architects, resulting in a response rate of 21% (42 valid questionnaires returned). The vast majority of respondents were from small architectural firms (83%), 79% of which could be termed 'micro-firms' (having less than 10 employees). The responses were analysed using the SPSS/PASW statistical analysis software. The data were coded, formatted and examined for errors by examining the frequency distribution of the variables and comparing them to the original survey questionnaires, scanning for double entry errors in the data set, and assigning missing values to each individual question that had not been completed by the respondents so as to avoid skewing the results.

11. Primarily based on micro to small architectural firms.

opportunities for improvement, i.e. knowledge gaps, and provides a bridge between explicit guidance and tacit knowledge in the sector.

2.6 The Five Principles of Designing out C&D W

In recent years, the UK Waste and Resources Action Programme (WRAP) has produced a series of resources on waste minimisation and designing out waste (DoW) for clients, design teams[12] and contractors in construction and civil engineering projects (WRAP, undated). The aim of these guidance documents, tools and case studies was to empower industry stakeholders to recognise the opportunities that exist to reduce waste and is framed within five key principles:

1. Design for reuse and recovery;
2. Design for off-site construction;
3. Design for materials optimisation;
4. Design for waste-efficient procurement; and
5. Design for deconstruction and flexibility.

Table 2.3 outlines a series of strategies framed within these five principles, which were used to review the waste management strategies implemented in the two case studies.

12. Design teams include architects, civil and structural engineers, building surveyors, landscape architects, consultants and manufacturers who contribute to, or have overall responsibility for, any part of the design, or who specify or alter a design, or who specify the use of a particular method of work or material, such as the design manager, the quantity surveyor who insists on specific material or a client who stipulates a particular layout for a particular project *(BS8895: Designing for Material Efficiency in Building Projects Part 1 Draft*, 2012).

Table 2.3. Summary of waste reduction strategies taken from Waste and Resources Action Programme designing out waste principles and case studies.

Designing out waste principle	Strategies
Design for reuse and recycling	• Reuse of land, buildings and building components • Reuse and recovery of materials from excavations, demolition and refurbishment works • Specifying the use of recycled content in new build
Design for waste-efficient procurement	• A more collaborative and co-operative procurement approach, e.g. design and build • Early co-ordinated involvement of project stakeholders • Good project communication with clearly defined responsibilities • Clear procurement and tendering documentation, including the setting of key performance indicators, a requirement for waste reduction plans and benchmarking of waste production
Design for materials optimisation	• Minimisation of excavations • Simplification and standardisation of building materials and components • Dimensional co-ordination
Design for off-site construction	• Use off-site systems, e.g. volumetric modular buildings, panellised modular building systems, including timber frame and steel frame panellised building systems • Use off-site building elements, e.g. bathroom and kitchen pods, building envelope components, including composite panels for exterior walls and roofing • Use off-site building components, e.g. structural insulation panels (SIPs), structural insulation roof panels (SIRPs) and precast structural panels
Design for deconstruction and flexibility[1]	• Adaptable and flexible in plan, detail and structure • Accessible components that are removable considering the building layers and anticipated lifespan • A fixing regime to facilitate removal of components • Specify durable materials to facilitate maximum reuse opportunities • Avoid the use of resins, adhesives and coatings • Plan services and service routes for easy maintenance and replacement

[1]Morgan and Stevenson (2005) recommended these six deconstruction detailing principles, which were based on 27 principles previously outlined by Crowther (2001).

2.7 Design Review of Selected Case Studies

The design review of the HBB was carried out during a 16-month collaboration with Scott Tallon Walker Architects during the design development, specification and contract preparation phases[13]. The design review of the MAH development was a retrospective analysis carried out during a 36-month collaboration with John Sisk & Son during the main construction works[14]. Both case studies were reviewed using the five WRAP DoW principles.

2.7.1 HBB Development

2.7.1.1 Design for waste-efficient procurement

The Waste Management Plan (WMP) design phase included a number of waste-efficient procurement recommendations as follows:

- A pre-demolition audit of the existing buildings was carried out prior to the commencement of the demolition works. This included proposals on selective demolition to maximise the potential for material recovery.

- A minimum key performance indicator (KPI) was set of 90% by weight or 80% by volume of the material in the existing building to be reused and/or recycled.

- A minimum KPI was set of 75% by weight or 65% by volume of non-hazardous construction waste generated by the construction works to be diverted from landfill by reusing on-site, reusing on other sites, salvaged/reclaimed for reuse, returned to suppliers via 'take-back' schemes, recovered from site by a licensed waste management contractor and or reused/recycled off-site. A more detailed non-hazardous construction waste benchmark to not exceed 15 m^3/100 m^2 gross internal floor area or 7.7 t/100 m^2 gross internal floor area was recommended[15].

- A detailed Site Waste Management Plan (SWMP) was prepared[16] to be implemented by the main contractor using the guidelines outlined in the *Best Practice Guidelines on the Preparation of Waste Management Plans for Construction and Demolition Projects* document published by the Department of the Environment, Heritage and Local Government (DoEHLG, 2006). This included recommendations on supplier 'take-back' schemes, co-operation with subcontractors, education and training through site-specific toolbox talks, waste auditing and record keeping.

- The tendering strategy for the HBB project used a Most Economically Advantageous Tender (MEAT) scoring strategy, where the preparation of a waste minimisation and management plan was to account for 2.5% of the available marks.

In addition, during the design development, a number of design decisions had to be signed off by the client to continue the process. This provided an opportunity to introduce 'design freezes', thereby avoiding subsequent design changes[17].

2.7.1.2 Design for reuse and recycling

The proposed HBB was situated on the current site occupied by the National Diagnostics Centre (NDC) and the Marine Science buildings (Plates 2.1 and 2.2), both of which were to be demolished.

The new building footprint was maximised on-site to 8,200 m^2 (HBB) from an existing footprint of approximately 1,250 m^2 (NDC and Marine Science outbuilding). An initial pre-demolition audit of both buildings was carried out by the research team to identify any building components or materials that had recovery and/or recycling potential (Tables 2.4 and 2.5).

13. Unfortunately, the project was put on hold due to funding cuts. The enabling works commenced on-site in November 2012 and were completed but no construction works have commenced on-site to date.
14. The study commenced on-site in October 2009.
15. These benchmarks were within the BREEAM (Building Research Establishment Environmental Assessment Methodology) 1-credit range of 13.3–16.6 m^3/100 m^2 and 6.6–8.5 t/100 m^2. The project was not seeking BREEAM accreditation but it was felt that this was a realistic first-time target.
16. This was to be submitted to the client's representative prior to the commencement of the construction works.
17. For example, where early agreement on room layouts, accommodation requirements and services equipment was required as any subsequent changes would have resulted in a significant redesign.

Plate 2.1. The existing National Diagnostic Centre building at NUI, Galway.

Plate 2.2. The existing Marine Science outbuilding at NUI, Galway.

Table 2.4. Summary of recommendations from the external visual assessment of the National Diagnostics Centre (NDC) building and the Marine Science outbuilding.

Category	Recommendation
Hazardous materials	• The asbestos facade panels of the NDC building and the asbestos roof of the Marine Science outbuilding to be removed by a specialist contractor.
Remove permanent fixtures	• External windows, doors, external lighting, signage, ventilation units to be deconstructed with a potential high reuse in other buildings on campus. If not suitable for reuse on campus, then other reuse and recycling alternatives should be investigated. The reuse and relocation of fuel storage tanks should be investigated.
Marine Science outbuilding facades	• The rear facade of stonework may provide an opportunity for reuse in the new build.
Other items	• Bicycle stands and shelters, fire assembly signage and recycling bins should be relocated on campus. The alternative fire assembly point should be agreed with the Galway Fire Officer.

As can be seen from the external and internal visual assessments (Tables 2.4 and 2.5), the primary objective was the safe removal of the asbestos and hazardous materials. Following this, the Demolition Recovered Material Potential[18] of building components, such as external windows, doors, external lighting, signage, internal doors, windows, ceilings and furniture, was high if deconstructed in an appropriate manner to enable direct reuse in other projects. The reuse of the existing stonework on the Marine Science outbuilding in the new development was recommended to contribute to the New Build Recovery Index[19] in this project.

2.7.1.3 Design for materials optimisation

There were limited opportunities for materials optimisation in the general design due to the curved and splayed plan shape of the proposed building. The basement depth was minimised by 1.5 m to reduce excavation requirements, which equated to preventing approximately 2,500 m^3 or 7,100 t of excavated materials. A shadow gap detail[20] was specified around internal doors, which was predicted to save approximately 3,000 m of architrave that would have been used in a traditional detail and a bespoke metal ceiling system design from SAS International was specified in accordance with the plan shape.

2.7.1.4 Design for off-site construction

During the design phase, building elements (cladding, glazing, doors, frames, furniture and equipment) were assessed for their off-site manufacture suitability but no details were available during the design review as the detailed designs were to be prepared by the

Table 2.5. Summary of recommendations from the internal visual assessment of the National Diagnostics Centre (NDC) building.[1]

Category	Recommendation
Remove furniture/fittings	• Furniture and fittings (office chairs, desks, work tables, etc.) have a high recovery potential. The design team should meet with the client to determine 'ownership' and responsibility for the management of internal furniture and fittings.
Remove permanent fixtures	• Internal doors, windows, suspended ceilings, lighting, etc., all have high recovery potential. Again, possible reuse in other buildings on campus should be discussed with the client. Electrical fixtures will require specialist removal.
Remove hazardous materials	• 'Loose' and stored hazardous materials should be removed by a specialist contractor. Equipment and machinery employing hazardous material needs to be assessed by a specialist to determine the level of contamination. The overall level of contamination should be assessed before deciding on recovery strategies for all categories listed.
Selective demolition of structure	• The steel trusses should be deconstructed and removed off-site for recycling with a selected recycling company. The masonry concrete and reinforced concrete structure can be demolished and removed off-site for processing to be used as a secondary material. There is potential to reuse this material on-site for non-structural applications but on-site processing may not be feasible considering the space limitations, noise and dust impacts.
Segregate demolition materials	• Depending on the reuse and recycling end uses identified, materials can be segregated according to the categories listed, i.e. metals/steel, inert materials, paper (documentation may require confidential shredding) and rubbish. Hazardous materials will be segregated and removed by a specialist contractor.
Waste materials removal	• Appropriate licensed waste management contractors and facilities will be selected for any materials removed off-site.

[1]An internal visual assessment was not carried out of the Marine Science outbuilding as access was not granted.

selected manufacturer who was not appointed at that time.

2.7.1.5 Design for deconstruction and flexibility

The stone facade and glazed sections of the new building were identified as deconstructable elements. It was recommended that the glazing units should be bolted on and the stone connection detail should have a mechanical connection to facilitate deconstruction.

2.7.2 MAH development

2.7.2.1 Design for waste-efficient procurement

The design-and-build procurement approach allowed the main contractor and the design team to carry out a value engineering exercise on the original design. The primary aim was to reduce costs and shorten the construction programme, while still producing a quality product that satisfied the client's requirements. This prioritisation did have some negative impact regarding potential waste generation, as was evidenced in the design decision to change the structural frame from precast to in situ[21]. This was contrary to previous research findings, which had demonstrated the waste reduction potential and improved efficiency to be gained from using off-site construction, i.e. precast components and elements (Tam et al., 2005, 2007b; WRAP, 2007; Jallion et al., 2009; Shen et al., 2009)[22]. Other design decisions, however, had a positive impact on waste generation. For example, the major subcontracting elements (mechanical and electrical services) were tendered early to initiate design

18. The Demolition Recovered Material Potential represents the tonnage of material that can be recovered from the building or infrastructure.
19. The New Build Recovery Index is the percentage of demolition materials that could be recovered and used in the new build.
20. A 'shadow gap' is where a space is left between two surfaces so they appear to 'float' apart rather than butted up tightly together.
21. The main reason cited to change from a precast structural concrete frame to an in-situ structural concrete frame was to allow for the on-site drilling of service openings when required, which would not have been possible with hollowcore without affecting the structural integrity.
22. Precast components and elements were used as outlined in Section 2.7.2.4.

collaboration between the main contractor, the design team and the selected subcontractors. The project tendering process for the work packages used the MEAT scoring system, which included a section on waste management[23], and each major subcontractor was requested to prepare a SWMP after the tender award. The project was aiming for BREEAM certification, which included credits for waste management. The project BREEAM waste target was set at <9.2 m^3 or <4.7 t/100 m^2 (gross internal floor area), which represented three credits[24]. The preparation and implementation of the SWMP outlined the:

- Waste minimisation strategies to achieve the targeted benchmark;
- Procedures for minimising hazardous waste;
- Auditing and reporting protocols;
- Designated responsibilities; and
- Source segregation guidelines.

The most effective procurement strategy implemented was the use of 'design freezes' applied to the design of the lift shafts and service risers early in the project, which facilitated the detailed design of the slipform system and reinforced concrete detailing.

2.7.2.2 Design for reuse and recycling

The project was an extension to the existing Mater Misericordiae University Hospital in Dublin. The extension added another 45,685 m^2 floor area, with 20,000 m^2 of basement over two levels. Bulk excavation was required across the entire site to facilitate the two-storey underground car park, which meant that approximately 200,000 m^3 of excavated soil were transported off-site by the designated waste contractor to be used in restoration works in a disused quarry. Concrete from demolition works[25] was also transported off-site to be recycled (crushed) and sold as class 6F4 fill.

23. This was usually scored by the project quantity surveyors at pre-tender meetings.
24. This dropped to two credits towards the end of the project as waste production increased in the fit-out phase.
25. Two large structures (part of the old hospital and nurses' accommodation) were demolished during the enabling works prior to the involvement of the research team.

2.7.2.3 Design for materials optimisation

The two main design decisions that influenced materials optimisation were the application of a grid layout in the overall design and the use of a reusable independent formwork system called slipform for the four main stairs and lift cores. The overall design of the building was based on a grid layout consisting of a basement grid of 8.4-m sections to optimise car parking and blockwork between columns, with the rest of the building in 7.2-m sections (multiple of 600 mm and 900 mm grids) to optimise the hospital layout[26]. The 11-storey lift shafts[27] and the four main stair cores were built using the slipform formwork system. This is a method of vertically extruding a reinforced concrete section (core walls) in high-rise structures, i.e. lift shafts, stair shafts, towers, etc. The formwork was raised vertically in a continuous process (depending on the concrete hardening rate), supporting itself on the core rather than on other parts of the building or permanent works[28]. The formwork consisted of three platforms (Plate 2.3):

1. The lower platform providing access for concrete finishing;
2. The middle platform, which is at the top of the poured concrete level and acted as the main working platform; and
3. The upper platform, which provided a storage, preparation and distribution area.

The use of the slipform system had a number of benefits as follows:

- Crane use was minimised as the slipform system did not require it to move upwards.
- As the formwork system moved upwards, the exposed concrete left was finished and integrated into the construction process.

26. The basement grid system layout was not suitable for upper floors and would have required more reinforcement and thicker slabs. In addition, the building does not extend over the full area of the basement so the columns would not have lined up.
27. This consisted of 14,000 m^2 of core walls.
28. The rate varied but generally aimed at 4 m/day based on a 10-h day.

Plate 2.3. Basic slipform rig on the Mater Adult Hospital Project.

- Minimal scaffolding and temporary works were required.
- It required considerable planning and detailing in the design phase as there was little flexibility for change once the continuous concreting had commenced. This initiated a 'design freeze' on these work packages.
- Once the shafts were completed, the system was disassembled, cleaned and made ready for use on a different project with virtually no formwork waste created (Plate 2.4).

Another materials optimisation strategy used was the replacement of the internal plasterboard ceiling finish specification to a grid-and-tile system to accommodate the services openings required (Plate 2.5).

The services design required hundreds of access panels to facilitate maintenance of fire dampers, stop valves, ducting, etc. The grid-and-tile system negated the need for access panels, thereby avoiding considerable plasterboard off-cuts, which was estimated to potentially produce 6,200 m^2 of plasterboard waste[29]. The cleanrooms retained the internal plasterboard finish due to concerns regarding dust collection with the grid-and-tile system. Other strategies included the specification of a post-tensioned floor slab[30] for the level 0 slab to allow for a thinner slab thickness to create more space for services in the level 1 ceiling and the use of Whiterock[31] instead of tiling (Plate 2.6).

Plate 2.4. Completed lift shaft with slipform being dismantled (right side) with other shafts near completion.

Plate 2.5. Grid and tile ceiling system prior to installation of tiles.

29. This estimate was based on a 14% wastage rate, which represented the waste generation of the partitions contractors on-site.

30. This design was recommended as one of WRAP's design detailing sheets which suggested associated waste, cost and carbon emissions benefits in comparison with a standard reinforced concrete slab.

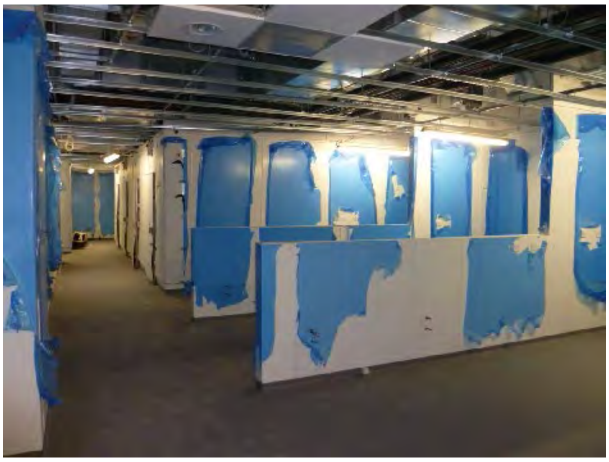


Plate 2.6. Whiterock sheeting fitted to catering area.

Plate 2.7. Facade panels with 75-mm rigid insulation board ready to be lifted into place on-site.

2.7.2.4 Design for off-site construction

The main off-site construction design decisions focused on building envelope components, resulting in the specification of concrete cladding panels from Techrete and terracotta and glazing modular facade panels from Architectural Aluminium Ltd[32]. The Techrete concrete cladding panels were produced off-site in its Dublin factory, with the manufacturing process using high-grade formwork and specialised[33] concrete to provide the required high quality fair-faced concrete finish. Insulation was fixed to the rear of the concrete units as required (Plate 2.7). Once manufactured, the panels were transported to site and lifted into place by a crane. The panels were bolted to the concrete frame using cast-in 'Halfen Channels', which were embedded into the concrete structure. This process allowed rapid progress on-site (two panels/hour), with a high-quality finish to strict dimensional tolerances[34].

The modular bespoke facade panels were also manufactured off-site by Architectural Aluminium Ltd in its Dublin factory. The aluminium-framed facade units comprised several different components, including terracotta tiles, glazing sections, mock ventilation panels, interstitial blinds, opening window sashes, electrical motors to power the blinds, and insulation backing for the panels. Each unit was produced individually depending on the internal and external requirements of where that unit was to be placed. The frames of the units were aluminium, which was cut to precise dimensions using a computer-controlled mill. The frames were placed into a template to ensure they were kept square during production. An assembly line process was then used to add each feature to the units as required. Each unit had a barcode, which was scanned at each workstation to ensure the correct elements were added. When assembled, the units were transported to site and lifted into place using a crane (Plate 2.8) and bolted into position using the Halfen Channels. The facade was sealed using a rubber membrane, which was bonded to the concrete columns and floor slab, in order to prevent water ingress and air leakage.

The other main off-site strategy was the use of the Stair Master formwork system for the internal staircases, which was a partial off-site construction approach in that the metal formwork was custom made off-site with structural steelwork built-in (Plate 2.9). This reduced the need for temporary formwork on-site, which would

31. This is a fully bonded hygienic system that provides a watertight seamless surface particularly suited to healthcare building applications.
32. A site visit to each of the manufacturing plants found that minimal waste was produced during the production of the building envelope components.
33. Coloured cement and aggregates are used to provide the required colour and finish.
34. Tolerance included a 10-mm gap between panels to allow for expansion and contraction. This was filled using a grey sealant to match the colour of the concrete.

Plate 2.8. Finished facade units ready for installation (in the foreground).

Plate 2.9. Stair Master formwork in place on the Mater Adult Hospital project.

have eventually ended up as waste. Concrete was poured on-site to complete the process.

The use of steel for the in-situ concrete structural frame was also targeted as a material to be cut and bent off-site in accordance with steel schedules prepared by the structural engineers.

2.7.2.5 Design for deconstruction and flexibility

Internal partitions were designed to be removed and altered to facilitate the reconfiguration of the internal layout. The steel frames and screwed-on metal facades used for roof-top plant area can be easily deconstructed (Plate 2.10).

Plate 2.10. Demountable structural steel frame plant area.

2.8 Design Review Summary

Table 2.6 provides a useful checklist to review the design strategies implemented on both case studies[35].

2.9 Construction Phase Review of MAH

The review was carried out over a 36-month period covering the main construction works from commencement on-site to the completion of Phase 1A. The contents of the project SWMP were used to analyse the following: implemented site waste management strategies, waste generation on-site, and the organisational waste management climate of the project stakeholders.

The implementation of site waste management strategies was informed by the SWMP and the setting of BREEAM KPIs. Due to the nature of the project and the associated large work packages, it was decided to assign the six main subcontractors[36] responsibility for their own waste management, which included the preparation and implementation of a SWMP specific to their work package detailing the predicted waste generation estimates and associated costs[37], preventative and minimisation strategies, and

35. In both case studies, the review covers implemented strategies.
36. Kone (vertical transport), Patrick Lynch (electrical), Leo Lynch (mechanical), Mid-West Formwork and Reinforcement (structural frame), Errigal Contracts (partitions) and Platt Reilly Partition and Ceiling Specialists.
37. At the request of the project participants, costs were kept confidential.

Table 2.6 Design review summary of Human Biology Building (HBB) and Mater Adult Hospital (MAH) case studies.[1]

	HBB	MAH
Design for Reuse and Recycling		
• Reuse of land, buildings and building components	✓	✓
• Reuse and recovery of materials from excavation, demolition and refurbishment works	✓	✓
• Specifying the use of recycled content in new build	×	×
Design for Waste-Efficient Procurement		
• A more collaborative and co-operative procurement approach, e.g. design and build	✓	✓
• Early co-ordinated involvement of project stakeholders	✓	✓
• Good project communication with clearly defined responsibilities	✓	✓
• Clear procurement and tendering documentation, including the setting of key performance indicators (KPIs), a requirement for waste reduction plans and benckmarking of waste production	✓	✓
Design for Materials Optimisation		
• Minimisation of excavations	✓	✓
• Simplification and standardisation of building materials and components	×	✓
• Dimensional co-ordination	×	✓
Design for Off-Site Construction		
• Use off-site systems, e.g. volumetric modular buildings, panellised modular building systems, including timber frame and steel frame panellised building systems	×	×
• Use off-site building elements, e.g. bathroom and kitchen pods, building envelope components including composite panels for exterior walls and roofing	×	✓
• Use off-site building components, e.g. structural insulation panels (SIPs), structural insulation roof panels (SIRPs) and precast structural panels	×	✓
Design for Deconstruction and Flexibility[2]		
• Adaptable and flexible in plan, detail and structure	×	✓
• Accessible components that are removable considering the building layers and anticipated lifespan	×	×
• A fixing regime to facilitate removal of components	×	✓
• Specify durable materials to facilitate maximum reuse opportunities	✓	✓
• Avoid the use of resins, adhesives and coatings	×	×
• Plan services and service routes for easy maintenance and replacement	✓	✓

[1]Due to the delay in the HBB project, a number of the strategies were not considered at the time of the review and are therefore listed as 'not implemented'. The 'implemented' strategies represent those that were implemented to some extent on the project and may not have been fully implemented, i.e. deconstruction fixing regime relates to some building elements on the MAH but not all.
[2]Morgan and Stevenson (2005).
✓, Implemented; ×, not implemented.

management of hazardous waste. In addition, each of the main subcontractors ordered and purchased their own materials[38], provided their own skips and selected their own waste management contractors. An 'ordering to use' policy was implemented on-site due to the limited storage.

John Sisk & Son's main role on-site was the co-ordination of work packages, including the arrangement of temporary works. This resulted in a high percentage of waste generated from these work packages being segregated at source (Plate 2.11).

Plate 2.11 Segregated subcontractor containers for timber, metals and inert waste.

The rest of the subcontractors[39] on-site were provided with skips by the main contractor (John Sisk & Son) who employed a mini-skip (1,100 l or 2 t) distribution network serving several subcontractors in any one zone. The mini-skips were rolled to a transfer point where a telescopic handler or crane would move them to the central waste management area. As the project progressed, the site became more confined and the central waste management area was also used for the delivery of materials. The contents of the mini-skips were transferred into large (35 yd^3/26.8 m^3) containers and returned empty to an appropriate zone. When full, the large containers were collected and transported off-site by the designated waste management contractor. Where possible, mini-skips that contained segregated material (Plate 2.12) were transferred and deposited into larger segregated containers.

Plate 2.12. Segregated insulation waste mini-skip.

On average, there were between six and ten large containers (20–35 $yard^3$) on-site with the same number of standard skips (12–14 $yard^3$), which were supplemented by the numerous mini-skips and wheelie bins used at various work stations. Generally, the large containers were not compacted before transfer off-site[40].

To inform the implementation of the skip distribution network, the large subcontractors recommended the delivery of waste management toolbox talks in their waste reduction plans. Three toolbox talks were developed by the research team, focusing on block laying, in-situ concrete, and plasterboard, and were delivered to the relevant site personnel. General waste management performance on-site was communicated through a weekly poster placed in the canteen that outlined actual versus planned performance in line with project progression.

38. Apart from the concrete and steel for the main structural frame, which was ordered and purchased by John Sisk & Son at a more competitive rate.
39. There were 103 subcontractors under John Sisk & Son's waste management control over the course of the project.
40. The BRE SMARTWaste tool applies a 40% estimate to all uncompacted skips but this was adjusted to reflect site practices and was applied on a skip-by-skip basis, ranging from 25% to 40% void estimates.

2.9.1 Site waste generation, causes and implemented waste reduction measures

Data on the type and volume of waste generated were based on actual waste movements from the construction site. The BRE SMARTWaste tool was used to benchmark waste performance. In total, based on detailed skip volume analysis, 13,087 m^3 of construction waste were generated over 36 months to Phase 1A completion. When the void percentages were applied, the total figure was reduced to 8,081 m^3. This equated to 11.9 m^3/100 m^2, which achieved two BREEAM waste management credits. The compositional breakdown of the total waste generated on-site (with void percentages applied) identified the major material waste fractions as: mixed (2,671 m^3), timber (2,263 m^3), gypsum (820 m^3), metals (675 m^3), and concrete (455 m^3). These five waste streams accounted for 85% of the total waste generated over the 36-month audit period.

2.9.1.1 Mixed waste

The high volume of mixed waste (2,671 m^3) was primarily due to the implementation of the mini-skip distribution network to serve the waste management requirements of the 103 subcontractors that the main contractor was responsible for. In total, 140 large (35 yd^3/26.8 m^3) mixed-waste containers were removed off-site for processing[41] during the study period.

2.9.1.2 Timber waste

Timber waste was generated consistently throughout the project, resulting in a total estimate of 2,263 m^3. A significant proportion was produced during the construction of the main structural frame, with 814 m^3 made up of timber formwork and framing off-cuts. Most of this was due to the layout design complexity requiring bespoke formwork, which could not be reused due to the quality of finish required. As already discussed, a number of design decisions, i.e. the use of the slipform and Stair Master systems, resulted in the reduction in the amount of potential formwork waste. In addition, the use of flat slab construction utilising formwork tables proved to be an effective waste reduction strategy as it allowed the formwork components to be reused throughout the construction process[42]. The formwork tables consisted of structural timber supports covered in high-quality shuttering plywood. They were placed side by side (Plate 2.13), with the void spaces between them filled with cut plywood as required. Both the tables and the cut plywood[43] were reused many times on-site.

Plate 2.13. Flat slab construction using formwork tables.

Timber was also used extensively in the temporary protection of works, with two layers of 18-mm plywood required over corrugated plastic sheeting in 10,000 m^2 of floor area[44] (Plate 2.14). Following site use, undamaged sheets were transferred to other John Sisk & Son sites for reuse but the majority of plywood sheets were damaged and placed in segregated timber skips.

The mini-skip distribution network deployed by John Sisk & Son for the subcontractors under their waste management control accounted for 62% of the total timber waste generated (1,398 m^3). Ninety per cent of all the timber waste was segregated at source (Plate 2.15) facilitating more effective recovery and reducing skip costs. The timber waste was chipped off-site at the recycling facility and sent to Finsa Forest

41. With a 90% recovery rate.

42. Flat slab construction also facilitates the installation of services and partitions due to its flat ceiling.

43. The cut plywood can be reused many times once it gives the required finish.

44. Floors were sequenced to be completed before the commissioning of services.

Plate 2.14. Two layers of 18-mm plywood laid out for temporary protection.

Plate 2.15. Segregated timber waste for reuse.

Products Ltd for use in producing wood products and SmartPly for use in the manufacture of plywood and orientated strand board (OSB).

2.9.1.3 Gypsum waste

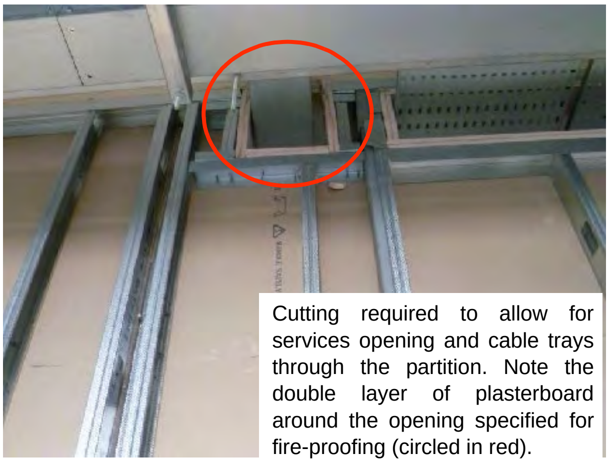
Gypsum waste (820 m^3) mainly consisted of plasterboard off-cuts (Plate 2.16). Plasterboard sheets were ordered and delivered in 2.4 m × 1.2 m sheets of varying thickness (9 mm, 12 mm, 15 mm, 18 mm) and were cut to size on-site to suit design openings and services requirements (Plates 2.17 and 2.18). In addition, improper storage resulted in damaged materials that could not be used for their original intended purpose.

Plate 2.16. Plasterboard off-cuts in a segregated skip on-site.

All of the segregated gypsum waste from the partition work elements were sent for processing to the Panda Waste Ltd recycling facility. The recycled gypsum materials was used by Lagan Cement as part of its cement production process and the paper was shredded and sold for animal bedding.

The design decision to switch to a grid-and-tile ceiling system significantly reduced the potential amount of plasterboard off-cuts due to the number of services openings required. During the construction phase, the research team recognised an opportunity to reduce plasterboard waste on-site and advised the main contractor to include waste minimisation plans as a requirement for subcontractors tendering for partition work packages. This was agreed in the pre-contract meetings and resulted in plasterboard sheeting being ordered to size, with the reuse of off-cuts encouraged where appropriate and the segregation of the plasterboard waste stream on-site. In addition, the partition subcontractor entered into a take-back agreement with the plasterboard suppliers, where the timber pallets used for delivery were taken back after use. Despite this good practice, over 220 t of plasterboard waste were sent off-site for recycling.

Large off-cuts resulted as doorways/entrances were cut away from standard-sized plasterboard sheeting.



Cutting required to allow for services opening and cable trays through the partition. Note the double layer of plasterboard around the opening specified for fire-proofing (circled in red).

Plates 2.17 and 2.18. Design decisions creating plasterboard off-cuts.

2.9.1.4 Metal waste

Metal waste (675 m^3) was generated from the cutting and bending of steel reinforcement to specific requirements during the construction of the main structural frame, although this was minimised by the design decision to fabricate the steel off-site. One of the largest elements generating metal waste was the internal partition work packages, which were constructed of a lightweight metal stud and plasterboard system, with the metal studs being ordered and delivered to site in various lengths from 2.4 m to 4.2 m. They were then cut to size on-site to fit the required dimensions and to provide the necessary openings, thus creating significant waste (Plate 2.19). This was addressed during the construction phase as part of the partition subcontractor's waste minimisation plan, where it was specified that "*metal studs were to be ordered and manufactured to suit the slab to soffit*

Plate 2.19. Lightweight metal stud partition off-cuts.

dimensions on-site to avoid cutting of studs and off-cuts".

2.9.1.5 Concrete waste

The construction of the in-situ concrete structural frame necessitated the use of a static pump system (125-mm diameter concrete pumping line, 120 m long) to provide an efficient and effective method of placing concrete. At the end of each working day, the pumping line had to be cleaned out, resulting in approximately 1.5 m^3 of concrete waste per day. Due to the timing and type of concrete (accelerating admixtures and specific slump requirement), it could not be used elsewhere in the permanent works. On reviewing this practice, it was decided to use this concrete more resourcefully to produce 'Kelly blocks' (0.5 m^3 each) for use as secure footings for perimeter hoarding around the site (Plate 2.20). In addition, most structural elements (depending on size) aimed to be poured in one section to ensure bonding and prevent the occurrence of 'cold joints'. This resulted in the production of 'leftover' concrete at the end of the pour. In some instances, this resulted in concrete being deposited directly into skips where it was left to harden. This was not suitable for removal by a waste contractor and so required several man hours to break up the concrete using hand-held tools.

2.9.1.6 Other waste streams

A series of other waste streams was identified through the research team's weekly site observations, including:

Plate 2.20. Production of 'Kelly blocks' using waste concrete from the static concrete pump pipe.

- Cable and wiring waste, where cables were supplied to site on standard rolls of 50 m, 100 m and 200 m and were trimmed to the local circuit requirements. It was common practice for tradesmen on-site to leave excess cables or 'tails' at the each end of a circuit to be trimmed at the second fixing stage. These 'tails' were observed to be consistently ranging from 2 m to 3 m in length when 300 mm would have met the requirements (Plate 2.21).

Plate 2.21. Cable 'tails' left for trimming at second fixing stage.

The electrical contractors were made aware of this by the research team on-site. The two main waste reduction barriers identified through discussion on-site were the culture among electrical contractors to leave 'more than enough' cable rather than risk leaving it short and the lack of financial incentive on their part to reduce the amount of cable used as they did not purchase the material.

- Entire sections of off-site manufactured air-conditioning and service ducting were disposed of in skips due to design modifications during the construction works. This also damaged installed insulation, rendering it unsuitable for reuse.

- Pipe and conduits were supplied to site in standard sizes, ranging from 2 m to 6 m in length. They were cut on-site to required dimensions creating off-cuts. Site personnel were advised to use these off-cuts for the shorter runs between joints, due to the high value of the pipe materials used, i.e. copper and stainless steel.

- Additional services waste occurred in the form of foil-covered glasswool that was specified for pipework and ducting. It was supplied either in 1.5-m lengths for different pipe diameters or in 1.5-m rolls, which were trimmed to suit ductwork on-site creating significant off-cuts. Some items of installed pipework (including insulation) were removed due to design changes or where clashes occurred between services that required re-routing. The insulation was generally damaged during the removal and so was unfit for reuse.

- Packaging accounted for 282 m^3 of the total waste generated, with plastics contributing another 172 m^3. Although best practice recommended the minimisation of packaging, this was not always feasible due to the nature of building under construction, e.g. some building services components required considerable protection against damage in transit (Plate 2.22).

- Waste was generated through the protection of works, which required 10,000 m^2 of corrugated plastic sheeting covered with two layers of 18-

Plate 2.22. Packaging of stop valve with built-in thermostats shipped from mainland Europe.

mm plywood and 17,000 m^2 of plastic sheeting covered with carpet. Insulation materials were also used for temporary protection, with 150-mm diameter pipe insulation split along its length and fitted around the powder-coated bespoke metal door frames and other insulation wrapped around work units (Plate 2.23), which eventually ended up as waste[45].

- Potential disposable formwork waste (estimated at over 200 m^3 of paper and cardboard[46]) was designed out by specifying reusable steel column boxes for the 600 circular columns specified throughout the upper storeys of the MAH building.

Plate 2.23. Insulation acting as temporary protection around door frames.

A summary review[47] of the waste causes and implemented reduction measures (Table 2.7) provided a project-specific waste performance benchmark for the main contractor but it did not address the influence of human factors, i.e. attitudes and perceptions. Hussey and Skoyles (1974) suggested that waste levels on-site were more dependent on human factors than on any one change in building technique. The influence of the organisational and site ‘culture’ on project stakeholders and employees can manifest itself in positive or negative attitudes towards effective waste management (Hussey and Skoyles, 1974; Skoyles and Skoyles, 1987; Soibelman et al., 1994; Heino, 1994; Pinto and Agopyan, 1994). To address this, a survey[48] of subcontractor management and site personnel was carried out on the MAH project to determine attitudes to waste and to evaluate how this could contribute to waste reduction on-site (Teo et al., 2000).

2.10 Waste Management Attitudes on the MAH Site

The online survey was disseminated to all subcontractor management staff[49], which was supported by a representative snapshot paper-based, survey of subcontractor personnel on-site on a selected day. Two research team members carried out the site survey through a series of ‘walk-throughs’ of

45. The reuse of protective insulation was maximised before eventual disposal.

46. Cardboard formwork size was approximately 0.33 m^3 for each column, with 600 columns giving a total of 200 m^3.
47. A detailed quantitative analysis of the implemented waste reduction measures is not available due to the cost confidentiality of the contractual arrangements.
48. The design and content of the survey was heavily influenced by previous research, which examined waste management attitudes and behaviour (Lingard et al., 2000; Teo and Loosemore, 2001; Poon et al., 2004a,b; Saunders and Wynn, 2004; Kulatunga et al., 2006; Osmani et al., 2006, 2008; Tam et al., 2007a,b; Begum et al., 2007, 2009; Cha et al., 2009). The survey consisted of four sections (27 questions) covering knowledge and awareness, policy and training, responsibilities and causes, implementation of waste management strategies, barriers and incentives, and demographics.
49. The online questionnaire was disseminated to 135 subcontractors via email, resulting in a response rate of 31% (42 valid questionnaires returned).

Table 2.7. Summary of waste reduction strategies by material type implemented during the construction phase of the Mater Adult Hospital project.

Material/Element	Waste causes	Waste reduction measures
Mixed construction and demolition waste (C&D W)	• Mini-skip distribution network employed by John Sisk & Son to manage the waste of the 103 subcontractors during the construction phase	• Where possible, mini-skips and/or large containers were source segregated
Timber	• Formwork required for main structural frame and resulting off-cuts • Formwork required for stairways • Formwork required for slab construction • Plywood sheets used for temporary protection of works • Mini-skip distribution network employed by John Sisk & Son	• Employed slipform system on-site • Employed Stair Master system on-site • Flat slab construction allowed for reuse of formwork tables and cut plywood • Where possible, undamaged plywood sheets were transferred to other John Sisk & Son projects for reuse • 90% segregated at source, facilitating more effective recovery through off-site processing
Gypsum	• Standard-sized plasterboard sheets cut to size on-site • Improper storage on-site • Specification of plasterboard for waste generating elements	• Waste minimisation plans prepared by subcontractors included ordering material to size to prevent cutting on-site. Any off-cuts were segregated at source facilitating more effective recovery off-site • Appropriate stacking and weather protection provided • Specification changes, i.e. grid-and-tile ceiling system more appropriate due to the amount of services openings required
Metals	• Cutting and bending of steel reinforcement throughout the construction phase • Internal metal stud partitions cut to size on-site	• Structural frame reinforcement fabricated and bent off-site in accordance with steel schedules • Subcontractor waste minimisation plans specified that metal stud partitions should be cut to size prior to delivery to site. Any off-cuts were source segregated on-site
Concrete	• Pouring of concrete using static pump system • Leftover concrete from pours	• Waste concrete used to construct 'Kelly blocks' for use as hoarding supports • Concrete was let harden and deposited into segregated inert waste skips
Packaging	• Building components required extensive packaging, i.e. services	• Packaging materials were source segregated where possible
Building services	• Cable tails, pipe and conduit off-cuts and sections of service ducts and air-conditioning units	• Metal elements were source segregated where possible

the site over a day, which involved distributing the questionnaire to personnel at the start of the day and collecting the surveys when completed[50]. The 90 valid responses (n = 568) provided a representative sample of the personnel on-site that day[51]. The main findings were:

- A high percentage of respondents (88%) reported a personal motivation to reduce waste as part of their job. This personal motivation persisted away from the workplace, with 95% of respondents stating that they recycled at home. Further support was found, with 89% of respondents agreeing or strongly agreeing that subcontractors have an important role to play in waste reduction on-site and 80% agreeing or strongly agreeing that it was a major growing issue. Despite this, 72% of respondents were never asked to provide feedback to site management in the development and implementation of waste management initiatives on-site. This may be due to the lack of

50. Ninety valid responses were collected using this approach, representing 16% of the personnel on-site.
51. The respondents were made up of 52% tradesmen, 13% labourers, 12% foremen, 12% 'others' and 10% apprentices.

waste documentation required for tendering purposes, i.e. 64% of respondents stated that they never had to prepare a tender WMP.

- When analysing the percentage of respondents who had prepared a tender WMP (36%), it was found that 48% were managerial staff and 31% were site staff. This highlighted a missed opportunity, considering that 65% of site respondents stated that their company had a waste management policy and 62% reported having received formal waste management training. Surprisingly, of the percentage (62%) who have received formal training, only 15% were managerial staff compared with 49% of site staff. This is an area of concern as management has been found to play a key role in the implementation of effective waste management strategies by applying consistent high waste management standards (Lingard et al., 2000; Teo and Loosemore, 2001). In addition to this, 44% of apprentices and 39% of tradesmen did not know if their company had a waste management policy, highlighting a lack of awareness. These issues are further supported by 66% of respondents who agreed or strongly agreed that there is a lack of waste management training and knowledge in the Irish construction industry.

- The top three waste causes identified by respondents were (i) waste from the application process, (ii) improper storage space and methods, and (iii) poor site management. Interestingly, the last two were also ranked in the top three causes during site operations in the architects' survey (Section 2.5). All of these refer to on-site practices and this focus is further emphasised by attributing to the main contractor the most responsibility, followed by the subcontractors. This is not surprising as the subcontractors represented the 'site' view and so reflected the 'traditional' arrangement, whereas the designers suggested a more even distribution of responsibility during site operations, especially the role of the building supplier.

- Sixty-two per cent of respondents identified '*poorly defined responsibilities*' as a major cause of waste on-site,[52] suggesting that clearer lines of communication were needed in practice as recommended by Teo and Loosemore (2001) and Osmani et al. (2006). To address this, Cha et al. (2009) recommended the appointment of specific waste management staff.

- When analysing the use of waste management strategies, it was discovered that on-site recycling of materials was ranked first (59%), followed by non-hazardous waste segregation (57%), on-site reuse of materials (44%) and waste reduction targets (28%). Surprisingly, the less difficult[53] strategies were ranked in reverse order, illustrated by the fact that 64% of respondents never worked on a project that had waste reduction targets. This is consistent with the 72% of architects who never set waste management goals for a project (Section 2.5).

- The main incentives identified addressed the lack of goal setting and clear responsibilities that are required for effective site waste management. This contrasted with architects who identified '*financial rewards*' as the biggest incentive and cost as the biggest barrier (Section 2.5). The subcontractors focused more on the core beliefs by identifying '*waste accepted as inevitable*' as the main barrier followed by a lack of site policy. This is interesting considering that the 'iron triangle' of cost, quality and time (Eriksson and Westerberg, 2011) was again reported to be the main goal of stakeholders, which was consistent with previous research (Poon et al., 2004a,b; Osmani et al., 2006; Jallion et al., 2009). It should also be noted that the '*purchasing of materials by subcontractors*' was the lowest ranked incentive, considering that this is one of the main policies used by management to assign clear responsibilities for waste management on-site.

In summary, respondents were aware of the importance of reducing waste on-site and were

52. This is in agreement to a lesser extent with the architects' survey results, where 39% viewed it as a major barrier and 56% viewed it as a minor barrier.
53. Obviously the 'difficulty' of implementing a waste strategy is dependent on a number of factors as each project has different constraints and limitations.

motivated to do so. The allocation of clear responsibilities was identified as a key issue for effective waste management on-site. The main causes identified by respondents all resulted from poor site practices, which may be due to a lack of training and/or agreed site policies. This gap in training was further highlighted by the fact that only 15% of site management had received formal waste management training in comparison with 49% of site personnel. Respondents reported a relatively low implementation rate of waste reduction measures on-site, particularly the setting of waste management targets. The preparation of site waste management policies was identified as the biggest incentive to counteract the general opinion that waste was an inevitable result of construction activity.

The link between attitudes and waste performance on-site (Lingard et al., 2000; Teo and Loosemore, 2001) make these ‘human factors’ (Yuan and Shen, 2011) key critical success factors (CSFs) in improving waste management performance.

2.11 CSFs for C&D W Management

There has been widespread use of CSFs in construction research ranging from the general analysis of the overall performance of construction projects (Toor and Ogunlana, 2008; Gudienė et al., 2013) to more effective construction management strategies (Norizam and Malek, 2013). Specific areas, such as project procurement (Yu et al., 2006; Chen and Chen, 2007), health and safety (Aksorn and Hadikusumo, 2008; Al-Haadir and Panuwatwanich, 2011) and subcontractor management (Ng and Tang, 2010), have used CSFs to determine the effectiveness of these strategies. Recent research[54] (Cha et al., 2009; Wang et al., 2010; Yuan, 2013) has utilised CSFs when assessing waste management performance on-site. Cha et al. (2009) identified 59 influencing factors as part of an assessment tool to improve waste management performance on-site. Wang et al. (2010) provided a more focused approach identifying six CSFs[55] for on-site sorting of construction waste, while Yuan (2013) broadened the research to a more holistic perspective and highlighted 30 key indicators for effective waste management, covering environmental, social and economic issues. These indicators were adapted[56] to provide a checklist to benchmark implemented design and construction waste reduction strategies on the MAH project (Table 2.8).

54. From China and Korea.

This checklist was also used to numerically rate the waste performance using a scale of:

- 3 marks for ‘excellent implementation’;
- 2 marks for ‘good implementation’;
- 1 mark for ‘basic implementation’; and
- 0 marks for ‘no implementation’.

Based on the details provided in Table 2.8, the MAH project achieved a score of 70 out of a possible 105 marks.

The next step was to make this explicit and tacit knowledge accessible and relevant to site personnel, the project supply chain and the construction sector though the use of ‘lessons learned’ (Fig. 2.2) (Carrillo, 2005). The capture and dissemination of the knowledge and understanding gained in the case studies aimed to facilitate learning in the participating organisations and provide an industry benchmark[57] for improved performance in the future.

55. These were manpower, markets for recycled materials, waste sortability, better management, site space, and equipment for sorting of construction waste.
56. The number of factors were reduced from 59 to 35 to exclude some industry policy factors and to account for some repetition.
57. The MAH project was awarded the Chartered Institution of Wastes Management (CIWM) Sustainable Construction and Demolition Project award in 2011.

Table 2.8. Review of waste management practices on the Mater Adult Hospital (MAH) project using critical success factors as a benchmark (Cha et al., 2009)[1].

Critical success factors	Tick
1. Commitment of contractor's representative on-site **Comment:** The main contractor employed an environmental officer who oversaw all their projects. Two members of the site management team were allocated waste management responsibilities. A member of the research team (Donall Dowd) was assigned 'Waste Champion' and was responsible for the preparation of the SWMP.	✓✓✓
2. Appointment of labourers solely for waste disposal **Comment:** Site personnel were responsible for the transfer and disposal of the mini-skips into the central designated large containers but no full-time staff were allocated to segregate the materials.	✓
3. Co-operation of subcontractors **Comment:** Six of the main subcontractors were responsible for their own waste management, which included the preparation of a SWMP for their work package, the ordering and purchasing of materials, the provision of skips, and the selection of waste management contractors. The other subcontractors were managed by John Sisk & Son, which employed a mini-skip distribution network.	✓✓✓
4. Education of contractor's staff **Comment:** The preparation of the SWMP by the Waste Champion raised awareness of waste management issues and recommended a number of waste reduction strategies. The BREEAM waste targets provided a benchmark for the site management team and a focus for discussion in site meetings. John Sisk & Son personnel had a good general awareness of waste management issues, although the majority of design and construction decisions were not influenced by waste management considerations.	✓
5. Education of subcontractor's staff **Comment:** Waste management was not included in the site induction. Toolbox talks on waste arising from block laying, and in-situ concrete and plasterboard applications were prepared by the Waste Champion and delivered to appropriate site personnel. The SWMPs prepared by the main subcontractors raised awareness and included a provision for delivery of toolbox talks on-site but no documentary evidence was provided.	✓
6. Supplier take-back schemes **Comment:** There was no evidence of a consistent policy with suppliers on-site.	×
7. Minimising rework in construction phase **Comment:** The use of 'design freezes' during the design phase facilitated the use of the slipform system and the reinforced concrete detailing, which minimised potential rework. Services design modifications during the construction phase resulted in rework and waste.	✓
8. Design and construction using standardised materials **Comment:** Use of the grid plan layout, the slipform system, the grid-and-tile ceiling system and Whiterock sheets were all design decisions that optimised materials use. During the construction phase, it was identified that the partitions work packages needed to order both the plasterboard sheets and metal studs to size, which reduced the amount of off-cuts produced.	✓✓
9. Prefabrication of materials **Comment:** The specification of the Techrete concrete cladding panels and the Architectural Aluminium Ltd external facade panels were the two main prefabrication design decisions. The use of the Stair Master system and the cutting to size of in-situ concrete frame steel also proved to be effective waste reduction strategies.	✓✓
10. Use of recycled materials **Comment:** Recycled materials were not used on-site although bulk excavation materials and concrete from demolition works were recycled and used off-site.	✓
11. Minimising materials loss due to handling and storage **Comment:** Generally, good materials management was demonstrated on-site but there was some evidence of materials (plasterboard) being stacked incorrectly, leading to damage and subsequent disposal.	✓✓

Table 2.8 ***contd***

Critical success factors	Tick
12. Prevent ordering excess materials	✓✓
Comment: The six main subcontractors were responsible for ordering and purchasing their own materials, apart from the concrete and steel for the main structural frame, which was purchased by the main contractor, John Sisk & Son, at a more competitive price. This strategy reduced the amount of excess materials on-site although wastage occurred particularly during the in-situ concrete works.	
13. Recycling of single-use temporary materials	✓
Comment: Flat slab construction allowed for the reuse of formwork tables and cut plywood. Undamaged plywood sheets used for temporary protection were reused on other projects.	
14. Setting up segregated skips/bins by material type	✓✓
Comment: Where possible and depending on the phase of the project, segregated skips were set up for timber, metals, packaging and inert waste. The mini-skip distribution network facilitated source segregation but a large percentage of skips taken off-site contained mixed waste.	
15. Sorting out individual waste fractions from mixed waste	✓✓
Comment: Source segregation was facilitated through the mini-skip network and central segregated containers but sorting of mixed waste was not carried out on-site.	
16. Designated storage areas	✓✓
Comment: Storage areas were allocated to align with the phase of the project. The central waste management area also contained materials storage facilities.	
17. Set up temporary skips/bins at each building zone	✓✓✓
Comment: The mini-skip distribution network achieved this.	
18. Sorting waste in easily accessible areas	✓✓✓
Comment: The mini-skips were rolled to a transfer point and moved to a central waste management area by a telescopic handler or crane. The contents of the mini-skips were then transferred into the larger containers and the mini-skips were returned empty to the appropriate zone.	
19. Provide skips/bins for collected waste from each subcontractor	✓✓✓
Comment: The six main subcontractors provided their own skips but all the other subcontractors were provided with skips by the main contractor.	
20. Provide skip signage indicating waste type and responsible staff	✓✓✓
Comment: Signage was placed on any mini-skips and large containers designated for segregated materials. Generally, segregated skips and a mixed waste skip were provided on-site. The responsibilities of staff were outlined in the project and work package SWMPs.	
21. Site operatives made aware of potential recyclability of materials	✓
Comment: Some toolbox talks were given for particular materials (concrete, plasterboard) but no general guidelines were disseminated on the recyclability of materials.	
22. Plant and equipment for recycling on-site	✓✓
Comment: Different sized skips were provided and moved around the site by crane or telescopic handler.	
23. Provide information board highlighting waste performance	✓
Comment: A waste performance graph comparing proposed targets and actual performance was posted in the site canteen on a weekly basis.	
24. Site rules for dealing with waste	✓✓
Comment: The project SWMP and the contractual arrangements with the subcontractors outlined the basic waste management rules for the project.	

Table 2.8 *contd*

Critical success factors	Tick
25. Contractual clauses for subcontractors on waste management	✓✓
Comment: The six main subcontractors were responsible for their own waste management while the rest of the subcontractors (103 over the course of the project) were co-ordinated by the main contractor.	
26. Positive incentives for subcontractors who minimise or recycle waste	✓
Comment: The contractual arrangements with the six main subcontractors incentivised their waste management approach as they incurred the costs involved. No other consistent incentive policies were evident on-site.	
27. Keep a waste management record	✓✓✓
Comment: A detailed waste management record was kept of waste generation on-site using the BRE SMARTWaste tool. A log of site observations was also kept to analyse waste management performance on-site.	
28. Collection of waste appropriate to site conditions	✓✓
Comment: Due to the increasingly confined nature of the site, waste skips were collected promptly once full.	
29. Contractual clauses for waste management companies regarding final end use/disposal	✓✓✓
Comment: Each waste management company was licensed by the EPA to manage C&D W so no contractual clauses about final end use were drafted. Waste management companies provided this information when requested to do so by the site Waste Champion.	
30. Establish a waste management plan early in the construction phase	✓✓✓
Comment: A project SWMP was prepared by the Waste Champion early in the construction phase. This was further supported by the six main subcontractors who also prepared specific waste minimisation plans.	
31. Site waste management plan implementation checklist	✓
Comment: No specific checklist was used although the project SWMP provided a series of recommendations to meet the waste production targets.	
32. Confirm competency of firms dealing with waste	✓✓✓
Comment: Each company dealing with waste had to be licensed by the EPA and, in some cases, held permits from the relevant local authority.	
33. Set waste management targets/goals	✓✓✓
Comment: The BREEAM healthcare waste generation targets of less than 9.2 m^3/100 m^2 or less than 4.7 t/100 m^2 were used to try and achieve three BREEAM credits.	
34. Consider waste management as part of the tender/bidding process	✓✓
Comment: The subcontractor tender scoring required the preparation of waste minimisation plans by subcontractors	
35. Use a database management system for reporting waste performance	✓✓✓
Comment: The BRE SMARTWaste tool was used.	

[1]*Note:* ✓**,** basic implementation; ✓✓**,** good implementation; ✓✓✓**,** excellent implementation; ×, not implemented.
SWMP, Site Waste Management Plan; BREEAM, Building Research Establishment Environmental Assessment Methodology; EPA, Environmental Protection Agency; C&D W, construction and demolition waste.

Figure 2.2. Lessons learned based on observations and findings from the selected case studies.

3 Conclusions and Recommendations

3.1 Major Conclusions

- The evolution of C&D W legislation and policy towards a more resource-efficient and preventative approach poses a number of challenges for the Irish construction sector, which is still, to a large extent, engaging in end-of-pipe waste management solutions.

- The transposition of the revised EU Waste Framework Directive into Irish law has moved the focus further up the waste hierarchy, with an increased emphasis on prevention. This, in turn, has highlighted the role of **all** construction stakeholders in contributing to the prevention, reduction and management of C&D W.

- The lack of a mandatory planning requirement for **all** projects has resulted in an inconsistent approach to C&D W management, representing a missed opportunity to embed waste prevention and minimisation principles into the planning application process.

- A review of C&D W management research has found considerable studies on:
  - C&D W benchmarking (international/national estimates, waste generation rates, origins and causes);
  - The preparation and implementation of C&D W prevention, minimisation, reuse and recycling strategies; and
  - C&D W management issues, including attitudes and awareness of construction stakeholders.

  Studies outlining results from case study research are particularly useful for international knowledge transfer across project types. The extensive C&D W guidance, case study analysis and tools produced by WRAP in the UK provide an excellent resource base for all stakeholders involved in C&D W management.

- There is a significant lack of data on C&D W production coming directly from Irish construction and demolition projects, which could be used to cross-check the data collected by the EPA from licensed, permitted and registered facilities for the National Waste Reports. This would also enable the development of project and company waste production benchmarks.

- The five DoW WRAP principles provide a useful framework to examine the opportunities for waste prevention and reduction in the design phases. These principles are:

  (i) Design for reuse and recycling;

  (ii) Design for waste-efficient procurement;

  (iii) Design for materials optimisation;

  (iv) Design for off-site construction; and

  (v) Design for deconstruction and flexibility.

- The preparation and development of SWMPs are recognised as an essential component of effective waste management on-site but an opportunity exists to develop a SWMP during the design phase to identify and recommend waste reduction strategies using the five WRAP principles as a guide.

- The attitudes of different industry stakeholders towards waste and their perception of their responsibilities are largely influenced by project or contractual requirements and financial implications. There is an acknowledgement that waste is an issue but it is seen as a lower priority below cost, time, quality, and health and safety. Clear communication, management commitment, contractual arrangements, appropriate training and information dissemination are all key to developing a suitable ‘organisational climate and culture’.

- The design review of both case studies identified a number of implemented waste reduction strategies which demonstrated the potential of the design phase to prevent and reduce waste. These strategies include:

  - Reuse of existing sites;
  - Minimisation of excavation works where possible;
  - Preparation of SWMP and subcontractor waste minimisation plans;
  - Setting of waste benchmarks;
  - Use of design-and-build contracts;
  - Application of design 'freezes';
  - Use of low-waste technologies, e.g. slipform and Stair Master;
  - Use of materials optimisation in selected work packages, i.e. partitions; and
  - Use of off-site construction techniques, e.g. external facade panels and cladding.

- The construction-phase review of the MAH produced estimated waste generation rates for different materials on-site and examined a number of strategies implemented that reduced the amount of waste produced, including:
  - Use of the mini-skip distribution network and source segregation;
  - On-site application of low-waste technologies, e.g. slipform and Stair Master;
  - Effectiveness of subcontractor WMPs, and
  - Reuse of waste materials on-site where possible.

  This demonstrated that waste reduction strategies were possible during the construction phase, but focused more on end-of-pipe solutions.

- The main causes of waste identified in the literature review, surveys and case studies are avoidable.
- The adapted CSF framework (Cha et al., 2009) provides a useful waste management performance rating system to be used during all phases of a project but especially in the early design phases and as a review tool post-construction.
- The main lessons learned from both case studies included:
  - The need for co-operative collaborative contractual arrangements to facilitate early involvement of project stakeholders.
  - The importance of considering waste management issues during the initial design phases through the preparation and implementation of a design-phase WMP to identify waste prevention and reduction opportunities.
  - The setting of waste performance targets for all the project stakeholders, particularly the main contractor and subcontractors.
  - The specification of off-site construction components and low-waste technologies based on materials optimisation principles.
  - Highlighting reuse and recycling opportunities both in the design and construction phases.
  - Use the design-phase WMP to prepare and implement the SWMP, focusing on clear lines of communication and responsibilities, effective materials logistics and management planning, benchmarking and auditing of waste performance, and cultivation of an 'organisational climate' that facilitates good waste performance.

3.2 Project Outputs

- The first detailed analysis of DoW principles applied to the design and construction phases of an Irish construction project.
- The first review of the critical success factors of construction waste management practices on an Irish case study.
- The identification of 11 design-phase and 11 construction-phase C&D W management lessons learned, which are widely applicable across the construction sector.
- The preparation of a Waste Reduction Toolkit for Design Teams comprising the following series of factsheets (Kelly, 2015):
  - Principles for Designing out Waste

- Procurement and Tendering for Waste Reduction
- Materials Optimisation and Standardisation
- Off-Site and Modern Methods of Construction
- C&D W Reuse and Recycling Opportunities
- Deconstruction and Flexibility

3.3 Recommendations

- There is a need to integrate a mandatory requirement to prepare and submit a design-phase WMP into the planning process. This plan will be updated prior to the commencement of construction works and will be used as a management tool throughout the project. This will mean adapting the thresholds currently outlined in the *Best Practice Guidelines on the Preparation of Waste Management Plans for Construction and Demolition Projects* (DoEHLG, 2006). The proposed Welsh model, which recommends three types of WMP – simple, standard and extended – depending on the type and scale of project provides a useful template to work from (WG, 2013).

- To support the above point, the existing building regulations should be examined to identify opportunities to incorporate C&D W management obligations.

- The prioritisation of waste prevention as outlined in the Waste Framework Directive hierarchy must be demonstrated in all design-phase WMPs.

- Construction-phase WMPs should be used as a data collection tool to develop waste production indicators and national estimates. These data will be reported to the relevant local authorities and include:
  - Project type;
  - Constructed floor area;
  - Waste generation totals;
  - Composition of waste;
  - Diversion from landfill; and
  - Recycling percentages.

- The core green procurement criteria outlined in the guidance documents *Green Tenders – An Action Plan on Green Public Procurement* (DoECLG, 2012b) and *Green Procurement: Guidance for the Public Sector* (EPA, 2014a) should be mandatory for all public sector construction projects and, where appropriate, should be implemented into all construction works that require planning approval.

- Clear construction material guidance and information should be made available by manufacturers and building suppliers on:
  - Reuse protocols and standards;
  - Recycled content;
  - Recyclability;
  - Take-back initiatives;
  - Durability; and
  - Deconstruction potential.

- A review of the current infrastructure and processing capacity for C&D W should be carried out to identify existing and potential markets.

- A collaborative training and education programme incorporating local authorities, designers, contractors, building manufacturers and suppliers should be developed to produce a series of best practice case studies and guidelines to demonstrate the effectiveness of implementing waste prevention strategies during the design phases.

Table 3.1 provides a more detailed breakdown of actions required to implement the listed recommendations.

Table 3.1. Actions required to implement recommendations.

Recommendation	**Introduce a mandatory planning requirement for C&D W management plans on all projects**
Action	A discretionary requirement already exists through Section 34(4)(1) of the Planning and Development Act 2000 and Section 26(1)(2) of the Protection of the Environment Act 2003. The thresholds in the *Best Practice Guidelines on the Preparation of Waste Management Plans for Construction and Demolition Projects* (DoEHLG, 2006) should be adapted to include all projects that require planning approval. A useful guideline to work from is the proposal by the *Waste (Wales) Measure 2010: Site Waste Management Plans* consultation document (WG, 2013) that three thresholds be used, which are based on duration of the project, the expected volume of waste, the site area and the estimated cost. This will determine what type of WMP (simple, standard or extended) is submitted as part of the planning process.
Target audience	Local authorities, DoECLG, EPA, clients
Recommendation	**Waste prevention should be prioritised in the preparation of design-phase WMPs**
Action	Design teams should aim (at the earliest possible stage) to design out waste through a combination of strategies, i.e. off-site construction methods, materials optimisation and standardisation, etc., and to benchmark their impact on cost, time, quality, safety and waste reduction throughout the construction process. The Waste Framework Directive waste hierarchical principles of prevention, preparing for reuse, and recycling should be used as a guide in combination with the five WRAP DoW principles. This will require a collaborative working environment engaging all members of the project supply chain.
Target audience	Clients, design teams, local authorities, contractors, material manufacturers and suppliers
Recommendation	**The construction-phase WMPs should be used as a data collection tool**
Action	The construction-phase WMP should develop an implementation and management plan for the waste reduction strategies proposed in the design-phase WMP. One key element of this is the benchmarking of waste production on-site. This will enable the project team to identify the main causes and the associated composition and quantities of waste produced on-site. These data should be submitted to the local authorities using a standard reporting template, which could be aligned with the type of WMP required (simple, standard or extended), or using the various auditing tools available, i.e. BRE SMARTWaste or WRAP's DoW and SWMP tools or simple paper-based audit sheets. The data collected can also be used for educational purposes on-site, i.e. providing feedback to subcontractors on waste generation rates and areas for improvement.
Target audience	Clients, design teams, quantity surveyors, local authorities, contractors, waste management contractors
Recommendation	**The core green procurement criteria should be mandatory for all public sector construction projects and, where appropriate, should be implemented into all construction works that require planning approval**
Action	The procurement and tendering approach is essential to the successful implementation of waste prevention and reduction measures on a project. The criteria outlined in *Green Tenders – An Action Plan on Green Public Procurement* (DoECLG, 2012b) and *Green Procurement: Guidance for the Public Sector* (EPA, 2014a) set out minimum requirements that should be implemented on all appropriate projects. The use of model clauses covering compliance, collaboration and project-specific targets during the pre-qualification and invitation to tender stages should be used to support these minimum requirements.
Target audience	Clients, design teams, quantity surveyors, local authorities, contractors, material manufacturers and suppliers, waste management contractors
Recommendation	**Clear construction material guidance and information should be made available by manufacturers and building suppliers on reuse protocols and standards, recycled content, recyclability, take-back initiatives, durability, and deconstruction potential**
Action	A national study in collaboration with construction product manufacturers and suppliers should be carried out to develop a database and clear guidance to facilitate a more resource-efficient approach to materials specification. This product information should also include embodied environmental impacts, including total energy and water use. This study should incorporate a series of demonstration projects to investigate the impact of appropriate materials labelling and information on the implementation of resource-efficiency measures in the construction sector. The application of BIM should also be investigated to determine its compatibility with a database of this type.
Target audience	Clients, design teams, quantity surveyors, local authorities, contractors, material manufacturers and suppliers, waste management contractors, BIM consultants

Table 3.1 *contd*

Recommendation	**A review of the current C&D W infrastructure and processing capacity should be carried out to identify existing and potential markets**
Action	This review should focus on the potential of applying the concepts of industrial symbiosis, closed and open material loops, to the Irish construction sector. C&D W should be tracked from the site through the off-site processing operations to its final end use or disposal to determine resource-efficiency opportunities, i.e. reducing the energy used and carbon footprint, and identifying current and potential markets. This will provide a geographical representation of C&D W processing infrastructure and associated markets.
Target audience	Clients, design teams, quantity surveyors, local authorities, contractors, material manufacturers and suppliers, waste management contractors
Recommendation	**A collaborative training and education programme incorporating local authorities, designers, contractors, building manufacturers and suppliers should be developed to produce a series of best practice case studies and guidelines to demonstrate the effectiveness of implementing waste prevention strategies during the design phases**
Action	The training and educational programme will be based around selected case studies where a full project life-cycle analysis will be carried out to demonstrate the implementation of waste prevention and minimisation measures from the initial design phases to the final deconstruction and end use. All stakeholders in the supply chain will be involved in the development of a flexible educational model, which will be based around key competencies, e.g. as part of their contractual arrangement on-site, subcontractors will complete resource efficiency modules through online or blended learning while on-site, which will be tailored to their specific speciality or trade. This dynamic form of learning based on real-time events will seek accreditation from professional bodies and explore potential academic recognition with third-level institutions.
Target audience	Clients, design teams, quantity surveyors, local authorities, contractors, material manufacturers and suppliers, waste management contractors, academic institutions

C&D W, construction and demolition waste; WMP, Waste Management Plan; DoECLG, Department of the Environment, Community and Local Government; EPA, Environmental Protection Agency; WRAP, Waste and Resources Action Programme; DoW, designing out waste; SWMP, Site Waste Management Plan; BIM, Building Information Modelling.

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Acronyms

BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Methodology
C&D W	Construction and demolition waste
CIWM	Chartered Institution of Wastes Management
CSF	Critical success factor
DoECLG	Department of the Environment, Community and Local Government;
DoEHLG	Department of the Environment, Heritage and Local Government
DoW	Designing out waste
EPA	Environmental Protection Agency
EU	European Union
EWC	European Waste Catalogue
GPP	Green Public Procurement
HBB	Human Biology Building
KPI	Key performance indicator
MAH	Mater Adult Hospital
MEAT	Most Economically Advantageous Tender
Mt	Million tonnes
NCDWC	National Construction and Demolition Waste Council
NDC	National Diagnostics Centre
NUI	National University of Ireland
OSB	Orientated strand board
SIP	Structural insulation panel
SIRP	Structural insulation roof panel
SWMP	Site Waste Management Plan
WMP	Waste Management Plan
WRAP	Waste and Resources Action Programme

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A Review of Design and Construction Waste Management Practices on Selected Case Studies – Lessons Learned

Authors: Mark Kelly and Donal Dowd

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

During this time of economic recovery, the Irish construction industry has an opportunity to rethink and re-imagine all phases of the design and construction process to enable a more resource-efficient approach prioritising sustainable materials management and waste prevention. This research aimed to investigate the implementation of waste reduction strategies on two selected case studies with a view to developing a series of lessons learned for the Irish construction sector.

Identifying Pressures

Construction and demolition waste (C&D W) generation has witnessed considerable fluctuations over the past 15 years, reflecting the unprecedented economic growth and decline during this time. Despite this, C&D W has consistently been one of the largest contributing waste sources in Ireland. One of the key steps towards a future resource-efficient construction sector is the decoupling of this correlation between construction output and waste generation.

Informing Policy

This study has outlined a series of recommendations focusing on the use of planning instruments, the preparation and implementation of design-phase and construction-phase waste management plans, the integration of green procurement criteria into all projects, the role of the construction supply chain, the potential of the circular materials loop concept and need for a collaborative action-based training approach embedded within selected best practice demonstration projects. This will enable the Irish construction sector to evolve from the more traditional end-of-pipe waste management solutions towards a more resource efficient approach that prioritises waste prevention and lifecycle thinking.

Developing Solutions

The main output was the production of 22 design and construction-phase lessons learned based on the observations and findings from the selected case studies. This informed the preparation of a waste reduction design team toolkit, consisting of a series of factsheets on waste reduction principles, procurement and tendering, materials optimisation, reuse and recycling, off-site manufacture and deconstruction opportunities.

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