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Design for Manufacture and Assembly with Design for Reuse

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Executive Summary

This report examines the application of Modern Methods of Construction (MMC) in Ireland, how this can be enabled through Design for Manufacture and Assembly (DfMA) and its relationship with Design for Reuse (DfR). MMCs offer significant potential productivity, sustainability and quality benefits in the delivery of new housing projects by employing off-site manufacturing methods, including modular construction and structural panels. However, the use of MMC can be restricted by wide-ranging challenges related to the co-ordination of project stages, stakeholder collaboration and operational requirements. Capturing the full cost and productivity benefits of MMC involves selecting the right solution between 2D panels, 3D modules, and hybrid designs; optimising the choice of materials; and overcoming challenges related to design, manufacturing, technology, logistics and assembly.

DfMA addresses these challenges by adopting a highly integrated approach to off-site manufacturing and on-site assembly that facilitates technological innovation and the use of digital construction tools. A DfMA approach to building design anticipates the use of specific MMC components and takes into account how these will be manufactured off-site and assembled together with other elements during construction. Materials are selected with manufacturing efficiencies in mind and interfaces with other MMC and traditional building elements are fully planned. This requires that component manufacturers have more input to design at an early stage and requires closer integration of project phases and stakeholders, which can be facilitated through BIM and other enabling technologies. DfMA with MMC also has the potential to be an enabler of DfR and the creation of a circular economy in the construction industry, with many of the design tasks required for successful DfMA adaptable for use in DfR.

This report assesses how the use of DfMA can enable the further adoption of MMC and DfR by reviewing the principles of DfMA and its application in construction; considering the opportunities, benefits and motivations for employing DfMA with MMC; identifying and categorising the barriers to MMC adoption and implementation; and identifying activities that contribute to the support and implementation of DfMA and MMC in Ireland. The principles of DfR are reviewed and the relationship of DfR with DfMA and MMC considered. This assessment leads to the definition of the conditions required for more widespread adoption of DfMA, MMC and DfR in residential construction in Ireland and recommendations on the supporting activities that are needed to achieve those conditions.

The identified challenges faced by the construction and built environment sector in adopting DfMA with MMC include those related to the implementation of DfMA as a general method for construction project delivery, and those related to the development of specific MMCs and their application in building construction. The challenges can be categorised as:

Organisational Structure: the structure of the team formed by the project stakeholders and the timing of their collaborative engagement in the project;

Contractual Framework: the regulative guidelines that align stakeholder goals with overall project objectives through compensation structures and risk allocations;

Operational Systems and Processes: the application of tools, technologies, and mechanisms to ensure effective collaboration and communication among participants.

The review of recent, current and planned activities that support the development of DfMA and MMC in Ireland identified over 40 activities within six categories: (i) studies and reports, (ii) guidance and rules, (iii) education and training, (iv) conferences and meetings, (v) centres and projects, and (vi) state, public and sectoral initiatives. A categorical comparison of the identified activities with the challenges to the adoption of DfMA with MMC is presented and used to assess how well the set of activities addresses the known challenges and where additional supports may be required.

A parallel analysis considers the concepts of Design for Deconstruction (DfD) and Design for Reuse (DfR), discusses current policy on DfD and DfR in Ireland and compares it to that on MMC, compares design principles that are integral to DfR with those of DfMA, identifies barriers to the adoption of DfR in construction, considers the relationship between DfR and MMC enabled by DfMA and makes a set of recommendations to promote DfR in construction in Ireland.

The adoption of MMC in construction projects in Ireland generally and in public housing specifically will require considerable changes within the construction and built environment sector. The challenges to DfMA with MMC are used to define a set of conditions that would support the widespread adoption of MMC, enabled by DfMA and supporting DfR, in housing delivery in Ireland. The fourteen conditions cover: Sectoral Commitment & Organisational Structures, Market Conditions & Contractual Framework, Regulatory Environment & Certification Processes, and Operational Systems & Knowledge Transfer. Recommendations are provided on how each of these conditions can be created through specific or multi-functional actions.

The conclusions address the development of MMC with DfMA alongside DfR in the context of construction and national policy in Ireland; the support of sectoral and stakeholder commitment by cost-benefit evidence and compatible methods of integrated project delivery; the importance of a strong regulatory environment including certification, standardisation and the need for investment in testing facilities; and knowledge transfer within a national MMC ecosystem through appropriate education and training programmes.

1 Introduction

International reviews of the construction sector have identified the need for transformation and modernisation (Farmer, 2016; CIF, 2021). Limited sectoral productivity and efficiency gains have not met the increasing demands associated with urbanisation, demographics, sustainability and technological change. For example, several studies have highlighted the problems of the UK construction sector and sought to develop a co-ordinated program for its development (Egan, 1998; Farmer, 2016). In contrast to most other technological sectors, the construction sector globally has displayed little productivity growth over the last 50 years, and productivity in Ireland is below the EU average (DPER, 2022). The challenges faced by the sector worldwide include fragmentation, resistance to change, barriers to innovation, low productivity and profitability and workforce recruitment and retention (Farmer, 2016).

The pressures for increased productivity, efficiency, quality and sustainability exist equally in Ireland (Ernst and Young, 2021), especially in the context of residential construction and the provision of housing (Housing for All, 2022). Innovation and digital technologies are recognised as being central to the transformation required in the construction industry. Specifically, improvements in three related areas have been identified as essential for the future success of the industry nationally: Modern Methods of Construction (MMC), digital adoption and technology innovation.

This report examines the application of Modern Methods of Construction (MMC) in Ireland, how this can be enabled through Design for Manufacture and Assembly (DfMA) and the links with Design for Reuse (DfR). As described below, MMC offers significant potential productivity, sustainability and quality benefits, including in the delivery of residential accommodation. However, the use of MMC can be restricted by wide-ranging challenges related to the co-ordination of project stages, stakeholder collaboration and operational requirements. DfMA addresses these challenges by adopting a highly integrated approach to off-site manufacturing and on-site assembly in a way that facilitates technological innovation and the use of digital construction tools (RIBA, 2021; RIAI, 2022). In turn, MMC has the potential to be an enabler of DfR (Iacovidou et al., 2021) and the creation of a circular economy in the construction industry (Gillett et al., 2023).

As modern buildings become more complex it becomes more difficult to achieve optimal solutions with bespoke designs. The use of repeatable and scalable design forms an integral part of modular construction, which is a key aspect of MMC, and facilitates the use of off-site manufacturing in building construction. However, as traditional methods of construction can be inefficient in a factory environment, construction professionals and clients usually need to adapt to the constraints of manufacturing when adopting offsite solutions. While some of the barriers to adaption are process- and tool-based, many more are based in professional practice, training and workflows, as well as definitions of value.

1.1 MMC Definition Framework

Modern Methods of Construction (MMC) describes a range of manufacturing and innovative alternatives to traditional construction (DHLGH, 2023a). These include approaches that span off-site, near-site and on-site pre-manufacturing, process improvements and technology applications. More specifically, MMC describes an approach to constructing buildings more quickly, reliably, and sustainably using various off-site manufacturing methods, including modular construction and structural panels, amongst others (CIF, 2021).

The wide range of activities and processes included within MMC led to the development of an MMC definition framework by a cross-sectoral working group within the UK Ministry of Housing, Communities and Local Government (MHCLG, 2019). This definition framework was created from a housing delivery perspective to facilitate better understanding and structured information collection and sharing about MMC implementation. Although originally intended to guide the mortgage, insurance and valuation communities, the framework has been more generally adopted by the construction and built environment sector in Ireland and the UK and is widely used to frame discussion and analysis of MMC developments. The details of the framework are presented in Table 1.1, followed by descriptions of the seven MMC categories that it defines.

Table 1.1: MMC Definition Framework

MMC Category	MMC Type *Category Description*
1	**3D Volumetric** *Pre-manufacturing – 3D primary structural systems* Structural; Off-Site Manufacturing
2	**2D Panelised** *Pre-manufacturing – 2D primary structural systems* Structural; Off Site Manufacturing
3	**Non-systemised Structural** *Pre-manufacturing - non systemised primary structure* Structural; Off Site Manufacturing
4	**3D Printing** *Additive manufacturing* Structural and Non-Structural; On Site and Off Site
5	**Non-Structural Assemblies** *Pre-manufacturing – non-structural assemblies and sub-assemblies including pods* Non-Structural; Off Site Manufacturing
6	**Building Products and Materials** *Traditional building product-led site labour reduction and productivity improvements* Non-Structural; On Site
7	**Construction Processes** *Site process-led labour reduction/productivity assurance improvements (innovative processes and approaches)* Non-Structural; On Site

Category 1: Pre-Manufacturing (3D Primary Structural Systems)

This category involves the manufacture of three-dimensional modules off-site that are then transported to and assembled on site to create a building. The modules may be fully- or partially-fitted out at the factory, and may include external cladding and insulation. The structural materials used are cold-formed and hot-rolled steel, precast/reinforced concrete and timber. This category facilitates the highest levels of pre-manufacture, although the building invariably requires elements of traditional construction including foundations and core. Applications of this category in residential construction are increasing worldwide, but to date has made a limited contribution to house building in Ireland, with greater prevalence in the industrial, education and healthcare sectors.

Category 2: Pre-Manufacturing (2D Primary Structural Systems)

In this category, two-dimensional panelised and framing systems are manufactured off-site and assembled on site to create various components of the building structure including walls, floors, roofs and stairs. The extent of pre-manufacture varies and can include structural elements only, or may also include insulation, cladding, doors and windows. This category of MMC is widely employed in residential construction in Ireland. Pre-manufactured roof trusses have long been employed in house building, and current applications in new houses and apartments include other structural and building elements manufactured in light gauge steel, timber with precast concrete. There is substantial variation in the amount of traditional construction that is also required to create the entire building.

Category 3: Pre-Manufacturing Components (Non-Systemised Primary Structure)

In this category, individual structural components are pre-manufactured off-site and transported to the site to be combined with other elements to form the structure of a building. This category is relevant for nearly all forms of structural elements, and has been extensively used in residential construction in Ireland. Examples include steel beams, columns and piles, precast floor slabs and walls, stairs and roofs. The use of engineered timber elements in this category is also increasing worldwide. Although a well-established part of house building and, especially, apartment building in Ireland and elsewhere, contemporary MMC element manufacture and/or subsequent construction usually takes place within digitally-enabled workflows.

Category 4: Additive Manufacturing

This category relates to 3D printing of building elements. Although many traditional construction methods can be viewed as additive processes, the specific application of 3D printing as an off-site manufacturing technique has to date found limited application in construction. While this category may contribute to future residential construction in Ireland, it is not expected to make a substantial contribution in the short-term.

Category 5: Pre-Manufacturing (Non-Structural Assemblies and Sub-Assemblies)

This category covers pre-manufactured non-structural components for buildings in which assembly work is carried out in a factory setting prior to delivery to site. These assemblies can be employed alongside MMC Categories 1 and 2 or in traditional construction projects. The category includes 3D assemblies such as bathroom and kitchen pods, 2D assemblies for facades, walls and roofs and M&E assemblies. The diversity of solutions covered by this category is reflected in its widespread and increasing application in Irish building projects, including residential construction.

Category 6: Traditional Building Product Led Site Labour Reduction / Productivity Improvements

This category considers improvements to traditional building materials and products aimed at facilitating quicker, easier and safer installation, often with reduced on-site labour or skilled labour requirements. Examples include pre-manufactured walls and roofing elements.

Category 7: Site Process Led Site Labour Reduction / Productivity / Assurance Improvements

This category involves new on-site processes to improve productivity, construction speed and safety. The processes are characterised by the use of new technology, including digital technologies. Examples include the integration of BIM with on-site processes, the use of augmented and virtual reality to aid assembly, digital scanning of building components and robotics. New technologies for these purposes are being developed and adopted by the construction sector in Ireland and worldwide and are expected to contribute to productivity improvements in the provision of residential accommodation.

The potential benefits of MMC are widely cited, and include:

- Improved productivity, including lower overall costs;
- Faster construction and shorter overall project durations;
- Improved quality control and building quality;
- Improved health and safety;
- Reduced labour requirements, better working conditions and workforce diversity;
- Improved pathways for the development and adoption of novel technologies;
- Greater sustainability and circularity with reduced waste and climate impacts.

While little quantitative evidence is available on the extent to which these individual benefits have been realised in actual building projects, the wider drivers for increased adoption of MMC in residential construction tend to be multi-faceted, and include:

- Developers looking for greater control of their projects;
- Governments looking for better productivity, reliability, quality and sustainability;
- The public looking for more accommodation, delivered faster;
- Contractors looking for added value by investing in off-site facilities;
- Employers looking to reduce dependency on local skilled workforces;
- Product developers looking for new markets;
- International trends, experience and competition.

Capturing the full cost and productivity benefits of MMC, including off-site manufacturing and modular construction is not straightforward, however, as it involves selecting the right solution between 2D panels, 3D modules, and hybrid designs; optimising the choice of materials; and overcoming challenges related to design, manufacturing, technology, logistics and assembly (Bertram et al., 2019). These decisions also need to take into account the availability of off-site manufacturers and the broader supply chain in the local market as well as local regulatory requirements.

Figure 1.1 3D volumetric modular construction (MMC Category 1) - Source: https://visionvolumetric.co.uk/project/scape-wembley

1.2 Enabling MMC

The MMC Definition Framework mostly focuses on physical elements such as modules, panels and pods, with less emphasis on the processes required to facilitate their inclusion in building projects. Building elements manufactured off site require integration with in-situ elements using on site methods that vary significantly between projects. This presents diverse project-specific challenges that are not generally encountered in most other industrial sectors such as product manufacturing.

The concept of industrialised construction can be employed to consider the broader issues associated with the widespread adoption of MMC. Construction industrialisation involves adopting manufacturing practices, mechanisation and automation in construction to improve efficiency and productivity, leading to better quality, value, reliability and sustainability (RIBA, 2021). Autodesk (Herridge, 2022) describe industrialised construction as the application of manufacturing techniques to the built environment, comprising a combination of prefabrication and manufacturing technology, along with technology enablers and process enablers. This description shares many common features with the MMC definition framework: the prefabrication continuum extends from advanced building products, through single- and multi-trade assemblies (including panelised elements) to volumetric modular, while the manufacturing technologies include robotics, automation and additive manufacturing. However, the identified enablers lie outside of the scope of the MMC definition framework and include the process enablers of BIM, DeMar and lean manufacturing, and the technology enablers of the cloud, big data, analytics and the Internet of Things.

Herridge (2022) also introduces the concept of productization as an evolved form of prefabrication. In productization physical MMC elements are conceived as a ‘kit of parts’ with well-controlled interfaces between them (e.g. Akerlof, 2023). The repeated use of a limited selection of products in multiple projects offers scalability and potential productivity benefits. This approach may also facilitate building customisation by designers without incurring additional manufacturing costs or responsibilities related to regulatory compliance.

Industry 4.0 involves the development of new methods of manufacturing based on the integration of physical and digital technologies. Sawhney et al. (2020) describe Construction 4.0 as the adoption and adaptation of the Industry 4.0 approach to the construction sector, leading to fundamental changes in how assets can be designed, constructed, and operated with improved efficiency, quality and safety. They observe that building information modelling and a common data environment form the foundation for the implementation of Construction 4.0.

Design for Manufacturing and Assembly (DfMA) has been proposed as means of enabling increased MMC adoption in construction, including housing, by closely integrating the design, manufacturing and construction phases of a project. RIBA (2021) and RIAI (2022) have created DfMA overlays to the Plan of Work commonly used to organise construction projects as a sequence of stages. As described in Chapter 2, when using the DfMA approach, building design anticipates the use of specific MMC components and takes into account how these will be manufactured off-site and assembled together with other elements during construction. Materials are selected with manufacturing efficiencies in mind and interfaces with other MMC and traditional building elements are fully planned. This requires that component manufacturers have more input to design at an early stage and anticipates that building designers can optimise the use of specific manufactured components over repeated projects. The process requires closer integration of project phases and stakeholders, which can be facilitated through BIM and other enabling technologies. Many of the design tasks required for successful DfMA could also be adapted for use in DfR.

The terms offsite manufacturing (OSM), offsite construction, prefabrication, MMC and DfMA are often used interchangeably in discussions and literature (Arup, 2019). This report adopts the interpretation of the relationships between these terms set out by van Vuuren and Middleton (2020), in which OSM is taken to be synonymous with offsite construction and prefabrication, and considered to be a subset of MMC (which also includes digital tools and on-site technologies). In turn, DfMA is considered as process that facilitates the application of OSM in construction projects, especially residential buildings.

1.3 Project Aims

The construction industry worldwide is still at an early stage of development in its use of MMC, DfMA and industrialised construction, while DfR has rarely been employed in actual construction projects. In Ireland, the extent of adoption varies greatly, with good experience in some fields including the construction of data centres and pharmaceutical production facilities and in vertically-integrated residential construction.

The widespread adoption of MMC will require co-ordinated activity across industry with public policy support. This project aims to assess how the use of DfMA can enable the further adoption of MMC and DfR in Irish residential construction by;

- Considering the opportunities, benefits and motivations for employing DfMA with MMC;
- Identifying and categorising the barriers to MMC adoption and implementation;
- Identifying activities that contribute to the support and implementation of DfMA and MMC in Ireland;
- Reviewing the principles of DfR in construction and considering its relationship with DfMA and MMC;
- Defining the conditions required for more widespread adoption of DfMA, MMC and DfR, including recommendations on the supporting activities that are needed to achieve those conditions.

1.4 Project Methodology

The methodology employed in this project comprised the following research tasks:

1. Review of existing information (national and international);
2. Collection of new information (including stakeholder information);
3. Collation and analysis of information relevant to project aims (gap analysis);
4. Preparation of this report describing the current situation, new and planned activities, and recommendations for future conditions and actions.

The review of existing and new information identified multiple national and international sources relevant to the application of the DfMA approach to construction projects employing MMC. Less published information was available on DfR and current activity on this topic in Ireland was found to be much lower than that on MMC and DfMA.

The analysis of new and existing information aimed to

- Review the principles of DfMA, its application to construction, and its role in enabling MMC adoption, with a focus on residential construction in Ireland;
- Identify the potential benefits of DfMA with MMC, especially with respect to the accelerated delivery of sustainable, quality housing;
- Identify the challenges to the wider use of DfMA in Ireland under the three headings of organisational structure, contractual framework and operational systems;
- Assess which of these challenges are addressed by recent and planned activities supporting DfMA and MMC in Ireland, especially with respect to residential construction;
- Review the concept of DfR and its relationship with DfMA and MMC, including a comparison of DfR and DfMA/MMC principles, barriers to adoption, policy and supports;
- Use this assessment to define the conditions under which MMC will be widely employed in Ireland, facilitated by DfMA and facilitating DfR;
- Recommend the activities and supports required to create these conditions and to accelerate the adoption of DfMA with MMC and DfR in residential construction in Ireland.

As there is substantial current interest in MMC and DfMA, new information from stakeholder groups across the private and public sectors is continuously emerging. Information which became available during the relatively short project period was included wherever relevant, with care taken to avoid recency bias. During the course of the project, the Department of Enterprise, Trade and Employment and the Department of Housing, Local Government and Heritage jointly published a roadmap for increased adoption of MMC in Public Housing delivery (DETE/DHLGH, 2023), the scope of which overlaps significantly with the subject of this study. Rather than replicating the same work, the aims and methodology outlined above allowed the published roadmap to be taken into account. Hence, many of the actions described in the roadmap are included amongst those considered in this report, along with their contribution to creating the conditions required for widespread use of DfMA enabled MMC and DfR.

This report presents the above research in a series of chapters. Chapter 2 discusses the application of DfMA with MMC and Chapter 3 identifies the associated challenges reported from global and national experience. Chapter 4 describes recent, current and planned MMC and DfMA activities in Ireland, and analyses how these are addressing the challenges identified in Chapter 3. Chapter 5 reviews the principles and application of DfR and its relationship with DfMA and MMC. Chapter 6 defines the conditions required for widespread use of MMC enabled by DfMA and of DfR, along with recommendations on how these could be achieved. Chapter 7 presents general conclusions from the research.

2 DfMA: Design for Manufacture and Assembly

Design for Manufacture and Assembly (DfMA) can be considered to be both a philosophy and a methodology in which products are designed in a way that is as amenable as possible for downstream manufacturing and assembly (Gao et al., 2020). As developed in the manufacturing sector, a common principle of DfMA is to create a product design with fewer parts to be assembled and to design the parts so that they are relatively easy to assemble. There are therefore two components of DfMA, design for manufacture (DfM) and design for assembly (DfA), with DfM principally concerned with the making of individual parts or components and DfA addressing how they are assembled.

2.1 DfMA in Construction

Although often treated together as DfMA, DfM and DfA can be considered as separate activities that both seek to optimise design while reducing materials, overheads, and labour costs. When applied in the construction sector, DfM leads to designs that enable specialist subcontractors to manufacture significant elements of the design in an off-site environment, such as a factory, whereas DfA considers how aspects of the design can be designed in a manner that minimises work on site (RIBA, 2013). Consequently, DfMA has come to be regarded as an essential facilitator of many MMC approaches. It can be implemented as part of an on-site construction design as well as with off-site prefabricated design and the degree of implementation may be the entire building, an individual apartment, or a building component. Recent international review studies report that the most common benefits identified in the DfMA literature are improved quality, reduced fabrication and construction cost, reduced construction time, reduced construction labour, improved health and safety and greater sustainability and circularity (Rankohi et al., 2022; Tuvayanond and Prasittisopin, 2023). These benefits are closely aligned with those for MMC generally, as set out in Chapter 1.

Recognising these potential benefits, in 2013 The Royal Institute of British Architects (RIBA) added a DfMA overlay to its Plan of Work to allow DfMA principles and guidelines to be implemented in construction projects, and this was updated for the 2021 revision of the Plan of Work (RIBA 2013, RIBA 2021). An equivalent overlay was added to the Royal Institute of Architects in Ireland (RIAI) Plan of Work in 2022 (RIAI, 2022). In this regard, DfMA practice in Irish and UK construction is more advanced than in most of the world. Similar official initiatives worldwide appear to be limited, but there are examples from the Singapore Building and Construction Authority which specifies minimum requirements for off-site components (BCA, 2016), the Government of Hong Kong (2018), New Zealand (Smarter Homes, 2023) and Australia (Office of Projects Victoria, 2023).

Gao et al. (2020) identified three ways in which DfMA can be deployed: as an holistic design principle based process for how a structure will be fabricated and assembled; as an evaluation system that can work with digital construction techniques to evaluate the efficiency of fabrication and assembly; and as philosophy that embraces MMC including prefabrication and modular technologies. The RIAI (2022) approach is aligned with the last of these, being applicable to a wide spectrum of tools and technologies employed in MMC, including volumetric approaches, kits of parts and prefabricated sub-assemblies.

Figure 2.1: 2D panelised construction (MMC Category 2)

2.2 General DfMA Principles

Jung and Yu (2022) describe DfMA as a design approach that prevents possible errors in production and assembly and improves production efficiency by inspecting various circumstances related to the product production phase in advance of the design phase. They reviewed several international studies that developed DfMA principles from different viewpoints (e.g. Bogue, 2012), including cost reduction, production time reduction, and the minimisation of environmental impact, identifying that most of these focus on minimising numbers of parts, simplifying assembly and handling, minimising waste and standardisation.

Several studies, including those reviewed by Jung and Yu (2022), have identified the following general DfMA principles:

- Reduce manufacturing time and cost, through design that considers ease of manufacturing, uses a minimum number of parts and connectors and minimises finishing work;
- Reduce assembly time and cost, through design that considers the planned assembly method and avoids complex assembly methods;
- Reduce handling time and cost, by simplifying the methods of handling and assembling parts and standardising connector types;
- Reduce procurement time and cost, through design that repeatedly uses standardised parts;
- Simplify the manufacturing process, by repeatedly using similar materials;
- Simplify design, by employing modular design approaches;

- Minimise manual labour and secure product quality and assembly efficiency, through design that applies mechanical assembly methods;
- Prevent unnecessary reworking, through error-free design;
- Prevent errors during the process of product handling and assembly, through design that considers the production environment and process;
- Reduce component failure, by minimising the use of fragile components;
- Minimise waste, through design that considers re-usability;
- Minimise the impact on the environment, through the selection of environmentally friendly materials;
- Ensure safety and quality during the manufacturing and assembly processes.

While there exist numerous principles and guidelines for DfMA implementation, Lu et al. (2020) caution that DfMA guidelines that originate from manufacturing are not necessarily a good fit with the characteristics of construction projects, including the downstream logistics and supply chain challenges that play a critical role in off-site construction. Unlike manufactured products designed and mass produced in-house, construction projects are invariably bespoke and contextualised within a site and socio-economic function, making it much more difficult for architects to conceptualise, optimise, prototype, and select a design to mass construct. Nevertheless, Lu et al. (2020) advocate for connecting the above general DfMA guidelines with the heterogeneities of the construction industry to develop a database of DfMA examples that could inspire and encourage practitioners towards future innovation and adoption. In this way, DfMA can enable the broader range of innovative solutions for housing construction required by a national programme for accelerated delivery. Customisation, the process through which the details of individual manufactured products can be tailored to suit specific customer or project needs, and design-build contracts, in which the design and construction phases of a project are carried out by the same entity, have been identified as potential means of widening the relevance of DfMA to all building sizes and forms (DETE/DHLGH, 2023).

2.3 Organisational Structures

While DfMA in any setting relies heavily on the integration of different activities, the project-based and fragmented characteristics of the construction industry make the essential collaboration more difficult to achieve. There is an absence of published empirical studies on how to create the collaborative environment required for successful DfMA in construction projects. On the other hand, the application of DfMA to MMC shares many features with more established productivity concepts in the construction sector such as buildability, lean construction and value management, and DfMA is implicitly employed in many infrastructure construction projects other than buildings.

Kremer (2018) noted that design software platforms are essential for DfMA value propositions in which efficiency is evaluated on the assessment, design and adjudication of the parts and elements that constitute the individual components of a building. BIM is widely believed to be critical to the success of DfMA and can facilitate DfMA implementation from two perspectives:

- by providing an analysis platform to identify opportunities for improving manufacturing and assembly processes through the design, and
- by enabling a seamless collaboration environment in which designers, engineers, suppliers, and contractors can exchange ideas, share knowledge and store information required for off-site fabrication and on-site construction.

In a review of recent published literature on DfMA for the construction industry, Rankohi et al. (2022) report that the application of DfMA worldwide is still marginal. Their review identifies several barriers to greater adoption including: a community resistive mindset, unsupportive embedded industry practices, insufficient regulations and incentives by governmental bodies, inadequate planning and building codes, limited organisational knowledge and readiness, inefficient supply chain management, the absence of a suitable delivery method and contracting strategy, and the lack of suitable technical requirements.

A challenge facing DfMA application in global construction is the lack of suitable ecosystems including guidelines, standards and affordable technologies to enable its widespread adoption (Lu et al., 2020). Guidelines and standards are important for stakeholders when extra investment in new technologies is required to shift from conventional means of design, production and construction, and are especially important for SMEs operating in a highly fragmented industry.

Rankohi et al. (2023) conclude that integrated business models, relational delivery methods, lean-based operational tools, and digital technologies are all required to enable a suitable environment for the implementation of construction-oriented DfMA strategies based on enhanced collaboration among project participants. The operational tools and techniques are based on the application of intelligent technologies and BIM, which acts as both a process enabler/implementation tool and an information source/model enabling knowledge sharing, communication and productivity monitoring. Information technologies that support both product- and project-level information management will be required for customisation-based DfMA in housing delivery.

Chapter 3 describes the wide range of challenges facing the implementation of DfMA with MMC. Many of the identified challenges are related to the fragmented nature of construction projects, which leads to a lack of integration associated with unsupportive organisational structures, contractual frameworks and operational systems. An appropriate organisational structure is required to co-ordinate stakeholder collaboration, an appropriate contractual framework will align stakeholder goals with project objectives and an appropriate operational system will ensure effective interaction and communication between project participants. Business models that support integration and longitudinal continuity are necessary for significant DfMA implementation. Vertically integrated models in which all project phases from initiation through design, manufacture, assembly and delivery are performed by the same company have been observed to be successful in the Irish housebuilding sector. An alternative, more difficult, model is digital systems integration in which a BIM-based platform is employed to support integrated design-to-delivery workflows employing multiple supply chain partners.

Figure 2.2: 2D panelised façade construction (MMC Category 2)- Photo source: Framespace Solutions

2.4 RIAI DfMA Overlay

The RIAI DfMA Overlay to the RIAI Plan of Work (RIAI, 2022b) presents a common framework for construction professionals and stakeholders to employ when applying the DfMA approach at project level. The overlay sets out eight work stages in the execution of a DfMA project. These are significantly different to the work stages followed in a traditional project as they are designed to enable the adoption of MMC, including off-site manufacturing, and to realise the anticipated benefits.

For each work stage the overlay identifies environmental and lean design considerations and the digital delivery requirements to ensure that necessary design information is available during each stage of DfMA implementation. To facilitate these goals, an additional initial work stage (Workstage 0 – Strategic Definition) addresses the strategic definition of the project, including the development of the business case and the greater collaboration required in DfMA project teams. This involves early appointment and engagement, coordination of design inputs, and design freeze before MMC component manufacture. This allows the potential for embedding MMC in the project to be maximised through committed DfMA, and helps to align client requirements on cost, delivery and sustainability goals with the properties of the selected MMCs.

The new role of MMC Advisor is introduced to bring the knowledge and experience of MMC categories and processes required to guide MMC optioneering and selection, and to advise on constraints and procurement options.

The work stages in the DfMA Overlay are (RIAI, 2022b):

- Workstage 0: Strategic Definition
- Workstage 1: Inception
- Workstage 2: Outline Design
- Workstage 3: Scheme Design
- Workstage 4: Detail Design
- Workstage 5: Production Information
- Workstage 6: Tender Action
- Workstage 7 & 8: Project Planning, Operations on Site and Completion

For each work stage, the overlay presents guidance on tasks to be performed and issues to be considered, with emphasis on those relating to DfMA and MMC, from three perspectives: design development, sustainability and digital delivery. The topics and considerations addressed under each of these are:

Design Development:

- Effects of MMC on the business case, cost model, funding, payment and risks;
- Project team collaboration, early engagement, specialist manufacturer input and design freeze;
- Experience- or case study-based knowledge of the influences of MMC categories on project constraints such as cost and time;
- Design coordination and quality assurance in manufacturing and construction;
- MMC optioneering and construction methodology selection considering building type, form and function;
- Opportunities for MMC-based design standardisation;
- Local and international MMC market capacity, suppliers and supply chain;
- Spatial constraints strategy to support MMC substitution;
- Insurance limitations for specific forms of MMC;
- Influence of selected MMC on procurement strategy, design responsibility matrix and project delivery programme;
- QA/QC requirements including MMC product and system certification and manufacturing process inspection.

Sustainability:

- Strategic definition of environmental goals, including client requirements;
- Role of sustainability champion, sustainability indicators and monitoring;
- Contribution of MMC to client or funder environmental accreditation requirements;

- Application of a sustainability strategy in MMC optioneering;
- Use of experience from other projects including environmental benchmarking;
- Sustainability responsibility matrix and specialist input requirements;
- Sustainability appraisal of developed design and tender returns;
- MMC manufacturer, contractor and sub-contractor responsibilities;

Digital Delivery:

- Digital delivery strategy, responsibility matrix and information protocol to facilitate DfMA at all stages;
- Incorporation of digital delivery workflows, including the earlier mobilisation requirements of DfMA and the optimisation of digital components for particular MMCs;
- Differences in information management function with a DfMA approach;
- Incorporation of standards and methodologies to optimise DfMA in the BIM Execution Plan;
- Sequencing of model elements with the project programme;
- Information formats required for different design, manufacturing and construction stages and throughout the supply chain;
- Data compatibility of specialised software used in different stages;
- Methodologies for processing sustainability metrics;
- DfMA stakeholder identification of Organisation and Asset Information Requirements;
- Implications of DfMA approach for the Project Information Production Methods and Procedures and the Common Data Environment;
- Appropriate Project Information Standards and Level of Detail for each DfMA stage;
- Identification of the Project and Exchange Information Requirements of all DfMA stakeholders;
- Information management risks associated with DfMA.

The breadth, complexity and interdependency of the above details indicates that DfMA with MMC be will difficult to implement within traditional construction project delivery in which project phases are fragmented and stakeholders have reduced incentive to collaborate. Greater success is likely with relational project delivery methods that emphasise integration and share risks and rewards. However, as confirmed by Lu et al. (2020), globally there has been little formal reporting of DfMA application in actual projects. Structured information from multiple case studies will be necessary to evaluate the effectiveness of the RIAI or RIBA overlays, which are expected to be updated as experience with their application evolves. Lu et al. identify insufficient hands-on training and re-training as a potential factor that is limiting global application. The need for additional professional and skills training in DfMA and MMC throughout the Irish construction sector has been identified in the Roadmap for increased adoption of MMC in Public Housing delivery (DETE/DHLGH, 2023). CPD education and training on the RIAI Overlay will be necessary if DfMA is to enable widespread adoption of MMC in housing construction in Ireland.

3 Challenges to DfMA with MMC

DfMA requires construction project stakeholders to shift their paradigm from the conventional means of design, production and construction. As in other fields, change on such a scale can occur slowly if the conditions required for the new approach are not in place and especially if capital or skills investments are required.

This chapter sets out the challenges faced by the construction and built environment sector in adopting DfMA, as identified in national and international studies on the subjects of MMC and DfMA. When considering the widespread adoption of DFMA with MMC the challenges include:

- those related to the complete or partial implementation of Design for Manufacture and Assembly as a method for construction project delivery, and
- those related to the development of individual or multiple Modern Methods of Construction and their application as components or methods in new building construction.

In many cases, however, the different challenges affecting DfMA and MMC overlap and need to be considered together. Some challenges represent constraints imposed by the unique characteristics of the construction sector, while others arise due to perception, established practice or the absence of appropriate technology (RIBA, 2021). For example, based on interviews of industry experts Langston and Zhang (2021) state that the reasons for slow adoption of DfMA in Australian construction include community mindset, government regulations and incentives, planning and building codes, finance, and supply chain management, in addition to project specific factors such as building type compatibility and transportation distance. Rankohi et al. (2023) identify a total of 45 different challenges, which they categorise as contractual, technological, procedural, cultural, commercial, geographical, financial, or technical/cognitive. The most important challenges identified in these and other studies and by stakeholders in Ireland, are described in this chapter. In Chapter 4 these are compared with existing, new and proposed initiatives that are intended to address these challenges and enable DfMA with MMC in Ireland.

Rankohi et al. (2023) discuss the findings of several studies on integrated programme delivery in the construction sector, observing that as a collaborative strategy DfMA relies heavily on integration. Therefore, noting that the integration of project teams is an essential characteristic of successful DfMA, the unique characteristics and project-based nature of the construction industry are accounted for by considering the identified challenges under three headings:

- *Organisational Structure*: referring to the structure of the team formed by the project stakeholders and the timing of their collaborative engagement in the project;
- *Contractual Framework*: covering the regulative guidelines that align stakeholder goals with overall project objectives through compensation structures and risk allocations;
- *Operational Systems and Processes*: describing the application of tools, technologies, and mechanisms to ensure effective collaboration and communication among participants.

In Table 3.1 the challenges facing the widespread use of MMC in general and DfMA in particular are categorised under the three headings of organisational structure, contractual framework and operational systems. This treatment of challenges is a combination and adaption of the approaches of Lu (2020) and Rankohi et al. (2023), together with synthesises information from the multiple national and international sources identified in the following sections. The categorisation of challenges in this way facilitates the identification of targeted actions designed to support more widespread adoption of DfMA with MMC. Two levels of adoption are covered (i) the need to develop DfMA with MMC generally within the industry including new policies, supports, procedures, regulations and testing, and (ii) the employment of MMC within a specific project, including stakeholder relationships, early engagement, design co-ordination and communications.

3.1 Organisational Structure

The integrated nature of DfMA with MMC implies more complex organisational structures than in traditional project delivery, while the requirement for better collaborative practices implies continued behavioural change in an industry used to transactional and adversarial contractual relationships (RIBA, 2013).

3.1.1 Stakeholder Integration

Challenges related to stakeholder integration arise from the fragmented nature of the construction industry (RIAI, 2022) which leads to a lack of vertical and horizontal integration between stakeholders. The consequent division of architectural design, engineering design, manufacturing and on-site construction makes the application of the DfMA principles set out in Chapter 2 more difficult than in other productive sectors (Buckley, 2023). Those principles were originally developed for parts of the manufacturing sector in which designers are closely involved in the making of their products. It is clear that they will be more difficult to apply in construction where the variety of buildings, components and construction processes encountered across different projects means that architects cannot have full knowledge of all aspects of component manufacture and assembly.

The complex organisational structures employed in construction projects can mean that responsibility for different elements of a building project is unclear. Different forms of relationship exist between clients and manufacturers, and the form of engagement between the two can vary considerably between projects, with associated variations in roles and responsibilities within design teams. There is generally a greater need for clients to engage with manufacturers in DfMA than in traditional building projects (RIAI). However, the disaggregated, fragmented nature of construction projects often does not support the collaborative behaviour required to commit to a DfMA approach, to make early appointments of essential project team members and to engage with the MMC supply (RIBA, 2021).

Early appointment of the complete project team can facilitate the early engagement of stakeholders that is frequently cited as an essential characteristic of successful DfMA (RIAI, 2022; RIBA, 2021; Rankohi et al., 2023). While it is clear that strong engagement can help to maximise the potential for including MMC in a project, give good opportunity to coordinate design inputs to a high level of detail and avoid design rework, in many real situations wider considerations prevent it happening. An example includes the pace and requirements for obtaining planning permission: clients may be reluctant to engage with all stakeholders prior to obtaining permission, but once permission is obtained the project constraints can make it difficult to adjust designs to incorporate optimum MMC (RIBA, 2021).

Table 3.1: Challenges for DfMA with MMC

Organisational Structures
Stakeholder Integration
• Fragmented industry • Lack of vertical and horizontal integration between stakeholders • Lack of longitudinal integration with teams disbanding at project termination • Need for early engagement with off-site manufacturing • Need for client and designers to engage directly with manufacturers • Allocation of responsibility for different elements of project
Stakeholder Relationships/Communications
• Early commitment to project team required • Need for strong communication among stakeholders • Need for trust and collaboration between buyers and their suppliers • Conflicting cultures between engineering and design teams • Confrontational approach as stakeholders aim to capture value • Lack of understanding of modular options • Reluctance of stakeholders to share data
Client Requirements
• Management of customer expectation in design • Perception that quality and durability of prefabricated building are reduced • Client concerns about poor image of industrialised construction and market confidence in products • Client reluctance to commit prior to observing MMC components on site • Lack of awareness of DfMA benefits among owners/developers • Risk adverse clients due to lack of awareness of MMC and supply chain • Strong relationships needed to convince clients to adopt DfMA • Late engagement of MMC consultants by clients • Client needs not understood by MMC manufacturers
Market Capacity
• Limited market options available, especially local options • Lack of competition among prefabricated/modular solutions • Low number of manufacturers with limited capacity • Absence of testing facilities to support certification • Resistance to change preventing stakeholders abandoning conventional means of design, production, and construction • Knowledge, education and training gaps on modular and MMC

Contractual Framework
Contract and Procurement
• Lack of agility and flexibility in standard contracts • Contract and procurement models favouring traditional delivery • Lack of a standard form of contract for DfMA and MMC • Inflexible public procurement procedures • More difficult for public clients to engage directly with manufacturers • Considerations of risk/reward sharing and allocation • Compliance risks related to regulations • Supply chain risks related to MMC availability and compatibility • Lack of clarity on guarantees and insurance • Lack of prefab and MMC consideration in tender documents • Bid overpricing and difficulty in cost estimation
Roles and Responsibilities
• Lack of clear scope of work, confusions and duplications • Lack of clear roles and responsibilities of stakeholders, including: • design standards, certification, and testing • facilitating inspections • interfaces between off-site and on-site elements • approval of MMC components for specific building projects • Supply chain co-ordination challenges • Co-ordinated adoption of new BIM modelling and verification tools
Financial
• Difficulty in financial management and lack of an efficient payment method • Payment schedules that recognise early manufacturing costs • Lack of insurance policies for different risks associated with DfMA/MMC • Potential of increased insurance costs • Uncertainly with respect to warranties and liabilities • Additional problems securing project financing with new MMC • Scarcity of resources for component development • High quality MMC seen as a cost not added value
Market Demand
• Inconsistent and low demand for MMC • Demand reduced by low MMC capacity and supply chain limitations • Scale of demand required for manufacturer investment • Lack of certainty of demand or predictable pipeline of projects • Project forecasting necessary for manufacturing efficiency • Market in Ireland limited by scale • Strong regulatory environment required for customer confidence

Operational Systems
Additional Co-ordination Demands • Additional coordination and collaboration between stakeholders • Additional coordination between phases and contractors • Critical importance of knowledge sharing with other stakeholders • Need to evaluate performance at every design stage • Need for additional project planning and design efforts • Increased organisational complexities and investment requirements • Higher design costs than the traditional design methods • Greater upfront costs • Extra technology investment required to support DfMA applications
Technical knowledge • Limited DfMA knowledge and experiences • Inability to exercise early design freeze • Reduced performance in initial installations • Lack of capabilities to manage the module configuration process • Management of assembly works and interface tolerances • Management of interfaces with subsystems • Design of interfaces between modular elements • Difficulty in identifying appropriate DfMA tools/techniques in each phase • Scarcity of documented DfMA application in actual projects • Logistics and transportation management complexities • Co-ordination of off-site manufacturing and on-site construction • Specialised labour requirements
Certification • Complex product and building compliance and inspection process • Shortage of standard details and connections • Necessity of first-run prototypes • Difficulty in obtaining certification for innovative products • Limited guidance available on certification requirements and process • Limited testing facilities to support certification • Limited R&D capacity within and supporting industry • Lack of a suitable ecosystem to enables widespread MMC adoption • Design inflexibility and difficulty making changes after ordering MMC components • Lack of innovation as product architecture is locked

Poor longitudinal integration in the construction industry means that project teams disband at project termination with consequent loss of knowledge and collaboration experience. This affects two of the key concepts for MMC delivery: developing effective collaboration between stakeholders and building a consistent pipeline of projects in which those collaborations can be employed. This also makes it difficult to build reliable supply chains based on consistent multi-annual demand patterns.

3.1.2 Client Requirements

DfMA is reported as leading to greater need for the management of customer design expectations, and the use of MMC can be rejected by risk adverse clients unaware of the potential benefits of DfMA (RIAI, 2022). Evidence exists that off-site manufacturing can carry a cost premium and clients will need information on whether that is likely to apply for their project, and how it relates to potential benefits such as quality and overall programme duration (EY, 2021). Project teams may need to actively convince clients to adopt DfMA with MMC in their project (O'Connor, 2023), clients may be reluctant to make payments until they observe manufactured components installed on site (CIF, 2021), and the need to finalise design details up-front can reduce the flexibility available to the client to change design choices prior to completion (Lydon, 2023). Joint client-designer visits to similar previous developments may be necessary to develop a shared project ambition, and programme time will be required to create and consider mock-ups of potential MMC solutions.

Clients may perceive that the quality and durability of modular buildings are reduced (RIAI, 2022) and fear customer rejection due to a poor image of industrialised construction (Rankohi et al., 2023), leading to reduced market confidence. This issue needs to be considered separately for houses and apartments where different customer concerns and perceptions of regulations apply. Strong relationships can therefore be required to convince clients to change from traditional delivery to DfMA, especially when there is a lack of awareness and understanding of important types of OSM and the associated supply chain.

On the other hand, client needs and demands differ greatly and are not always well appreciated by MMC manufacturers, who need to understand each customer's particular motivations with respect to quality, programme and cost. Manufacturers may need to invest in the development of their in-house capability to engineer solutions that match individual project design demands; including specialist skills and tooling, on-site testing, and sophisticated delivery and installation technology. Alternatively, manufacturers may employ design for market concepts that aim to ensure that the manufactured quality of standardised components is sufficient to be accepted by a large proportion of their customers. This allows the actual costs of higher quality standardised solutions to be lower than those of lower quality bespoke options but can result in clients being offered a more limited range of MMC options.

There are knowledge and experience gaps related to the decision-making required for optimisation of a project from site selection through design and construction. Evidence- and data-based decision-making approaches are not well supported by openly available information and are characterised by manual processes that do not employ software or IT-based tools optimally.

3.1.3 Market Capacity

DfMA with MMC requires the integration of four project stages: market, design, assembly and maintenance (Buckley, 2023). For successful implementation, clients and designers need to take into account the markets for both the finished building and for the MMC components to be procured for assembly. Designers may find it difficult to provide good information about the quality of manufactured components needed to satisfy client requirements, especially with regard to future maintenance and durability.

Globally, and compared to traditional construction projects, there are often relatively few market options available for MMC components, a lack of competition among prefabricated and modular solutions and few local options available (Rankohi et al., 2023). In Ireland, for any given MMC technology, there are likely to be a low number of manufacturers with limited capacity (RIAI, 2022). Investment in manufacturing facilities needs to be underpinned by a consistent pipeline of projects, which in turn requires sufficient de-risking of the supply chain for designers and clients.

The standardisation of production delivery by manufacturers is essential for scale and cost control but it can be seen to imply an associated standardisation of design and a restructuring of the value chain. Where designers wish to employ DfMA, a shortage of testing facilities can act as a barrier to the introduction of new MMC solutions or to variations in existing solutions to meet the particular requirements of individual projects, reducing the ability of the market to provide the capacity required in a timely manner. The likelihood that more complex systems will require more testing promotes the fear that designers will be forced to adopt pre-existing, standard solutions, with consequent loss of creative influence and building individuality.

The ability of DfMA with MMC to contribute to increased housing supply and reduced housing costs is clearly linked to the need to support market capacity through sufficient availability of product and system testing facilities (Wallace, 2023). This implies that the testing requirements for certification should be aligned with available testing capacity, taking into account the allocation of risk between stakeholders. Research, development and innovation activities supported by effective knowledge transfer can contribute to an increase in market capacity by offering multiple solutions to emerging design requirements. However, the construction sector in Ireland has experienced little public or private investment in research, and the existing research and innovation ecosystem requires strengthening if it is to play a strong role in industrial capacity development.

Looking forward, different certification and testing requirements may apply for standardised MMC products than for customised products to be employed within a productization (e.g. platform) approach. If the requirements for customisation are less onerous than for standardisation, productization could offer the potential to increase effective market capacity.

3.2 Contractual Framework

The contractual framework underpins complex projects by aligning added value, compensation and risk allocation between stakeholders with overall project objectives. However, contractual frameworks developed for traditional delivery approaches will not be optimal for MMC enabled by DfMA.

3.2.1 Contract

Standard forms of contract often do not offer the agility and flexibility required for DfMA. Risk and reward sharing is not adequately considered and there can be a lack of clarity in terms of guarantees and insurance. Projects employing DfMA with MMC carry two forms of risk that need to be managed differently to traditional building projects:

- Compliance risk: relating to whether the assembly of products used to form the building complies with the Building Regulations, even when each individual product has been separately tested and certified for that purpose, and
- Supply chain risk: relating to the dependency of a project or programme on the availability and capacity of MMC manufacturers and the flexibility of the DfMA approach if substitution is required.

Where added value is re-allocated to earlier stages of the value chain, such as in the increased use of off-site manufacture over on-site construction, both risks and rewards also need to be re-allocated. In the absence of a specific form of contract designed for DfMA projects, off-site manufacturers working with public clients may be asked to employ an amended version of a traditional public sector contract. The standard contract and procurement model encourages traditional delivery and discourages innovation generally and the use of OSM, especially in the public sector where decision-making procedures can be governed by procurement procedures. Ideally, a standard DfMA with MMC form of contract would be developed, however, any public procurement strategy to increase use of DfMA for MMC will need to comply with public procurement principles (RIBA, 2021) limiting the extent to which this issue can be mitigated.

While MMC is becoming more present in tendering and procurement (Hughes, 2023) there is often insufficient prefabrication and MMC consideration in tender documents influenced by a lack of understanding of modular construction. Difficulties and inexperience in relevant cost estimations can lead to bid overpricing. Quality can be seen as a cost rather than added value, which causes particular difficulties in the public sector when a preferred manufacturer is not the most cost-effective bid.

3.2.2 Roles and Responsibilities

The roles and responsibilities of stakeholders can be less clear with DfMA than in traditional delivery models, especially at the interfaces between MMC components supplied by different manufacturers, or between MMC and on-site elements. This uncertainty can arise due to the absence of a clear scope of work or poor co-ordination leading to omissions and/or duplications of tasks. In each project, responsibilities for defining design standards, certification requirements and testing standards need to be allocated amongst multiple designers and manufacturers in an expanded project team. The roles of the different participants responsible for the design, manufacture and assembly of each component need to be defined, as does responsibility for making and facilitating inspections and ensuring adequate insurance provision. The integration of multiple technologies in modular buildings, or buildings incorporating MMC generally, can present additional supply chain co-ordination challenges.

Adopting a DfMA approach involves changes in required knowledge, in the mix of people involved, and in the extent and timing of collaboration (RIBA 2021). The associated changes to workflows depend heavily on the co-ordinated adoption of new BIM modelling and verification tools to automate design and assembly, which may require human and capital investment by individual partners. Responsibility for certification and approval of MMC components for specific building projects can be uncertain, and the burden of any associated testing can be too great for some SMEs (Wallace, 2023) preventing their participation in the market unless supported by other stakeholders in the value chain.

Figure 3.1: Building Information Model of a multi-storey building (Source: CP Skillnet, 2023)

3.2.3 Financial

DfMA-based project delivery presents additional responsibilities and complexities in financial management including the need for efficient and project-appropriate payment methods. DfMA- and MMC-based projects often require payment schedules that recognise early manufacturing costs. This is especially relevant when DfMA-enabled MMC is employed to reduce programme duration, as manufacturers will need to build up their stock in advance of the installation stage if the installation process is to proceed faster than manufacturing production.

Additional problems may be encountered in securing project financing for projects that include significant amounts of new MMC, even when employing off-site manufacturing in a traditional design and delivery model. Financial institutions may be hesitant about new methods of construction with limited track records, which has the potential to cause working capital issues (EY, 2021). Inflexible public procurement processes make it more difficult for public clients to engage directly with contractors and manufacturers (RIAI, 2022). The absence of a confirmed pipeline of projects hinders advance investment in manufacturing facilities, with an associated scarcity of resources for component development.

Some clients can have extra concerns about finance, insurance and certification; or in the sign-off stages are concerned about risk. There is a shortage of insurance policies to cover different risks associated with DfMA and MMC, and insurance costs overall can be greater due to the lack of data on the long-term performance of homes built using MMC (RIBA, 2021). Additional uncertainties with respect to warranties and liabilities have also been reported.

3.2.4 Market Demand

An inconsistent and low level of demand for MMC in residential construction projects can represent a challenge for widespread adoption of DfMA with MMC in the sector. Demand can be effectively inhibited by low supply capacity, but manufacturers and suppliers may not be able to increase capacity if demand is inconsistent (RIBA, 2021).

Manufacturers and contractors need certainty of demand if they are to develop and offer repeatable solutions. Clients would like certainty that the supply chain can respond, provide the capacity, and can meet the level of quality, regulation and standards that their projects demand. The market in Ireland is necessarily limited by scale, and while public sector demand has grown recently, large private clients are not well co-ordinated in building the desired pipeline of projects.

For off-site manufacturers, forecasting which job will proceed is critical for optimising factory efficiency, but this is difficult in a volatile industry and may not assure the scale of demand required for long- and medium-term investment in equipment and skills. Investment can only take place if clients and their designers demand MMC options. For homebuilding, demand for innovative solutions such as MMC requires customer confidence, which is strengthened by a strong regulatory environment.

The sectors in which DfMA has been widely adopted, such as data centres, pharmaceutical production and healthcare, are characterised by future revenue streams that encourage developers to accept more risk and thereby lower the risk imposed on the construction supply chain. Public sector commitments to the use of MMC in social and affordable housing can also bring more certainty to the housing sector generally and help to de-risk the associated application of DfMA.

3.3 Operational Systems

3.3.1 Additional Co-ordination Demands

DfMA-based projects require strong coordination and collaboration between stakeholders, with project integration requiring closer coordination between phases and between the design team, suppliers and contractors. The sharing of knowledge and information with other shareholders is more critical than in traditional build projects and requires greater harmonisation of information systems, technology, software and data. In Ireland, there is a shortage of data on the use of MMC in building projects (DHLGH, 2023) and no open library of related technical information.

DfMA places additional demands on designers and the supply chain. Overall, additional project planning and design effort is required, and performance needs to be more closely evaluated at every design stage. Additional project costs can be incurred due to greater organisational complexities and investment requirements, including higher design costs than with traditional delivery methods, and higher capital costs and investment requirements. These include the extra technology investments required to support general or specific DfMA applications (Lu et al., 2020). Collectively, this means that greater upfront costs are often encountered early in the project (RIAI, 2022; RIBA, 2021) and a reliable pipeline of projects is often required to justify these additional costs and investments.

3.3.2 Technical knowledge

Limited knowledge and experience of the DfMA approach and methodology amongst design teams and wider stakeholder groups can restrict its widespread application. As the skills for undertaking the related processes are variable (RIBA, 2021) reduced performance can be anticipated in initial installations by stakeholder teams as they explore new procedures. DfMA involves digitisation, automation and collaboration between disciplines, and requires good knowledge of construction and manufacturing processes and logistics. The required mix of skills is not provided by any one profession, instead being distributed across many different roles including architects, engineers and project managers (RIBA, 2021). In contrast to the application of DfMA in other sectors, designers of residential construction projects often do not have broad manufacturing knowledge and experience (Langston and Zhang, 2021) and need the factors that influence manufacturing costs to be made available to them on a project-specific basis.

Experience and knowledge gaps can contribute to an inability to exercise the early design freeze generally required in successful DfMA, and increase the need for cross-sectoral capabilities to manage the off-site assembly configuration processes. This includes the design and management of assembly works and interfaces with other subsystems (e.g. modular elements) and consideration of interface tolerances, which implies knowledge throughout the design team of MMC component detailing. The on-site field connection of different off-site built systems to each other and to traditionally built elements needs careful planning, design, execution and verification to protect design intent, avoid re-work and preserve regulatory compliance. As OSM components can be difficult to adjust on site, good dimensional accuracy and allowance for in-service movement including environmental effects are often more critical than in traditional solutions, with additional demands for on-site workmanship to achieve compatible tolerances for traditionally built elements (RIBA 2021).

Project teams can experience difficulty in identifying appropriate DfMA tools/techniques for each phase of a project, or in transferring tools between phases. There is a scarcity of documented DfMA applications in actual projects (Lu et al., 2020) that can be used as guidance in this regard. Full automation of the design, manufacture and assembly process requires strong IT skills across all stakeholders, implying additional roles related to data management and security. When new MMC components or methods are being employed, on-site construction workers may be required to develop new skills relating to materials handling, component assembly, specialised equipment, safety and record keeping. They will also require knowledge and training on how to demonstrate that each MMC element has been installed correctly when inspected, which may require different procedures for different forms of MMC component.

DfMA projects present additional logistics and transportation management complexities. Greater complexity in the MMC components of the design solution is likely to require longer lead-in times and more complex logistical procedures. The distance from manufacturing location to site needs to be considered along with available means of transport, potential import controls and on-site or near-site storage. Site installation requires sophisticated logistics and supply chain optimisation and strong project management skills to coordinate timely production, delivery and installation of MMC components and assemblies. These activities may also have specialised labour requirements, which can be reduced if the interfaces of offsite elements are designed to allow for simple assembly.

3.3.3 Certification

Globally, it is recognised that the potential benefits of DfMA with MMC can be restricted by complex regulatory compliance and inspection processes. Certification by local building control and fire authorities can be difficult, expensive and slow to obtain for innovative products and applications, which design teams can view as a project risk (Langston and Zhang, 2021). In Ireland, an inconsistent approach to building control and fire inspection has been reported for projects in different locations. MMC applications are liable to be subjected to dual inspection at the manufacturing location and again after assembly on site to fulfil separate but related regulatory requirements (CIF, 2021).

There are few appropriate testing facilities (RIAI, 2022) available in Ireland for the verification of fire, acoustic and structural performance and limited guidance on testing requirements and experimental programme design is available for project teams. There is generally limited relevant R&D capacity within and supporting industry, which can be characterised as the lack of a suitable ecosystem of guidelines, standards and affordable technologies to enable widespread adoption of MMC (Lu et al., 2020).

Certification requirements lead to a reduction of innovation as product details often cannot be varied between applications and projects without additional expense and delay. This adds to the expectation or experience that DfMA designs are inflexible and changes are more difficult to make after placing an order (RIAI, 2022), while requirements for prototyping and mock-ups can further reduce the number of manufactured components available for selection.

Standardisation and repeatability whereby the same building components are repeatedly employed across multiple building projects are widely believed to be an essential means of realising the benefits of MMC, especially those relating to productivity. However, standard details and connections for components are often not available for manufacture and application, and where they are designers and clients may be reluctant to adopt IP-protected building systems. This is less important for projects delivered with vertically-integrated organisational structures and business plans, but does need to be considered carefully in most other cases, including public housing projects. For example, standard details developed for one housing programme by a designer, manufacturer and contractor from separate organisations may not be useable by the same people when working with other collaborators on future projects. Better understanding of the value of the intellectual property created by design teams and how this can be exploited in later projects is necessary for wider adoption of DfMA with MMC (RIBA, 2021).

Project-specific variations reduce the value of standardisation, and the associated need to obtain additional product certification increases the costs involved. Yet, standard details and the accompanying technical guidance documents required for their manufacture and application are generally not available. This is a real barrier to adoption of DfMA with MMC for residential construction in Ireland where the absence of testing facilities creates delays in the introduction of new products.

4 Activities Supporting DfMA and MMC in Ireland

This chapter presents recent, current and planned activities that support the development of DfMA and MMC in Ireland. Over 40 activities are identified under six categories: (i) studies and reports, (ii) guidance and rules, (iii) education and training, (iv) conferences and meetings, (v) centres and projects, and (vi) state, public and sectoral initiatives. These include both small and large scale actions which, while not an exhaustive list of all activities related to DfMA and MMC in Ireland, represent a summary of the current status of the field.

The final section of this chapter presents a categorical comparison of the identified activities and the challenges to the adoption of DfMA with MMC set out in Chapter 3. This aids an analysis of how well the set of activities addresses the known challenges and where additional supports may be required.

4.1 Studies and Reports

4.1.1 'Economic analysis of productivity in the Irish construction sector', 2020

KPMG, Future Analytics Consulting and TU Dublin

This report was commissioned by the Department of Public Expenditure and Reform to investigate low levels of productivity in the Irish construction sector. It recommends appropriate actions for productivity improvement that are guided by three high level principles addressing collaborative relationships, workforce conditions and digital technology and innovation.

4.1.2 'A Detailed Description of Needs for the Irish Construction/Built Environment Sector', 2021

EY for Enterprise Ireland

This report identified the needs of the Irish construction and built environment sector in three areas: modern methods of construction, digital adoption and technology and innovation. It also considered the themes of environmental sustainability and circularity. The report supported the establishment of the national Construction Technology Centre (now Construct Innovate), one of seven priority actions recommended by KPMG et al. (2020). It contributed to the definition of the scope and responsibilities of the new centre, with a view to enabling stronger industry participation in research, development, and innovation and promoting sectoral digital and technology adoption and collaboration. These aims are central to the success and increased application of DfMA with MMC for residential construction.

4.1.3 'Modern Methods of Construction', CIF, December 2021

Construction Industry Federation

This report by the CIF Modern Methods of Construction (MMC) Working Group comprising members from off-site/modular manufacturers, house builders, and specialist M&E, civil engineering and general contracting companies represents a comprehensive contemporary assessment of the state of MMC adoption in Ireland. It includes valuable primary data from 29 structured expert interviews with participants from off-site manufacturing, general contracting, consultancy and the public sector. An analysis was performed of the wide range of issues influencing MMC application in Irish construction projects, and the requirements for further adoption.

This assessment and analysis led to detailed recommendations addressing a wide range of issues, including:

- testing facilities: acoustic, thermal, structural, fire and moisture;
- building physics expertise;
- technology/product development, commercialisation and adoption;
- technology demonstration and investigation in a living laboratory environment;
- centres-of-excellence: Construction Technology Centre, MMC Demonstration Park and Build Digital Project;
- supports for standards and building regulations to enable new product development and introduction;
- industry-focused advanced education and training facilities;
- environmental sustainability including waste, climate and social issues;
- open-source interoperable digital technical content;
- consumer interests;
- certification systems for standardised typologies to enable repetition and scalability;
- regulatory, audit, inspection, and certification to support insurance, finance and investment requirements;
- supply chain, logistics and project management optimisation;
- skills and labour requirements for design, manufacture and installation;
- role of public sector projects in creating demand for MMC solutions.

4.1.4 'Modern Methods of Construction: Defining MMC Business', April 2022

Construction Professionals Skillnet

This report addresses the additional skillsets required throughout the construction sector workforce to deliver projects using MMC, making recommendations for construction businesses, policy makers and training and education providers. It emphasises the new roles and skills that are required in MMC-based construction, and by association DfMA. Recommendations at end of the report place CPD for construction professionals, including architects and engineers, in the wider context of skills, training and education needs for MMC and highlight the dual construction-manufacturing context.

4.2 Guidance and Rules

4.2.1 'RIAI DfMA Overlay to the Plan of Work', October 2022

RIAI

The RIAI DfMA Overlay sets out the steps to be followed in a series of design stages when following a DfMA approach to incorporate MMC in a project. This includes consideration of lean design methodologies, environmental design considerations and the digital delivery activities required at each design stage, as well as project team collaboration and coordination. The aims of the overlay are to enable and maximise the benefits of MMC throughout the project lifecycle.

4.2.2 RIAI Design for Manufacture and Assembly Report, October 2022

RIAI

This report aims to increase understanding of MMC amongst Architects and other construction sector stakeholders and provide guidance on how it can be embedded into the design and construction processes using a DfMA approach without losing design quality. It accompanies the RIAI Design for Manufacture and Assembly Overlay document and supports the implementation of recommendations set out in the CIF Guide to the Development of Modern Methods of Construction Report (2022).

4.2.3 Digital Construction Pack, July 2023

Construction Professionals Skillnet

This guide sets out procedures for the pre-construction and delivery of construction projects using digital technology in Ireland. This guide has been developed by construction companies to support service delivery underpinned by digital tools and processes, describing the relevant framework of digital standards, tools and policies. It provides advice on how to structure and resource commercial digital project delivery, establish skilled teams and maximise operational efficiency.

4.2.4 'Design Manual for Quality Housing', Quality Housing Design Series, 2022

Department of Housing, Local Government and Heritage

This manual provides guidance on the design of residential site layouts and internal layouts of new apartments and houses for local authorities, approved housing bodies and others involved with the design and delivery of social housing. It complements other MMC-relevant guidance documents in this area including Quality Housing for Sustainable Communities (2007), Sustainable Residential Development in Urban Areas (2009), Design Standards for New Apartments (2018) and Employer's Requirements for Detail Design of Quality Housing (2019). A review of a selection of designs in the manual will consider how design standardisation in public housing projects can facilitate adoption of a range of MMC-based solutions suitable for DfMA with multiple forms of construction.

4.2.5 Building Regulations, Inspection and Control Initiatives

DHLGH, BCAs, NSAI, DAFM, Professional Bodies, Education Providers

The Building Regulations Advisory Board is to be re-established by DHLGH to provide expert independent advice on updating the Building Regulations and Technical Guidance Documents, which will include sectoral and technological developments related to MMC. An NSAI committee has been established to provide stakeholder and expert advice on gaps in standards relating to off-site construction and MMC, including alignment with developing international standardisation. The DAFM is to establish a Working Group on Timber in Construction to examine the regulations, standards and certification processes relating to the expanded, innovative and safe use of timber in Irish construction.

New CPD and training programmes are to be introduced for construction sector professionals and staff in Building Control Authorities to address skills and knowledge gaps arising from the increased adoption of MMC and DfMA, including those related to standards and certification. These new programmes are to be developed in collaboration with professional bodies, education providers and State agencies.

4.2.6 'Guide to Agrément Certification for Modern Methods of Construction (MMC)', 2021

NSAI

Agrément Certification is applicable to recently developed building materials, products and processes for which published national standards do not yet exist. An efficient Agrément process is essential for the introduction of new MMC components and products to construction projects in Ireland. This guide sets out the national Agrément assessment and certification process in the context of MMC, including off-site and modular construction. It describes the role of the Technical Assessment Specification in defining the requirements for demonstrating compliance with the Building Regulations and TGDs, and the role of testing and inspection, both at the manufacturing facility and on-site. Intended to improve certification efficiency, the guide has been supported by an expansion and restructuring of the NSAI Construction Division, and a planned review of the Agrément certification process considering international practice and increasing complexity.

4.2.7 'Guide for use of PW-CF2 Public Works Contract for Building Works Designed by the Contractor', 2023.

Housing Agency

This guide supports the use of Design and Build housing projects that offer increased potential for the adoption of MMC leading to improved productivity and speed of delivery. The guidance provides a contractual mechanism for the use of MMC within the Capital Works Management Framework, specifically PW-CF2 Public Works Contracts for Building Works Designed by the Contractor. This facilitates design and build public works projects to encourage increased innovation in the delivery of social housing and includes treatment of key issues such as the allocation of risk for specialist design arising from the use of specific forms of MMC and BIM-based information sharing protocols.

4.2.8 Supports for BIM Adoption

DPER, OGP, Build Digital

The Build Digital Project with the OGP will create a range of materials including templates and guidance for clients to support procurement with high BIM standards. BIM requirements are to be introduced on a phased basis for all public contracts through the Capital Works Management Framework. This will help to create the conditions for stakeholder collaboration and project co-ordination that are essential for successful DfMA with MMC.

4.3 Education and Training

4.3.1 'Skills for Zero Carbon', November 2021

Expert Group on Future Skills Needs (EGFSN)

The Skills for Zero Carbon report supports the delivery by 2030 of some of the key enabling actions in the Government's Climate Action Plan, including the energy efficient retrofit of the existing housing stock, by advising on the skills required to deliver targets set for built environment energy efficiency. The EGFSN have also commissioned a report on the workforce skills required to support a significant increase in MMC in Ireland, the recommendations from which will be used by the Department of Further and Higher Education, Research, Innovation and Science (DFHERIS) to create an action plan in response.

4.3.2 RIAI Design for Manufacture and Assembly Training Prospectus, 2023

RIAI

This training programme has been developed by the RIAI to support the wider adoption of DfMA with MMC in Ireland, by providing guidance to architects and other stakeholders in line with the RIAI DfMA Overlay to the Plan of Work and accompanying DfMA Report.

4.3.3 Training Needs Identified in the 'Roadmap for increased adoption of MMC in Public Housing Delivery', 2023

DHLGH, DETE

The Roadmap (see further details below) identifies training needs for various groups involved in the application of MMC in public housing projects. These were informed by a study to identify and quantify the scale of the skills needed by enterprises, including off-site manufacturing, to support wider MMC adoption, and associated recommendations for the education and training system. The training needs address

- skills gaps in MMC for construction sector professionals;
- training for BCAs, on MMC-relevant standards and certification;
- reskilling of the construction workforce, including planned courses at the National MMC Demonstration Park, SOLAS information on MMC courses nationwide, and leadership development training.

4.3.4 ‘What is Modern Methods of Construction (MMC)’ Skillnet, 2023

Construction Professionals Skillnet

A set of videos produced by Skillnet aimed at providing an introduction to the topic of MMC for a wide range of construction professionals and stakeholders.

4.3.5 MMC Courses at the National MMC Demonstration Park

LOETB

Laois-Offaly ETB offer a range of MMC related programmes at the MMC Demonstration Park, Mount Lucas. These include courses on Introduction to Tekla Structures, Building Information Modelling, AutoCAD 2D & 3D, Offsite Construction, Introduction to BIM & Revit Structures, and Management of Construction Projects.

4.3.6 Micro-Credentials and CPD in Modern Methods of Construction

Construction Professionals Skillnet, Griffith College and Enterprise Ireland

Skillnet and Griffith College offer a new micro-credential course on ‘Strategic Co-ordination and Collaboration for MMC’ that addresses important DfMA project management topics related to stakeholder integration and co-ordination, including organisational structure and collaborative relationships. The same partnership is planning an additional course on MMC procurement and finance.

Skillnet and Enterprise Ireland run CPD leadership development training suitable for construction sector professionals leading the change and transformation required for DfMA with MMC.

4.3.7 Postgraduate Diploma in Construction Innovation

University of Galway, Construct Innovate

The University of Galway together with Construct Innovate, the national research centre for construction technology and innovation, has introduced a new postgraduate programme in Construction Innovation in response to critical and skills needs in the construction/built environment sector. The programme is suitable for CPD of a wide range of construction professionals, equipping them with the knowledge and skills needed to develop sustainable technological solutions, including Digital Construction Technologies and MMC. A module on MMC covers key areas of standardisation and routes to certification, next generation rapid build systems (off-site panelised and modular construction), automation and autonomous construction.

4.3.8 CitA Skillnet Training

Construction IT Alliance

CitA’s role is to support the Irish construction sector in adopting new and emerging information and communications technologies. CitA Skillnet addresses skills gap in the construction industry through the delivery of courses that assist in the advancement of technology in construction. Current courses address AutoCAD, BIM and Revit Training, Drone Training, Project Management and Professional Development and Lean Training, which are all supportive of MMC adoption by industry. Additional courses directly addressing modern methods of construction are also proposed.

4.4 Conferences and Meetings

4.4.1 'Can Modern Methods of Construction deliver housing targets?', Webinar 2022

Engineers Ireland with Construct Innovate

On 26 October 2022, this webinar brought together MMC experts from different backgrounds, including designers, manufacturers, installers, contractors, and professionals responsible for certification and standardisation. It aimed to enhance the construction sector's knowledge base and to discuss how the adoption of MMCs can be accelerated in Ireland and help achieve housing targets.

4.4.2 'Next-Generation Construction in Ireland - Education, Research and Training as Key Enablers', 2022

Royal Irish Academy

This report from a conference held in the Royal Irish Academy on 24 November 2022 contains recommendations on research and development, education and stakeholder integration in support of the transformation of the construction industry including MMC adoption.

4.4.3 Accelerating MMC adoption in Housing delivery - Stakeholder Workshop 'Collaborate to Innovate', Trinity College Dublin, 2023.

Department of Enterprise, Trade and Employment & Construct Innovate

This workshop with invited participants from across the construction and built environment sector was held in Trinity College Dublin on 22nd February 2023. Its primary purpose was to raise awareness across the construction sector of the ongoing work within Housing for All under the auspices of the MMC Leadership and Integration Group to boost productivity and innovation in the residential construction sector, including through the adoption of MMC. The event was organised by DETE with support from Construct Innovate.

4.4.4 MMC Ireland National Conference 2023

Croke Park, Dublin; 6th June 2023.

This national conference of MMC Ireland, an industry representative body for companies involved in offsite and other modern methods of construction (MMC), included presentations and panel discussions on different forms of modular construction, industrialised construction, digital platforms, certification and testing requirements, sustainability and the application of MMC to house building in Ireland. The conference was attended by participants from across the construction and off-site manufacturing sectors, as well as the public sector.

4.4.5 Modern Construction Conference 2023

Aviva Stadium, Dublin; 22nd June 2023

This conference addressed MMC, Digital Innovation & Transformation and Industry 5.0. The speakers included experts from off-site manufacturers, construction and built environment consultancy; industry associations, public sector, general contractors, legal services and client organisations.

4.4.6 Construct Innovate AIMDays

University of Galway, 30th May 2023; Trinity College Dublin, 24th October 2023

Construct Innovate held two networking events for members in 2023. These Academic Industry Meeting days were based around workshops at which challenges submitted by participating industrial organisations are discussed with academic researchers from relevant university disciplines. Each workshop was organised within a central theme, most of which directly or indirectly addressed the topic of MMC. As the research programme of Construct Innovate is driven by working groups formed by its members, the AIMDays serve to support and empower industry to align the centre's research, development and innovation activities with the business challenges faced by their organisation.

4.4.7 Supporting Procurement Reform and MMC through Digital

CitA, 25th October 2023

This event, which was part of the Construction IT Alliance's SME Digital Acceleration Series, included presentations from representatives of the DHLGH, the Housing Agency and NSAI addressing the benefits of MMC, the roadmap for increased adoption of MMC, design and build procurement and MMC certification, all in the context of housing delivery.

4.5 Centres and Projects

4.5.1 Construct Innovate

University of Galway

Construct Innovate is Ireland's national construction technology centre. Funded through Enterprise Ireland's Technology Centres programme, the centre is hosted by the University of Galway with Trinity College Dublin, University College Dublin, University College Cork, TU Dublin and the Irish Green Building Council as research partners, complemented by over 50 industry partners. With a strong profile in research and innovation in modern methods of construction, sustainability and digital adoption, the short-term focus of the centre is on housing delivery, with a longer-term ambition of make Ireland a global research and innovation leader for sustainable construction and built environment technology.

Research in Construct Innovate is structured under the five pillars of (i) productivity, affordability & cost; (ii) quality & safety; (iii) sustainability; (iv) skills & training and (v) collaboration. All of these are directly relevant to the development and adoption of MMC in house building and generally. A key role for the centre is the dissemination of research results throughout the sector through publications, events and online tools.

4.5.2 Build Digital

TU Dublin

The Build Digital project co-ordinated by TU Dublin aims to increase digital adoption in the Irish construction and built environment sector by adapting international best practice in BIM deployment and innovation for Irish construction. Guidance including interoperable tool kits and templates will be made available through an exchange hub and help to build the capabilities required by the BIM mandate.

4.5.3 National MMC Demonstration Park at Mount Lucas

Laois-Offaly ETB and Solas

The National Demonstration Park for MMC at the National Construction Training Campus, Mount Lucas, led by Laois-Offaly ETB and Solas, will disseminate information relating to MMC, host applied research and provide specialist skills training. It will showcase and demonstrate MMC products, systems and technologies to a network of stakeholders including clients, manufacturers and construction professionals. Technological innovation activities will also take place in a set of experimental and proof-of-concept residential unit test beds. The demonstration park will be an important resource in enabling the adoption of innovative DfMA with MMC solutions for the sustainable and affordable homebuilding targets in Housing for All.

4.5.4 Construct Innovate Research Projects

Construct innovate is undertaking a set of research projects defined by DETE and DHLGH to support the Accelerated Housing Applied Research, Dissemination and Demonstration Programme 2023 and address goals for residential construction in Housing for All. Some of these projects address MMC directly, including:

- Design for Manufacture and Assembly with Design for Reuse (DfmA + DfR): This project examines how the adoption of MMC in housebuilding can be enabled through the DfMA approach. The challenges facing the adoption of DfMA with MMC are examined and compared with recent and ongoing initiatives, such as those by the CSG and RIAI, to assess the additional sectoral supports required.
- Creation of Standardised Design Details for MMC Builds: This project will develop compliant standardised details for a selected form of MMC and provide open access test data (including Structure, Fire, Energy and Sound) to create Building Regulation compliant structures and sub-structures.
- Behavioural Attitudes to MMC: This project addresses the psychology of change involved in more widespread adoption and acceptance of MMC in housing delivery, and ascertaining the necessary steps needed to build confidence in more innovative approaches.

4.6 State, Public and Sectoral Initiatives

4.6.1 MMC Leadership and Integration Group

The MMC Leadership and Integration Group was established by DETE as a cross-Departmental and cross-agency group to identify and co-ordinate MMC initiatives with potential to contribute to construction sector innovation and productivity improvements. It has a strategic leadership role in promoting a culture of innovation in residential construction, and ensuring the integration and coordination of MMC initiatives in the construction sector ecosystem; across research, development, innovation demonstration, regulation, education, training and enterprise support, with a particular focus on house and apartment building. This includes activities within the National MMC Demonstration Park and Construction Training Centre at Mount Lucas, Construct Innovate, and Build Digital. In the context of the broader work of the Construction Sector Group Innovation and Digital Adoption Sub-Group, it also considers issues related to the wider development needs of the sector, including those concerning finance, procurement and compliance, amongst others. Membership of the group includes representatives of five government departments, the CSG, Enterprise Ireland and Solas.

4.6.2 Construction Sector Group (CSG)

Formed in 2020 to support the delivery of Project Ireland 2040, the CSG comprises representatives of key industry bodies and senior representatives of Government departments and agencies with responsibility for policy for the delivery of infrastructure and residential construction. The CSG Digital Adoption and Innovation Subgroup has responsibility for the implementation of priority actions on cost reducing innovations and productivity measures, with particular focus on housing and sustainability as cross-cutting actions.

4.6.3 'Roadmap for Increased Adoption of Modern Methods of Construction in Public Housing Delivery', 2023

DETE & DHLGH

This Roadmap was developed by DETE and DHLGH working with the interdepartmental MMC Leadership and Integration Group to address key goals in Housing for All. It identifies and recommends a series of actions to overcome challenges related to the more widespread use of MMC and to progress the most advanced and efficient construction methods in innovative solutions for the delivery of public housing in Ireland. Recognising that the State has a significant presence in the housing market as a major procurer of construction services, the recommended actions address the need for collective action across the construction ecosystem to create the conditions required for MMC adoption.

The Roadmap meets the requirements set out in Housing for All Action 13.2 – Public Procurement Roadmap to develop a roadmap for MMC adoption in publicly procured residential construction that addresses the tender and evaluation process, design standardisation, skills development, the sharing of best practice, pilot projects and sustainability. The overall aim of the Roadmap is to build capacity in the supply chain to achieve delivery and cost reduction benefits, to which end it establishes 28 milestones under 6 themes:

- Procurement Approaches
- Regulations & Standards
- Capital, Finance and Insurance
- Skills Development
- Industry Competitiveness and Capacity
- Policy Execution and Communication

4.6.4 Public Procurement Initiatives

DHLGH

Commitments in Housing for All imply that public procurement will account for a large portion of the demand for new residential construction in Ireland with corresponding potential to support increased adoption of MMC and DfMA. DHLGH has introduced initiatives to support Local Authorities to employ Design and Build and/or MMC in public housing developments. These initiatives are aimed at contributing to the Housing for All objectives for public housing delivery across multiple locations, including those under the Accelerated Social Housing Delivery programme for which programme delivery time is to receive increased emphasis at tender stage. This will support the wider adoption of DfMA with MMC by strengthening market capacity and stakeholder integration. The extension of DHLGH support for MMC adoption in new public and social housing projects to Approved Housing Bodies will further increase confidence in market demand and encourage the human and capital investment required to build market capacity. Increased rate of direct build and turnkey developments by LA and AHB will improve vertical and longitudinal integration and promote improved stakeholder integration practices, including alignment with client requirements.

4.6.5 Expansion of Housing Agency

The Housing Agency

Under the provisions of Housing for All, the Housing Agency Procurement and Delivery Unit has been expanded to provide a stronger resource for Local Authorities and Approved Housing Bodies. The Housing Agency provides technical services and supports in procurement, design and MMC. This includes the development of Framework Agreements for professional services and construction works, and design and project support services to enable D&B projects under PW-CF2 for building works designed by the contractor. This enables LAs to reduce some risks associated by D&B contracts by completing the preliminary design and planning stages, while allowing scope for innovation and MMC adoption by the D&B contractor. The Housing Agency support also covers site supervision and technical advisory team responsibilities for projects adopting MMCs.

4.6.6 NSAI Certification for MMC

NSAI

In the context of European Technical Assessment and Agrément Certificates**,** NSAI Certification ensures certified products are suitable for use under Irish site conditions and comply with the Building Regulations, thereby facilitating the supply of reliable building materials and products to the construction industry. On-site inspection allows NSAI sign-off on building system installation to be obtained for MMC products with Agrément Certification. NSAI also offers certification to ISO 19650, the international standard for managing information over the whole life cycle of a built asset using BIM. Both of these facilitate the integrated delivery anticipated with DfMA-based projects adopting MMC. More than 15 MMC systems have received certification under this process, including light gauge steel frames and insulated concrete formwork. Timber frame systems are not covered by the Agrément process as there is an existing standard (NSAI I.S.440) in place.

4.6.7 Built to Innovate

Enterprise Ireland

The Built To Innovate initiative provides support for companies in the Irish residential construction sector to enhance the operational performance of their business through increased usage of MMC, lean training implementation, use of digital tools for productivity and research and innovation. This will be complemented by the expansion of the role of Enterprise Agencies to include funding and support for innovation and productivity-related projects in the domestic residential construction sector.

4.6.8 Ukrainian Refugee Accommodation, 2022

Office of Public Works

This national programme to provide emergency modular housing for refugees from Ukraine acted as an effective pilot study on the use of 3D modular systems in rapid delivery. It employed a DfMA with MMC approach by co-ordinating several off-site module manufacturers to build high-quality emergency housing at various locations in Ireland with reduced programme durations.

4.6.9 Residential Construction Cost and Innovation Unit

DHLGH

This unit is focused on delivery of Housing for All actions related to the long term economic sustainability of new housing, including reduction of construction costs, the capacity of the construction sector and innovative approaches to more productive and efficient housing delivery especially MMC.

4.6.10 Pilot 3D Volumetric Modular Systems

DHLGH

Pilot projects to deliver social or affordable housing using a 3D volumetric system will allow appropriate procurement approaches to be identified that take into account the more innovative building systems used in this form of MMC and the differences with 2D panelised systems.

4.6.11 MMC in Purpose-Built Student Accommodation

DFHERIS

The design requirements and characteristics of purpose-built student accommodation make it well-suited to modular construction, including 3D volumetric modules, and by extension DfMA for MMC. DFHERIS is investigating the potential of, and developing policies for, State support for new student accommodation construction, including design standardisation to facilitate MMC application. This will have wider benefits by increasing both MMC demand and capacity.

4.6.12 Promotion of MMC in public contracts, 2023-24

DHLGH

Suitable evaluation criteria and metrics are to be developed to support evaluations of tenders for public housing contracts for housing that capture the benefits of MMC. An associated training programme on MMC for public procurers of residential construction will be introduced.

4.6.13 MMC Data Dashboard

DETE

The lack of consistent and comprehensive information on the use of MMC in Ireland has consequences for policy and support development. Research is planned to determine which data should be collected in this regard, the sources it can be collected from, and how it can be presented to users. This will lead to the creation of an MMC dashboard within the Data Insights Service.

4.6.14 Embodied Carbon Framework

DHLGH, SEAI

The Energy Performance of Buildings Directive will require the development of a national framework for the accounting for embodied carbon in new buildings linked to BER certification. This will be directly relevant to the increased adoption of DfMA with MMC which facilitates closer control of construction materials and processes and thereby the minimisation of carbon footprint.

4.6.15 Residential Construction Cost Study Report, May 2022

DHLGH and CSG

This study compared the cost of different forms of residential construction across a set of countries in northern Europe, including Ireland. The steering group included representatives of the Society of Chartered Surveyors of Ireland, the Royal Institute of Architects of Ireland and the Construction Industry Federation. It advocates government-industry collaboration to develop standardised approaches for housing design and construction to both inform policy initiatives, and for use as best practice by industry. Greater use of standardisation and MMC in construction systems for apartments and purpose-built student accommodation was identified in some of the other states. Stakeholders noted that diversity in the design and appearance of housing can make it more challenging to increase standardisation, including materials selection, and recommended the development of standardised approaches to the design of housing for wider application.

4.7 Comparison of Activities and Challenges for DfMA with MMC

Table 4.1 presents a category-by-category comparison of the activities described in this chapter with the challenges to the adoption of DfMA with MMC set out in Chapter 3. Each activity is assessed for its relevance to each of the 11 challenge sub-categories within organisational structures, contractual frameworks and operational systems. This aids analysis of how well the complete set of activities addresses the known challenges and where additional supports may be required.

The challenge-specific relevance of each activity is assessed using a simple scale: relevant, very relevant and focus area, as explained in Table 4.1. The assigned relevance takes into account the number of individual challenges in a sub-category that are addressed by an activity, and the extent to which that activity could help overcome them.

Table 4.1: Comparison of Challenges and Supporting Activities for DfMA with MMC

Challenge Category	Organisational Structures				Contractual Framework				Operatnl Systems		
Sub-category / Activity	Stakeholder Integration	Stakeholder Relationships	Client Requirements	Market Capacity	Contract and Procurement	Roles and Responsibilities	Financial	Market Demand	Additional Co-ord Demands	Technical Knowledge	Certification
Studies and Reports											
Economic Analysis of Productivity in Irish Construct Sector	very relevant	very relevant	focus area	very relevant	very relevant	very relevant	focus area	very relevant	very relevant	relevant	relevant
A Detailed Description of Needs for Irish Const/BE Sector	relevant	relevant	relevant	very relevant			relevant	relevant		focus area	relevant
Modern Methods of Construction: CIF Report	relevant	very relevant	very relevant	focus area	very relevant	relevant	relevant	very relevant	very relevant	focus area	very relevant
Modern Methods of Construct: Defining MMC Business	very relevant	focus area	relevant	very relevant	relevant	very relevant	very relevant	relevant	very relevant	focus area	very relevant
Guidance and Rules											
RIAI DfMA Overlay to the Plan of Work	focus area	very relevant	very relevant	relevant	relevant	focus area	relevant	relevant	focus area	very relevant	very relevant
RIAI Design for Manufacture and Assembly Report	focus area	very relevant	very relevant	relevant	relevant	focus area	relevant	relevant	focus area	very relevant	very relevant
Digital Construction Pack	relevant	very relevant		very relevant		relevant			focus area	focus area	
Design Manual for Quality Housing			relevant	relevant				very relevant	relevant	very relevant	focus area
Building Regulations, Inspection and Control Initiatives	relevant		relevant	very relevant		very relevant		relevant	very relevant	very relevant	focus area
Guide to Agrément Certification for MMC			relevant	very relevant	relevant	very relevant		relevant		very relevant	focus area
Guide to PW-CF2 Public Works Contract	very relevant	very relevant	very relevant	relevant	focus area	very relevant	very relevant		relevant		
Supports for BIM Adoption	very relevant	very relevant	relevant	very relevant		very relevant			very relevant	focus area	
Education and Training											
Skills for Zero Carbon			relevant	relevant				relevant	relevant	focus area	
RIAI DfMA Training Prospectus	very relevant	very relevant	very relevant	relevant	relevant	focus area		relevant	focus area	very relevant	relevant
Training Needs Identified in Roadmap Adoption of MMC	relevant	relevant		very relevant		relevant			very relevant	focus area	very relevant
What is MMC Video Series	relevant	relevant	relevant	relevant		very relevant		relevant	very relevant	very relevant	relevant
MMC Courses at the National MMC Demonstration Park	relevant	relevant		very relevant					very relevant	focus area	
Micro-Credentials and CPD in MMC	very relevant	very relevant	relevant	very relevant	relevant	very relevant	relevant		relevant		
Postgraduate Diploma in Construction Innovation	relevant	relevant		focus area		relevant		relevant	very relevant	focus area	focus area
CitA Skillnet Training	relevant	very relevant		very relevant		relevant			relevant	very relevant	

Key: relevant ▢ very relevant ▢ focus area ▢

Table 4.1 (cont.): Comparison of Challenges and Supporting Activities for DfMA with MMC

Challenge Category	Organisational Structures				Contractual Framework				Operatnl Systems		
Sub-category / Activity	Stakeholder Integration	Stakeholder Relationships	Client Requirements	Market Capacity	Contract and Procurement	Roles and Responsibilities	Financial	Market Demand	Additional Co-ord Demands	Technical Knowledge	Certification
Conferences and Meetings											
Can MMC deliver housing targets? Webinar											
Next-Generation Construction in Ireland Conference											
Accelerating MMC in Housing Stakeholder Workshop											
MMC Ireland National Conference											
Modern Construction Conference											
Construct Innovate AIMDays											
Supporting Procurement Reform and MMC thru Digital											
Centres and Projects											
Construct Innovate											
Build Digital											
National MMC Demonstration Park at Mount Lucas											
Construct Innovate Research Projects											
State, Public and Sectoral Initiatives											
MMC Leadership and Integration Group											
Construction Sector Group (CSG)											
Roadmap for Increased Adoption of MMC in Housing											
Public Procurement Initiatives											
Expansion of Housing Agency											
NSAI Certification for MMC											
Built to Innovate											
Ukrainian Refugee Accommodation											
Residential Construction Cost and Innovation Unit											
Pilot 3D Volumetric Modular Systems											
MMC in Purpose-Built Student Accommodation											
Promotion of MMC in public contracts											
MMC Data Dashboard											
Embodied Carbon Framework											
Residential Construction Cost Study Report											

4.7.1 Studies and Reports

Table 4.1 shows good coverage of all challenges in the four review studies and their reports. This indicates that the challenges in all categories have been identified and are largely understood. The reports make recommendations for specific and general actions to address these challenges, with many of these addressing operational systems challenges, including technical knowledge and the development of market capacity.

4.7.2 Guidance and Rules

The most comprehensive recent guidance on employing DfMA with MMC is the RIAI Overlay to the Plan of Work and accompanying report. Table 4.1 shows that these cover all challenge topics, with particularly strong guidance on related to project teams, including stakeholder integration, roles and responsibilities and co-ordination demands. Less information is provided on market-related topics, finance and procurement.

More specific guidance documents and supports display an emphasis on either operating systems or organisational structures. On operating systems, recent actions have provided improved guidance and clearer rules on certification and building control, while improved supports for BIM adoption are important for well-functioning organisational structures. New guidance on the PW-CF2 form of PWC is one of relatively few actions addressing challenges related to contract and procurement.

4.7.3 Education and Training

Education and training activities display a bias towards operational systems challenges, especially those related to technical knowledge and co-ordination requirements and the related aim of increasing market capacity. A number of programmes address stakeholder integration and relationships including courses on project management and IT tools, while the RIAI training prospectus also covers project team roles and responsibilities. Otherwise, however, challenges related to the contractual framework and client requirements appear to receive little attention.

4.7.4 Conferences and Meetings

Table 4.1 indicates that the conferences and meetings considered achieve broad overall coverage of the challenges in all categories, although there is relatively little coverage of financial and market demand challenges. Most attention appears to be paid to the technical and co-ordination challenges associated with establishing strong operational systems and contract and procurement issues. The MMC Ireland National Conference achieved good coverage of all challenge sub-categories, including topics related to business development.

4.7.5 Centres and Projects

Activities in the construction and built environment research centres and associated projects most often address challenges in the operational systems category, especially the generation and dissemination of technical knowledge to improve market capacity. There is little activity related to the contractual framework. The National MMC Demonstration Park provides notable support for market demand.

4.7.6 State, Public and Sectoral Initiatives

The Roadmap for Increased Adoption of MMC in Public Housing contains actions relevant to all issues, with some challenge sub-categories addressed by multiple activities. The Roadmap makes strong contributions to market capacity related challenges, including actions designed to support stakeholder integration, technical knowledge and certification.

The aims of the Roadmap and Housing for All generally are broadly supported by the MMC Leadership and Integration Group and the Construction Sector Group which both address most challenges in the organisational structures and contractual framework categories, including financial and market demand issues. The contractual framework is also supported by the identified initiatives related to public procurement and the expansion of the Housing Agency.

The other state, public and sectoral activities considered make focused contributions to specific challenges or broader contributions to wider ranges of challenges. The focused contributions relate to certification (NSAI), financial challenges (Built to Innovate) and contract and procurement (promotion of MMC in public contracts). Project team roles and responsibilities, co-ordination and relationships receive relatively little attention by this category of activity.

5 Design for Reuse and Modern Methods of Construction in Ireland

5.1 Introduction

This Chapter discusses the concept of Design for Reuse (DfR) and examines its current position in Ireland in light of the increased focus on MMC. As discussed in previous Chapters, MMC is receiving increased attention in response to a series of problems facing the construction industry. As described by the Farmer Review of the UK's construction industry (Farmer, 2016), and similar reports in Ireland (e.g. Ernst and Young, 2021), the sector is facing multiple economic challenges associated with low productivity, unreliable project delivery, poor performance, skilled labour shortages and resource inefficiency, but also an array of environmental and sustainability related challenges. MMC is seen by both the Irish government (e.g. DETE/DHLGH 2023) and the construction industry (CIF, 2021) as something that can improve efficiency and productivity in construction, particularly through the prefabrication of modular or volumetric elements or structural components of a building off-site and their assembly on-site.

While MMC has the potential to improve sustainability across in the entire construction value chain, globally the sector's activities are concentrated on using offsite construction to improve upstream resource efficiency, i.e. at the design, manufacture and construction stages (Iacovidou et al., 2021) with limited awareness of circular design philosophies and associated design actions. However, this move towards MMC appears to be divorced from the need to promote resource efficiency and productivity at the stages occurring downstream (i.e. disassembly and end-of-life management) of the construction value chain. In the Irish context, this is illustrated by the fact that many recent key policy documents do not appear to consider deconstruction or reuse in any meaningful way (for example DHLGH (2023a)). A failure to consider such downstream impacts will hamper the industry's long-term ability to become more sustainable and reduce the negative environmental impact of construction. The complete life cycle of a building project needs be taken into account when calculating embodied and operational carbon in climate impact assessments. This includes construction product materials and manufacturing, construction processes, building use and end-of-life activities such as deconstruction, recovery and recycling that benefit from DfR.

This lack of focus on end-of-life (EoL) stands in contrast to the recent attention that has been devoted elsewhere to the idea of a circular economy (CE). The overarching concepts of CE emphasise the need to keep materials in the socioeconomic system for as long as possible, at their highest possible value (Gillott et al., 2023), thereby reducing waste and the need to extract new resources. However, while the idea of reuse is central to the development of a CE, it is rarely considered in the construction industry. At present, the biggest barrier to recovering building components for reuse is that the buildings are not designed for deconstruction (Rakhshan et al., 2020).

Iacovidou and Purnell (2016) listed five different interventions that can be made in in the construction industry to promote reuse and environmental efficiency:

1. Adaptive reuse
2. Deconstruction

3. Design for Manufacture and Assembly (DfMA)
4. Design for Demolition or Design for Deconstruction (DfD)
5. Design for Reuse (DfR)

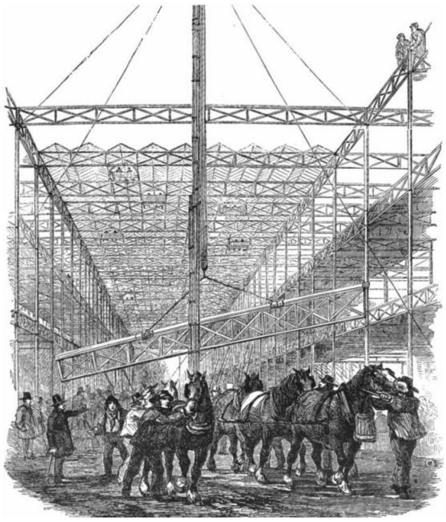
Of these, the later three are pertinent for new developments, and out of these techniques, DfMA appears to have gained the most momentum, illustrated by the extent of the activities detailed in Chapter 4 of this report. As discussed, there is an abundance of research demonstrating the potential upstream benefits of DfMA in construction, particularly through various forms of modular construction, including higher quality and precision in the manufacturing stage, better quality control, speedier construction and installation compared to traditional methods, reduced costs and improved resource efficiency (e.g. Lawson and Richards, 2010; Generalova, Generalov and Kuznetsova, 2016; Molavi and Barral, 2016; Ferdous et al., 2019; Hough and Lawson, 2019). However, the ability of MMC to yield benefits downstream of the system (i.e. at the operational and end-of-life (EoL) stage of buildings), via the disassembly of construction components and reuse in consecutive structure lifecycles, has received comparatively little attention (Iacovidou et al., 2021), representing a missed opportunity in maximising the sustainability performance of the sector.

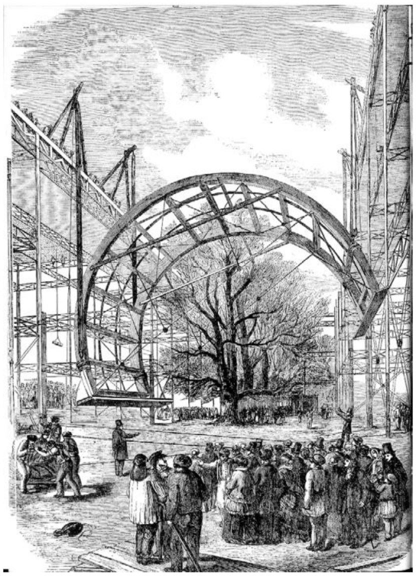
A related, and extremely important and pressing topic for consideration for the construction industry, is the reuse of components present in existing buildings (e.g. Rakhshan et al., 2020, IStructE, 2023b). However, this is not addressed in this report, which focuses solely on how new developments can be made more amenable for reuse at EoL. Having said that, lessons learned from the study of the reuse of pre-existing building components can be applicable to new construction.

5.1.1 Design for Disassembly (DfD) and Design for Reuse (DfR)

Therefore, in addition to the existing focus on DfMA, there is an obvious need for increased consideration of both DfD and DfR in the construction and built environment sector. The exact definition of these two ideas can vary with different sources, but essentially DfD refers to the integration of deconstruction in the design of buildings to increase the recovery of materials and structural components at the end of life (Durmisevic and Yeang, 2009). DfR (which is also sometimes denoted as D4R) can be thought of as a broader concept that considers reuse, in addition to disassembly (Bertin et al., 2022). It is worth noting that some studies define reuse as completely separate from deconstruction, and thus consider DfD and DfR as independent ideas. However, it is more logical to consider deconstruction as fundamental to reuse, and therefore to view DfD as a subsection of DfR (Bertin et al., 2022).

As of now, end of life is generally a secondary consideration, or not considered at all, in the design and construction of building structures. Less than 1% of existing buildings are fully demountable (Kanters, 2018). Having said that, application of the fundamental ideas of DfD and DfR in buildings is not new. Many nomadic tribes constructed their buildings with disassembly and reconstruction in mind, while the Crystal Palace exhibition building (Figure 5.1) originally constructed in London in 1851 was an early example of a large-scale building that was designed for reuse. The structure employed a simple system of prefabricated structural and cladding modules that could be easily joined together in a way that allowed for the quick assembly (the building was three times the size of St Paul's Cathedral but was erected in 17 weeks) and disassembly of the building, and its relocation and reuse at a site 12km away after the exhibition (Kihlstedt, 1984; Addis, 2006).





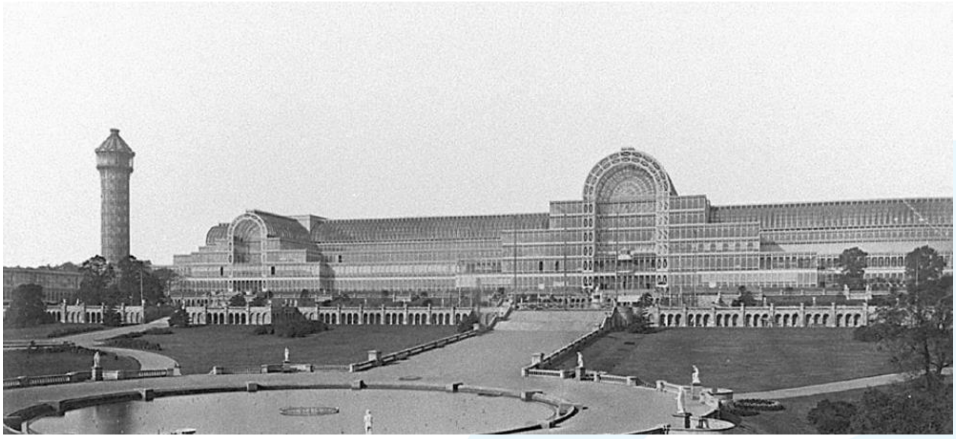


Figure 5.2 Illustrations of the Crystal Palace in London under construction showing the use of 'modular' elements. Source for the top left image: Kihlstedt, F.T. (1984) 'The Crystal Palace', Scientific American, 251(4), pp. 132–143. Source for the top right image: Addis, B. (2006) 'The Crystal Palace and its Place in Structural History', International Journal of Space Structures, 21, pp. 3–19. Bottom image source: https://en.wikipedia.org/wiki/The_Crystal_Palace#/media/File:Crystal_Palace_General_view_from_Water_Temple.jpg

Within architecture, the formal concept of DfD has existed since the 1940s (Kanters, 2018). Crowther (2001) produced a comprehensive discussion introducing many of the central ideas and motivations behind DfD and DfR. These include the idea that a building is composed of different 'layers', such as the structure, services and skin – each of which has a different lifespan and therefore needs to be considered separately in deconstruction. Based on adapting theory from industrial design and product manufacture (e.g. Ayres et al., 1996), Crowther (2001) also proposed a 'theory of a hierarchy of recycling and reuse', illustrated in Figure 5.2, which serves as a useful means to understand the variety of possible EoL scenarios for a building.

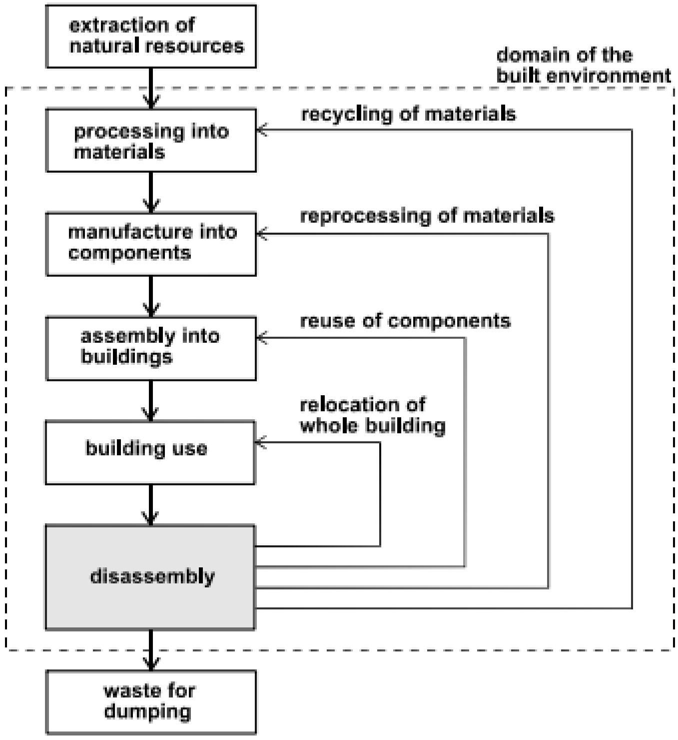


Figure 5.3 Hierarchy of End of Life scenarios for a building (Crowther, 2001)

The first, and least wasteful, scenario is that of relocation or reuse of an entire building, as with the Crystal Palace. The second scenario is the reuse of components in a new building or elsewhere on the same building, thus saving on resources, waste disposal, and energy use during material processing as well as during component manufacture and transport. An example of this is the reuse of steel sections (e.g. IStructE, 2023a). The third scenario, reprocessing of materials into new components, involves materials or products still in good condition being used in the manufacture of new building components, for example through using recycled concrete aggregates in the production of new concrete (Addis, 2012). As well as the waste disposal advantages, this reprocessing also reduces the energy required for material processing. The final scenario, recycling of resources to make new materials, involves used materials being employed as a substitute for natural resources in the production of manufactured materials, as is done for example when used steel is melted down and rolled into new sections. While this scenario does reduce the solid waste stream and resource extraction, other environmental issues such as total energy use and resultant pollution may actually be greater than if new resources were used (Addis, 2012). It should be noted that a significant amount of recycling is already achieved by the construction industry – for example in the UK it is estimated that 91% of non-hazardous construction waste is recycled (DEFRA, 2023). Finally, the least desirable scenario is when a structure is demolished, and waste is sent to landfill.

It should be noted that similar versions of this hierarchy have been published elsewhere, for example via the EU Waste Directive (European Union, 2008) the reader is referred to (Zhang et al., 2022) for a detailed summary of these in the context of construction waste in Europe. While small differences and technical distinctions exist between different frameworks, the basic hierarchy of reuse before recycling before landfill is widely accepted.

5.2 Principles of Design for Reuse

There are numerous sources that list sets of principles that designers should attempt to follow in order to facilitate DfR (for example Crowther, 2001; Guy, Shell and Esherick, 2006; Webster and Costello, 2006; Densley Tingley, 2013; Guy and Ciarimboli, 2017; Kanters, 2018; Forghani, 2019). The list produced below has been compiled from the various principles identified in these works, in addition to the recommendations in ISO 20887:2020 'Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance' (ISO, 2020).

Here, the principles are divided into four categories and numbered accordingly:

1. 'Overarching Principles', which encompasses general, almost philosophical, recommendations related to the overarching ideas underpinning DfR – in a construction project the client would typically be required to accept, and potentially lead, these;
2. 'High-level Design Principles', which encompasses recommendations related to broad design decisions, which would typically be taken relatively early in a project and be led by the architect;
3. 'Principles for Detailed Design and Connections', which encompasses recommendations related to the details of the design, and would typically be led by the structural engineer or contractor;
4. 'Principles for Documentation', which encompasses recommendations on the information that should be documented.

Details of the principles in each category are listed in Table 5.1, from which the overlap with the general principles of DfMA presented in Chapter 2 can be identified (see Section 5.3.1).

Table 5.1 Principles of Design for Disassembly

1. Overarching Principles
1.1. Use an open flexible building system that allows the functions to change in the future, but avoid over-design
1.2. Ensure that the whole design team is on board
1.3. Establish targets for the percentage of a building that can be reused
1.4. Allow extra time to ensure DfR is incorporated
1.5. Train contractors in DfD
1.6. Use prefabrication where possible
1.7. Use modular design
1.8. Use standard construction methods and techniques
1.9. Ensure structural systems can be easily deconstructed
1.10. Consider the lifespan of components during design
2. High-level design
2.1. Use a standard structural grid
2.2. Design components and joints to be durable so that they can be reused
2.3. Use components with low maintenance costs

2.4. Develop a deconstruction plan during the design process
   a. Ensure structural stability is maintained during deconstruction
   b. Allow for parallel disassembly
   c. Allow for safe disassembly

2.5. Services
   a. Where possible design in passive measures instead of active service elements
   b. Design building so that elements are layered according to anticipated lifespan (i.e. incorporate the concept of 'layering'), with MEP systems separate from the building structure
   c. Plan service routes so they can easily be accessed and maintained

2.6. Size components to suit the means of handling
   a. Use lightweight building components
   b. Design lifting points on the components for ease of handling

2.7. Materials
   a. Select easy separable materials with good reuse potential
   b. Select recycled materials
   c. Avoid composite systems
   d. Design for locally produced materials
   e. Avoid hazardous substances
   f. Protect valuable components using less valuable materials

2.8. Allocate space for on-site sorting

2.9. Provide spare parts and associated storage

3. Detailed Design and Connections

3.1. Use mechanical connections that can be easily removed, as opposed to chemical connections

3.2. Use connections that do not require specialist tools

3.3. Provide access to all parts and connection points

3.4. Use the minimum number of connections

3.5. Limit the different types of connectors

3.6. Designate fixing-free zones to maximise length of materials for reuse

3.7. Provide adequate tolerances and gaps between components for disassembly

3.8. Avoid secondary finishes that cover connections

4. Documentation

4.1. Ensure there is a full set of as-built drawings

4.2. Provide identification of component types

4.3. Provide a full inventory of all materials and components used in the building

4.4. Develop an adequate BIM model

4.5. Permanently label building components

4.6. Indicate points of disassembly on building components

4.7. Create appropriate handover documentation

Some of these recommendations are perhaps obvious and repetitive. However, key ideas -corresponding to the four headings – are evident. On a general level, DfD must be central to the overall design and need to be considered throughout the design process. More practically, this involves the separation of building layers, thoughtful connection design and good documentation.

It is clear that technology and digitisation can also assist greatly with disassembly (Iacovidou et al., 2021). An adequate BIM model, especially one that is maintained over the life of the structure, can achieve much of the required documentation. Likewise, 3D visualization can be beneficial for achieving successful layering and ensuring disassembly is possible.

Most of these ideas are contained in ISO 20887:2020. This document presents 7 'principles' and 4 'practices' for disassembly (Table 5.2). The practices are all directly relevant to DfMA, emphasising the potential compatibility of assembly and disassembly methods if both are planned together.

Table 5.2 Principles and practices of DfD listed in ISO 20887:2020

Principles of Design for Disassembly according to ISO 20887:2020
1. Ease of access to components and services; (corresponding to principles 2.5c and 3.3 in Table 5.2) 2. Independence (referring to what Crowther (Crowther, 2001) and others term 'layering') and reversible connections (principle 3.1) 3. Avoidance of unnecessary treatments and finishes 4. Supporting re-use (circular economy) business models 5. Simplicity 6. Standardisation 7. Safety of disassembly
Practices of Design for Disassembly according to ISO 20887:2020
1. When possible, materials and components that can be easily, safely, and more cost-effectively replaced or removed and transported should be used. 2. A means of handling components during disassembly should be provided. Handling during disassembly can require points of connection for lifting equipment or temporary supporting devices. 3. Components that are sized to suit the intended means of handling should be used. Various possible handling options at all phases of assembly, disassembly, transport, reprocessing, and reassembly should be considered. 4. Spare parts, and on-site storage for them, should be provided, particularly for custom-designed parts, to allow broken or damaged components to be easily disassembled and replaced, and to facilitate minor alterations to the design.

The standard also contains a section on documentation, emphasising the need for proper recording of design details, materials and connections as well as the importance of maintaining documentation after the building is handed over to the user.

In addition to these recommendations, Annex C of ISO 20887:2020 presents examples of how the performance of a design can be measured and quantified from a deconstruction viewpoint. However, this Annex is only informative and has not been developed into a full rating system.

As DfD can be considered a subset of DfR, all the above recommendations are relevant for DfR. However, in terms of work specifically relating to DfR, Forghani (2019) performed an extensive study surveying 172 construction industry professionals in Australia to establish which principles were most important for reuse. From this work the following 9 principles were identified as 'critical' for reuse:

1. Avoid hazardous substances (corresponding to principle 2.7e)
2. Use components with a long lifespan (2.2)
3. Use components with low maintenance costs (2.3)
4. Consider the lifespan of components during design (1.10)
5. Maintain information about structures and their details (3.1 -3.3)
6. Use durable joints and connectors (2.2)
7. Use bolted connections instead of welded connections (3.1)
8. Use components that need common equipment for assembly/disassembly (3.2)
9. Design lifting points on the components for ease of handling (2.5 b)

5.3 Design for Reuse in the Current Irish Policy Landscape

There appears to be little or no focus on DfD or DfR in current policy in Ireland. Table 5.3 shows the number of times the key words 'Disassembly', 'Deconstruction' or 'Reuse' appear in various important Irish publications related to MMC. From these low numbers, it appears that neither the industry nor public sector are giving particular consideration to the EoL aspects of construction.

Collectively, these documents indicate that there is an awareness that 'reuse' is desirable. For example, '*Housing for All'* lists reducing '*construction and demolition waste and associated costs through demonstration projects*' and reducing the '*demand for virgin raw materials and [supporting] reuse*' as objectives. Interestingly however, the first objective appears to be focused on reducing costs as opposed to reducing waste: *Housing for All* recommended that the Department of the Environment should '*ensure that [construction and demolition] material currently going to facilities as recovery/ landfill engineering is also exempt from the recovery levy so that there will be no cost impact on the construction sector arising from the introduction of / increase in levies.*' Since then the Circular Economy (Waste Recovery Levy) Regulations 2023 Bill (Irish Statute Book, 2023) has been published and 'construction and demolition waste,' has been made exempt from landfill levies. As will be discussed later, this contradicts recommended best practice to encourage DfR.

Similarly, the CIF report on '*Modern Methods of Construction*' (CIF, 2021) identifies considering '*the full life cycle of product development and manufacturing through to design, installation, use and reuse with* *standards, accountability and traceability at the heart of the process*', and '*maximising waste reduction and drive circularity to support a decarbonisation, climate resilience, social and community wellbeing agenda*' as important steps for the industry. A similar action is listed in the KPMG/TU Dublin report: '*The circular economy presents considerable opportunities to embed resource efficiency, material recycling and reuse within the sector including the use of innovative, low carbon, zero waste materials. With coordinated enhancements in digital technologies, circular economy initiatives for renovation and maintenance, including the traceability of materials for future re-use and recycling, can be facilitated.*' However, the links between deconstruction and reuse, and potential benefits of considering design in reuse is not highlighted.

Table 5.3. Number of times the key words 'Disassembly', 'Deconstruction' and 'Reuse' appear in key Irish MMC publications

Document	Organisation	'Disassembly'	'Deconstruction'	'Reuse'
Government Policy Documents				
'Housing for All'	DHLGH (2022a)	0	0	9*
'Introduction to Modern Methods of Construction'	DETE/DHLGH (2023)	0	0	0
'Roadmap for increased adoption of Modern Methods of Construction in Public Housing delivery'	DHLGH (2023a)	1	0	1
Studies & Reports				
'Economic analysis of productivity in the Irish construction sector'	KPMG & TU Dublin (2020)	0	0	3
'A Detailed Description of Needs for the Irish Construction/Built Environment Sector'	Ernst & Young (2021)	3	0	9
'Modern Methods of Construction'	CIF (2021)	0	0	11
'Modern Methods of Construction: Defining MMC Business'	Construction Professionals Skillnet (2022)	0	0	0
Guidance and Rules				
'DfMA Overlay to the RIAI Plan of Work'	RIAI (2022)	0	0	0
'RIAI Design for Manufacture and Assembly Report'	RIAI (2022)	3	0	1
'Design Manual for Quality Housing'	DHLGH (2022b)	0	0	0

*(*all in the context of repurposing of existing buildings or existing sites)*

The transcripts of 29 interviews with different stakeholders in the industry reproduced in the CIF report provides an interesting insight into the mindset of different people active in MMC. Of these interviews, only two make any mention of reuse. One interviewee identified '*the reuse of structures and putting a process around carrying out an assessment on an existing structure that will be reused somewhere else*' as an objective for the Construction Technology Centre (now Construct Innovate). A different interviewee also says:

'A question worth asking is would buildings that are provided from an offsite modular solution be mobile? How would we be able to reuse them in a different location? How does that work with the lifecycle of the building? The structural integrity of it, and the circular economy? We'd like to think that buildings could be taken apart and rebuilt, reinstalled in different locations and that when they are reinstalled, they are given a dispensation that they still meet the regulations, even if the regulations have changed because they were fit for purpose when they were built originally.'

This comment, and the statements elsewhere in the report, shows that there is at least some awareness of the potential for reuse associated with MMC, but the speculative nature of the comment and the fact that only two out of 29 stakeholders mention it, illustrate that reuse does not appear to be a priority or major driver of modernisation in construction in Ireland. However, the comment does raise an important issue about how the evolution of standards over time impacts reuse.

The '*RIAI Design for Manufacture and Assembly Report*' contains a short section of DfD:

'DfD is increasingly considered an essential (design-led) focus of progressive MMC. Building components (regardless of whether they contain high or low embodied carbon materials), and the collection of components to make a whole building, can be assembled or manufactured in ways that support later disassembly or hinder it. The technical detailing of the building or component design (e.g. the way in which the materials or components are brought together, choice of fixings etc.) massively impacts upon this. Therefore, architects have a leading role to play. The use of 'material passports' and tracing technology are additional tools that can ensure that the nature and provenance of those materials are better understood in the future and therefore more likely to be selected for re-use.'

While specifically mentioning DfD, the detail in this section provides limited guidance to architects. However, it is promising that an understanding of the importance of the role of the architect in DfR is highlighted.

The EY 'Detailed Description of Needs for the Irish Construction/Built Environment Sector' report (Ernst & Young, 2021) includes a survey of firms, in which 72% of respondents identified 'Construction technologies / detailing for disassembly and logistics for re-use of building elements' as an area of research that should be undertaken by a Construction Technology Centre, i.e. Construct Innovate. The report also states that 'To deliver a more climate resilient economy, a huge culture shift is needed towards actions and policies that tackle the full lifecycle of buildings and their impacts. All of the actors along each stage of the construction and built environment value chain may need to be incentivised to co-ordinate their efforts and embrace the possibilities for decarbonisation, to reduce the negative environmental impact of their activities,' thereby demonstrating an awareness of ideas like circularity and the possible need to introduce economic incentives to achieve this.

The roadmap for increased adoption of MMC in Public Housing delivery specifically mentions DfR – in the context of the research that should be undertaken in the 'Accelerated Housing Applied Research, Dissemination and Demonstration (AHARDD) Programme Fund 2023,' i.e. in the context of this study. It states that '*research on how to incorporate the re-use of building materials (Design for Reuse) into Design for Manufacturing and Assembly (DfMA), a key enabler of MMC, setting out a pathway to ensure DfMA and D4R can be supported in the delivery of housing (including social housing)*' has '*direct relevance for MMC*'. This indicates a belief that DfR can form part of the broader MMC and DfMA picture, but also shows that consideration of DfR in policy is essentially non-existent beyond being a topic that should be examined, similar to how disassembly is addressed in the EY report.

In general, from reviewing these key documents, it is apparent that while there is awareness of the broad concepts and high-level benefits or reuse and circularity, DfD or DfR have not been addressed in any detail in the various MMC-related reports and guidance published in recent years. This suggests that DfR is currently not at the forefront of the current MMC and DfMA landscape, either for industry or within government.

5.4 Challenges to Design for Reuse

A series of studies have identified numerous barriers to DfD and DfR (Gorgolewski, 2008; Densley Tingley, 2013; Rios, Chong and Grau, 2015; Akinade et al., 2017; Tingley, Cooper and Cullen, 2017; Kanters, 2018; Rakhshan et al., 2020). These are summarised in Table 5.4. As with the principles outlined above, they are grouped into four categories, this time 'perception and mindset', 'economic', 'legislative' and 'technical'.

Many practices which are considered to be sustainable design are supported by legislation e.g. insulation standards, or schemes like BREEAM that reward sustainable design considerations. However, there is no specific legislation in Ireland that requires a design team to consider designing for deconstruction, and there is no explicit wording within BREEAM, for example, to reward design for deconstruction. It is noted that the recent life-cycle based EU Level(s) framework contains a relatively straight forward 'deconstruction score' (Dodd et al., 2021). However, critics argue that this promotes recycling over reuse (Ghyoot et al., 2021).

Table 5.1 Barriers to DfR

1. Perception and mindset
1.1. Belief that end-of-life may not occur for a long time
1.2. Common negative perception by the end user of reused materials
1.3. Designer and constructors conceive their design to be permanent
1.4. Time constraints due to the fact that disassembly might take significantly more time than mechanical demolition
1.5. Perception that deconstruction costs more than demolition and disposal, which is not always true
1.6. Lack of involvement to minimise waste amongst manufacturers
2. Economic
2.1. Designing for deconstruction is likely to have a higher initial cost, both in terms of design time and construction price. In many cases clients will find it hard to justify this higher initial cost, particularly if they cannot see how they will benefit from a building that is designed to be deconstructable.
2.2. Value of building materials and components at EoL is uncertain
2.3. The lack of an established market for the reused building components; while even after establishing a market, it is necessary to create a demand for reused components
2.4. Lack of accounting methods for measuring the benefits of DfD
2.5. Ease of landfill; this is particularly relevant in Ireland given the exemption of construction waste from the landfill levy.
3. Legislative
3.1. Lack of formal schemes to support DfD and DfD
3.2. Lack of legislation supporting DfD and DfR
3.3. Lack of standards can make some components unusable or difficult to reuse
3.4. Contract constraints that could make reuse less feasible;
4. Technical
4.1. Lack of technical knowledge and supporting tools
4.2. Uncertainty of the quantity and quality of the used material
4.3. Traceability of reused components
4.4. Damage of components on-site during deconstruction
4.5. Integrating reclaimed components into new structures increases the complexity of projects, and some contractors may be unsure about getting involved in such projects

5.5 Future Steps towards Design for Reuse

5.5.1 Application of MMC to DfR

As illustrated by the example of the Crystal Palace shown in Figure 1, DfD and DfR are not inherently linked to ‘modern‘ construction. However, many of the hallmarks of MMC, particularly the ideas of modularity and prefabrication, were integral to its design and reuse. In MMC terminology the Crystal Palace employed Category 2 (pre- manufactured 2D primary structural elements) and Category 5 (pre-manufactured non-structural assemblies and sub-assemblies) modular elements.

In general, MMCs are seen as being more amenable to DfR than traditional construction methods. Prefabrication and the use of modular components are both central to MMC and have both been identified in various studies as beneficial for DfD and DfR.

The potential of prefabricated building components manufactured off-site to contribute to sustainability and waste minimisation has been investigated in several studies ((Tam et al., 2007; Villoria Saez et al., 2013; Wang, Li and Tam, 2014, 2015)). From a reuse viewpoint, the main benefit of prefabrication appears to relate to quality control. Prefabricated components can be used to ensure the compatibility and adaptability of components for reuse. As these components are built off-site in accordance with standards and guidelines, their quality, lifespan and performance is more predictable than components constructed on-site (Forghani, 2019). Additionally, prefabrication should make the development of the documentation required for DfR more straightforward.

The use of modular design has also been identified as being beneficial for DfD and DfR in a number of studies. However, the word ‘modular’ can have slightly different meanings and is often used ambiguously. In this context, it can be assumed that ‘modular’ refers to modular subassemblies, either structural or non-structural and either 2D or 3D, corresponding to Categories 1, 2 and 5 of MMC classification framework (MHCLG, 2019). Using such subassemblies, or modules, facilitates reuse as entire modules can be reused thus limiting the number of connections that need to be undone and redone for reuse. For example, a 2D structural truss subassembly (Category 2 MMC) consisting of multiple individual members, could be reused in its entirety. Likewise, a carefully designed volumetric 3D module (Category 1 MMC) could be reused in its entirety without dismantling. In short, the idea of creating subassemblies is central to MMC, and subassemblies can facilitate DfR. Therefore, it is logical to conclude that MMC enabled by DfMA can facilitate DfR in a way that traditional construction, which relies less upon subassemblies, cannot.

This idea has been mentioned in the literature, where it has been discussed hypothetically as a benefit of modular construction, and conceptually the idea of reusing modular subassemblies is quite straight-forward to understand. However, the practicalities of actually doing that does not appear to have been the subject of much published work. In part, this is because modular/MMC buildings are generally relatively new and there are not very many examples of such buildings that have reached the end-of-life stage.

However, given the compatibility between the two concepts, if the principles of DfR are applied with MMC, reuse potential should be improved. DfR can be achieved by designing modules with reuse in mind, ensuring that inter-module connotations are reversible and ensuring that concepts of layering are obeyed in design. The latter is particularly pertinent, especially for 3D modules, where the ability to incorporate services within the structure of a module is seen as a positive. However, for reuse, this needs to be done in such a way that layers are stacked according to end of life. This problem has been encountered on train carriages (which are essentially volumetric modular elements) in the UK for example, where CCTV cameras cannot be replaced without a major overhaul of the entire carriage (Rail Business UK, 2022).

5.5.2 Linking DfMA and DfR

Many of the principles of DfR listed above align with the principles of DfMA presented in Chapter 2. These are listed in Table 5.5.

Table 5.2 DfMA and DfR principles

Principles of DfMA that align with principles of DfR	
1.	Reduce manufacturing time and cost, through design that considers ease of manufacturing, uses a minimum number of parts and connectors and minimises finishing work
2.	Reduce handling time and cost, by simplifying the methods of handling and assembling parts and standardising connector types
3.	Reduce procurement time and cost, through design that repeatedly uses standardised parts;
4.	Simplify the manufacturing process, by repeatedly using similar materials
5.	Simplify design, through modular design
6.	Reduce component failure, by minimising the use of fragile components;
7.	Minimise waste, through design that considers re-usability;
8.	Minimise the impact on the environment, through the selection of environmentally friendly materials;

DfMA permits prefabrication and the use of modular subassemblies. In turn, these permit DfR. Additionally, DfMA also should make the process of correct documentation more straightforward. Therefore, there is a direct link from DfMA to MMC to DfR, and it is clear that DfMA can be an enabler of DfR.

However, it is also clear that many of the key principles of DfR, such as use of reversible connections or layering are not integral to DfMA. Indeed, there are likely to be scenarios where DfMA may contravene these principles – for example robotic welding may in some cases allow for easier manufacture or it may be more straight-forward to assemble components in which services are incorporated into the structure. Therefore, an awareness of DfR is required when adopting DfMA approaches, as DfMA does not automatically lead to DfR.

5.5.3 General Recommendations

The primary recommendation from this chapter is the very general one that DfD and DfR should be considered alongside the widespread adoption of MMC. At present this does not appear to be happening; there is no meaningful consideration given to disassembly and reuse in many recent policy documents. However, increased use of MMC represents a time of change for the construction industry, and this change presents an opportunity for DfR concepts to be incorporated in building practices and standards. These changes should account for EoL scenarios and not impede DfR. Given the societal need for new development, particularly in the housing sector, there is a danger that new ways of working will be focused on short term benefits and neglect EoL considerations. Or, to make the above point less formally, MMC will to some extent require a rewriting of the rulebook in the construction industry. It is important that the rulebook doesn't need to be rewritten again in 10 year's time to account for EoL.

More specifically, recommendations can be made to address many of the general barriers to the adoption of DfR identified elsewhere. As described in Section 5.4, the barriers to DfR relate to perception, economic issues, a lack of legislation and technical challenges. Table 5.6 proposes some potential avenues that can be pursued to address each of these.

Table 5.3 Recommendations to address barriers to adoption of DfR

1.	**Perception**
1.1.	There is a need for dissemination of information to stakeholders including the general public to emphasise the importance of DfR and overcome the negative connotations associated with employing reused components.
1.2.	A national programme of technical education and CPD on DfR for designers and quantity surveyors is required.
2.	**Economic**
2.1.	The lack of a market for reuse of components is a challenge. This could be addressed through the development of a national database or online marketplace of components that are available for reuse.
2.2.	There is a need to develop accounting methods that quantify the benefits of DfR. A system similar to the BER system that ranks a design's reuse potential may be a suitable approach.
2.3.	Economic pressure can be placed on stakeholders to encourage reuse by increasing the cost of landfill. Landfill costs could be related to the component age, i.e. higher landfill costs would apply for new components included in buildings constructed after an agreed implementation date, thereby encouraging design for reuse. Alternatively, anticipated landfill costs could be included in tendering for public contracts.
3.	**Legislative**
3.1.	DfR should be encouraged through green building standards. A straightforward way to achieve this would be the adoption of a scoring system such as that proposed in Annex C of ISO 20887 or in the Level(s) Green Building Framework. This would allow buildings to be ranked according to reuse potential. Such a ranking would motivate designers and stakeholders to achieve higher rankings, in the same way that BER ranking motivates stakeholders to achieve improved energy performance for example.
3.2.	The effect of removing the exemption for C&D waste from the landfill levy in encouraging reuse should be assessed.
3.3.	Research is needed into the standards required for used components and how the evolution of building regulations will affect components designed for reuse.
3.4.	Minimum reuse rates could be specified in contracts.
4.	**Technical**
4.1.	Improvements in connection design (including inter-module, panel-to-panel and wall-to-floor) to aid disassembly.
4.2.	Standardisation of connection designs.
4.3.	Provision of detailed technical guidance on DfR for designers of new buildings.
4.4.	Provision of guidance on the reuse of existing building components.

5.5.4 Specific Recommendations for Research & Education

Based on the above general actions, more specific recommendations can be made for further work to be undertaken to create the conditions necessary for the adoption of DfR in Irish construction projects including homebuilding. These can be broadly split into two parts - education and technical research - and could be carried out by the national construction research and education centres and agencies identified in Chapter 4, including Construct Innovate, the National MMC Demonstration Park, Build Digital, CP Skillnet and CitA with the support of professional associations including RIAI and IStructE.

Education & Information Dissemination

1. On a general level, Construct Innovate, The National Demonstration Park, RIAI and IStructE can lead on increasing awareness of DfR in the built environment sector. This may involve focussing on DfR at appropriate fora, such as Construct Innovate events or national conferences that also address MMC and DfMA.
2. There is a need to disseminate information about best practice in DfR to designers. This could be achieved through the creation and publication of guidance documentation that detail specific technical steps that designers should take to achieve DfR successfully. This would involve developing detailed rules for how the principles of DfR described can be implemented in practice. An applied research programme could lead to specific guidance on, for example, limits on the weight of components to facilitate handling or on distances between connections. These rules would be a development of the less specific guidance currently available, to use lightweight components or designation fixing free zones to maximise the lengths of materials for reuse.
3. Design guidance and rules should be accompanied by case studies and examples demonstrating best practice in DfR, including its implementation within DfMA.
4. Another task in terms of information dissemination involves addressing negative public perception about reused materials and components. This should build on current Construct Innovate work on influencing public perception of MMC in general.
5. Education, training and CPD course in DfR can be developed and delivered by existing construction education providers once sufficient detailed guidance has been developed. This should include the use of digital technologies and BIM to meet building documentation requirements.

Technical Research

1. It is clear that from a technical viewpoint appropriate connection design is key for DfR. Connection design can be complicated by competing needs to provide adequate structural integrity and adequate tolerance for construction while also facilitating later deconstruction and reuse. However, relatively little scientific research has been carried out on this topic. At present, a wide range of connection types and designs are used in a variety of structural forms, but few of them are very suitable for disassembly. The development of standard connections designed with disassembly in mind is essential for future reuse objectives. Innovation, research and development is needed to improve and test new designs suitable for the structural forms and scales typically encountered in Irish building construction, including modern methods of construction.
2. Research studies into advanced interlocking systems for modular and panelised building system connections and the capabilities of these systems to automate fast assembly and disassembly would improve construction industry productivity (Rajanayagam et al., 2021). Similarly, (Nadeem et al., 2021) identify the need for improved analytical modelling of connections, experimental work to understand the

exact load transfer mechanisms and behaviour under complex loading conditions like wind and blast and ensure connection designs meet the durability requirements of DfR. A goal for Construct Innovate should be the development of guidance and standards for the design of connections between modules, assemblies and sub-assemblies, covering hot-rolled steel, cold formed steel, timber and precast concrete construction. This would support both faster adoption of MMC enabled by DfMA in residential construction and long-term sustainability goals achieved through DfR.

3. Technical research is also required towards the development of a rating system for deconstructability and reuse. Annex C of ISO 20887 provides some guidance on how this could be done, but is generally quite vague, and not directly implementable in Irish construction projects. Alternatively, the ranking system proposed in the Level(s) green building framework could be further investigated and applied to case study examples. Aa definitive ranking system suitable for Irish construction practice would encourage and support designers to make decisions that support reuse.

5.6 Summary

The traditional end of life scenario in the built environment has involved demolition and landfill. However, this is not compatible with evolving ideas about a circular economy, which based on keeping materials in the economic system for as long as possible. In the built environment, the concept of reuse is central to achieving circularity in construction. At present the greatest barrier to reuse is that buildings are generally not designed for deconstruction. Therefore, in order to achieve the variety of economic and environmental benefits associated with a circular economy, the concept of Design for Deconstruction (DfD), and the broader idea of Design for Reuse (DfR), need to become part of the conventional design process.

This chapter has:

- introduced the concepts of DfD and DfR;
- discussed current policy on DfD and DfR in Ireland and compared it to that on MMC;
- lists a series of design principles that have been identified as integral to DfR and compares these to the principles of DfMA;
- identifies a series of barriers to the adoption of DfR in construction;
- considers the interaction between DfR and MMC enabled by DfMA;
- makes a set of recommendations that would promote the adoption of DfR in residential and general construction in Ireland.

On a broader level, the main conclusion from this review is that DfR will be an important feature of a modernised construction industry and that it deserves more consideration than it is currently receiving. There are a variety of potential economic and environmental benefits associated with DfR and it should be considered as an essential part of the MMC landscape. Furthermore, MMC and DfMA are broadly compatible with DfR given that the greater use of modular subassemblies is beneficial for both. However, the benefits associated with DfR are long term and not fully realised until the later stages of a building’s life cycle, and therefore not a focus of attention at design stage. This creates a risk that DfR will be ignored in the move to MMC, as current drivers for MMC adoption are mainly short-term benefits at the front end of the value chain. This appears to be the case in Ireland, with DfR not being considered in recent public and industry studies and reports on MMC. The future actions recommended in this study will ensure a greater focus on DfR and initiate national activity on the topic.

6 Conditions and Recommendations for DfMA with MMC and DfR in Ireland

The adoption of MMC in construction projects in Ireland generally and in public housing specifically will require considerable changes within the construction and built environment sector. While DfMA can facilitate some of these changes, additional necessary or desirable conditions that are substantially different to traditional construction will also need to apply. To meet future sustainability goals, these new conditions will also need to be suitable for DfR. This chapter therefore identifies a set of conditions that would support the widespread adoption of MMC, enabled by DfMA and supporting DfR, in housing delivery in Ireland. These conditions are informed by the challenges to DfMA with MMC discussed in Chapter 3, the relevant activities presented in Chapter 4, including sectoral studies and reports and the Roadmap for Increased Adoption of MMC in Public Housing, and the review of DfR presented in Chapter 5. Recommendations are provided on how each of these conditions can be created through specific or multi-functional actions.

6.1 Sectoral Commitment & Organisational Structures

MMC enabled by DfMA will make substantial contributions to all residential construction projects in Ireland

Condition: Design teams and their clients will assume that a substantial proportion of each building will be manufactured off-site, especially with MMC Categories 1 and 2. A long-term commitment to OSM and DfR will foster the other conditions required for widespread use of MMC in housing delivery. This condition will require a change in the value chain towards pre-manufactured value and significant human and capital investment by stakeholders. The integrated nature of the construction and built environment sector implies that this condition could not be restricted to public housing alone, but public sector commitment will be essential.

Recommendations: The achievement of this condition will require the sector to commit to considerable change, for which strong leadership will be required. Collective events such as the stakeholder workshops, national conferences and Construct Innovate events discussed in Chapter 4 will be essential for industry co-ordination, as will the continued focus of the MMC LIG and the CSG. Many of the actions identified in the Roadmap for Increased Adoption of MMC in Public Housing will also contribute directly, including the development of an MMC Data Dashboard to allow the evolution of MMC usage to be monitored. The scope of these activities should be extended to include DfR, which has received little attention to date in Ireland.

There will be strong cross-sectoral confidence in Irish housing constructed with MMC

Condition: Consumer confidence and public trust in the quality and durability of buildings constructed with MMC will be necessary to realise the full potential productivity benefits offered by new technology. This also applies to the confidence of financial institutions in OSM. Designers and clients committing to DfMA and DfR will have confidence in the reliability of MMC products and in supply chain certainty, including trust in the on-site procedures employed for materials handling, assembly and disassembly. Potential risks will be minimised, including compliance risks relating to building controls, supply chain risks relating to the capacity of MMC manufacturers and the flexibility of the DfMA approach, and end-of-life risks associated with disassembly and reuse.

Recommendations: The current Construct Innovate project on behavioural attitudes to MMC will form a strong basis for identifying actions that will support this condition. Both consumer interests, in the form of homeowner, occupier and investor attitudes, and industry interests relating to MMC product and supply chain reliability should be taken into account. Examples of high-quality housing incorporating MMC at the National MMC Demonstration Park and in the proposed pilot project on volumetric modular systems can make strong contributions to confidence, as will a strong and well-resourced regulatory environment. Housing built using MMC should aim to be of higher quality and more sustainable than traditionally constructed buildings. Effective guidance and procedures to enable DfR with MMC will provide investors with confidence that risks associated with EoL obligations under future sustainability regulations will be minimised.

Stakeholders in Irish residential construction will have strong awareness, knowledge and experience of MMC, DfMA and DfR

Condition: Good information and knowledge of evolving MMC technology and DfMA and DfR procedures will enable their widespread application in housing delivery. The National MMC Demonstration Park will make an important contribution to the awareness of developers and design teams of the opportunities offered by MMC. Living laboratory programmes will be developed to explore and demonstrate compatible assembly and disassembly methods. Other forms of information gathering and sharing will also be developed including online databases and marketplaces. At project level adequate programme provision will allow designers to access and compare MMC options, and to record and share their learned experiences.

Recommendations: General information on MMC should be regularly provided and updated in a variety of formats similar to the Skillnet video series, the DHLGH Introductory Guide to MMC and the Construct Innovate webinar series, as well as formal education and training activities. There will be an ongoing need to share knowledge and information arising in construction and manufacturing throughout both sectors, which can be facilitated by technology demonstrations in real environments, documented detailed case studies of recent projects and comprehensive information on market availability of MMC products and services. Knowledge and experience gaps related to the decision-making required for optimisation of a project from site selection through design and construction will need to be addressed.

Better information and data on levels of MMC deployment in Irish construction projects and housing delivery is required. Improved methods of sharing knowledge and information should be developed based on the integration of information systems, technology, software and data. Open libraries of related technical information including open-source interoperable digital technical content should be created. New supports will be required to enable construction professionals to protect and exploit IP developed in the course of their design work and to facilitate its re-use by others.

New approaches to project delivery based on stakeholder collaboration will achieve the high levels of integration required to realise the benefits of MMC in Ireland

Condition: Design for Manufacturing and Assembly, Design & Build and other forms of Integrated Programme Delivery will be widely employed to exploit the full potential benefits of MMC. These will be supported by structured guidance and compatible contractual frameworks including the RIAI DfMA Overlay and Public Work Framework Agreements that address the high level of complexity expected in the planning, design and execution of residential construction projects employing substantial MMC. This guidance will encompass processes required for whole life cycle based DfR. Project teams will employ improved communication and co-ordination methods based on enhanced use of information and communication technologies. BIM will be extensively employed as a collaboration environment where stakeholders exchange ideas, share knowledge and store information required for off-site fabrication, on-site construction and building documentation.

Recommendations: Training and CPD programmes will be essential to ensure that construction professionals understand their different roles and responsibilities under various approaches to programme delivery. New and improved forms of programme delivery that can enable MMC application in public housing should continue to be developed. Supports for BIM adoption will be required to support seamless workflows and communications and to ensure that BIM can be extensively employed as a collaboration environment where stakeholders exchange ideas, share knowledge and store the information required for off-site fabrication and on-site construction. As identified in Chapter 4, there is a need for additional State, public and sectoral initiatives focused on project team roles and responsibilities, co-ordination and relationships.

6.2 Market Conditions & Contractual Framework

Strong and consistent market demand for MMC will encourage investment in OSM and DfMA-based project delivery in Ireland

Condition: Sectoral commitment to MMC, confidence in building quality and understanding of the role of DfR in meeting sustainability goals will all strengthen demand for MMC products and services. Consistent demand will support investment by all stakeholders, including MMC manufacturers seeking to offer repeatable solutions. The availability of a reliable selection of MMCs within the market will encourage clients and designers to invest in the skills and relationships required for DfMA-based project delivery. This includes the development of commercial alliances and collaborative partnerships to minimise supply chain risks, and the co-ordination of public and private sector clients in building the required pipeline of projects.

Recommendations: Actions aimed at driving increased productivity and sustainability including increased investment and collaboration in research, development, and innovation will support growth in off-site manufacturing. New MMCs for application in housing should seek to improve productivity and sustainability. It will be important to make reliable and independent information on programme and cost benefits available to clients and to provide associated guidance to designers to ensure that those benefits are achieved. Related workforce education and training programmes will also be required. Planned and further actions promoting the use of MMC in public contracts will be vital for creating commercial demand for MMC solutions. These will need to be complemented by extensive MMC use in private sector projects if benefits of scale are to be realised and the MMC supply chain, include SMEs in the manufacturing sector, is to be strengthened.

Sufficient market capacity for OSM and MMC will be available to satisfy the needs of Irish residential construction

Condition: Commitment to OSM throughout the construction and built environment sector will provide the consistent commercial demand required to grow MMC market capacity through product development and a reliable supply chain. Designers of residential construction projects will be able to select from a range of suitable MMC options that achieve productivity and sustainability goals and excellent housing design and urban development. The development of strong market capacity will be facilitated by substantial investment in manufacturing facilities for and by the construction sector.

Recommendations: A large number of the current activities identified in Chapter 4 are focused on the improvement of MMC market capacity including supports for certification, digital adoption and training, as well as public procurement initiatives and the establishment of centres for research and demonstration. Opportunities for DfMA to enable the broader range of innovative solutions for housing construction required by national programmes for accelerated delivery should be further investigated through these initiatives. To date, the potential for applying general DfMA guidelines within the construction industry has not been well explored and there remains a need for DfMA examples that can inspire designers towards future MMC adoption. This should be linked to both the co-ordination of standardisation in residential construction and the creation of a diverse range of MMC options suitable for different developments.

Contractual frameworks including tendering and procurement procedures will be amenable to forms of project delivery such as DfMA that enable MMC

Condition: Procurement procedures and contracts will provide for OSM and offer greater flexibility and early engagement with MMC suppliers. This will support project delivery methods including DfMA and D&B that improve vertical and longitudinal integration and promote improved stakeholder integration practices, including alignment with client requirements. Contracts will recognise the different allocation of responsibilities, added value, liabilities, assurance, financing and payment conditions required in MMC enabled projects, including the whole life cycle responsibilities addressed through DfR. BIM and other information technologies will be employed to align the roles of clients, designers, engineers, suppliers and contractors. Co-ordination will be improved by facilitating longitudinal continuity through the formation of collaborative partnerships to deliver multiple housing programmes.

Recommendations: There are demands for new forms of contract and procurement that are less inflexible, meet the need for payment schedules that align with actual DfMA and MMC cost profiles, and are better suited to enabling innovation. These should explicitly recognise the role of off-site construction, allow OSM providers to undertake design and build project delivery, and support other hybrid integrated project delivery models. Contractual frameworks should also facilitate a two-stage bidding process with early contractor involvement, accommodate better assurance schemes, allow financiers to accept MMC insurance and warranty, and address emerging end-of-life obligations in the context of DfR. Recent public procurement initiatives including the PW-CF2 PWC for building works designed by the contractor have made important contributions in this direction, but the analysis of activities and challenges in Chapter 4 shows that issues related to the contractual framework have received relatively little attention overall.

6.3 Regulatory Environment & Certification Processes

A robust regulatory environment will underpin confidence in the use of MMC in Ireland

Condition: The investments required to increase MMC capacity and adopt DfMA and DfR practices in housing delivery will be underpinned by a strong regulatory environment. This applies especially for multi-unit buildings where strong building regulations are essential for homeowner and investor confidence. A strong regulatory environment will also protect the business models of SMEs involved in the manufacture and supply of specific MMC products to defined quality standards. Public and private sector collaboration and consultation will ensure that regulations are regularly updated in line with evolving technology and practice, including new regulations required to mandate DfR.

Recommendations: Recent actions related to the support of Building Regulations, Inspection and Control Initiatives are essential for achieving this condition. The regulatory system will need to be responsive to changes in technology and practice. The proposed BCAR training on MMC and similar supports should aim to ensure sufficient inspection capacity and ensure that off-site and on-site inspections are aligned, complementary and efficient. Inspection and control, including fire inspection, should be consistently applied. All stakeholder groups in the construction and built environment sector need to contribute to frequent updating of regulations as MMC technologies evolve and as new sustainability obligations including reuse arise. Open information on all aspects of the regulatory environment should be made available in formats suitable for SMEs.

Certification of new MMCs and controls on their application in building projects in Ireland will be carried out with efficient, accessible and widely understood processes

Condition: MMC product developers and designers will be confident that they be able to seek and gain quick approval for new building components and for novel applications of MMC in new buildings. Subsequent building control inspections will be fully aligned with the certification process, and uniform consistency will apply throughout Ireland. The construction industry ecosystem will have good knowledge of the certification and inspection requirements including the availability of specialist advice from outside of the regulatory agencies. Public investment in NSAI certification and building control will need to continue to grow and additional private sector investment in skills and expertise development will also be required.

Recommendations: An efficient Agrément process is essential for the introduction of new MMC components and products to construction projects in Ireland. Recent improvements to procedures for NSAI certification of MMC should be enhanced as MMC deployment increases. Independent guidance and advice on achieving certification will be needed to support new entrants and SMEs. Training, online toolkits and specialist support for designers seeking to employ MMC components in housing delivery will also be required. These supports will need to be linked to laboratory testing expertise and to knowledge of building control. To facilitate the innovation cycle and housing delivery programmes, certification processes should be completed promptly, without excessive costs, and be linked to subsequent building control procedures. Ways of exploiting the potential of European standards harmonisation to extend the MMC supply chain should be explored.

Appropriate use of standardisation within high quality residential construction will benefit housing development in Ireland

Condition: Cost and programme benefits arising from the widespread adoption of MMC in residential construction will be optimised through repeatability and scalability, both of which are facilitated by standardisation. In housing developments, standardisation can apply to both design (e.g. plan layouts) and to components/materials (e.g. façade elements). The manufacture of repeatable and scalable building components will increase MMC market capacity, and in time may open pathways to productization. Standardisation will support greater circularity in building products and materials through DfR.

Recommendations: Standardisation is frequently cited as an important pathway to achieving the full potential benefits of MMC, but a clear process through which this is to be achieved for residential construction in Ireland is not yet evident. Current activities are spread across government departments and agencies, research centres, and enterprises in the manufacturing and construction sectors. Prime responsibility for promoting standardisation should be assigned to a centre of excellence to co-ordinate the contributions of the multiple stakeholders who will need to be involved.

While the benefit of standardisation in reducing construction programme time has been demonstrated in

Ireland, additional work is required to secure and demonstrate lower project costs. There is industry demand for certified universal housing systems employing standardised typologies that can be produced by multiple manufacturers using cost-efficient production techniques, while allowing reasonable variations in design. This approach would mirror recent product platform initiatives in the UK and could offer repeatability and scalability benefits for housing delivery in Ireland.

Current activities examining the MMC compatibility of standard public housing designs in the Design Manual for Quality Housing, and the planned Construct Innovate project on the Creation of Standardised Design Details for MMC Builds, which will develop and provide open access test data on compliant standardised details for a selected form of MMC, can make strong contributions in this direction. Further steps will need to combine these ideas, expand their scope to multiple forms of housing and construction, and create technical guidance documents useable by construction and manufacturing professionals. It will be important to develop standardised solutions that can be applied in both DfMA and DfR.

Sufficient testing facilities and expertise will be readily available in Ireland to satisfy all certification and regulatory requirements

Condition: MMC product developers and housing project teams will have access to local experimental facilities to meet all their testing needs, including evaluation of the structural, acoustic, fire, thermal and moisture properties required by Building Regulations. Accredited laboratories will have all the technical, engineering and scientific expertise and experience required to carry out these tests, be able to advise on the correct test parameters, and experience consistent demand for their services to ensure that skill and knowledge levels are maintained. The laboratories will be closely linked to national construction research and education programmes through Construct Innovate. The National MMC Demonstration Park will host living laboratory experiments to test and demonstrate the in-situ performance of MMC products. Current national capacity in this area is very low due to the weak prior investment in construction research and innovation, with many essential testing services only available outside the State. This implies that substantial additional investment will be required linked to Housing for All, the National Development Plan, the Climate Action Plan and Construction Products Regulation.

Recommendations: The shortage of construction testing facilities in Ireland is a barrier to the introduction of new MMC solutions or to variations in existing solutions to meet the particular requirements of individual projects. This is limiting the ability of the housing market to increase output. Removing this barrier is an essential requirement for the development of a modern construction industry that will feature certified MMC in all projects.

The shortage of laboratory facilities nationwide prevents SMEs from participating in MMC innovation initiatives as the access cost burden of the required testing can be too great. Full participation in the market should be supported by other stakeholders in the value chain, including the eventual beneficiaries of any resulting innovation as represented by the State and residential construction sector. Funding mechanisms for public and private sector financial support for the required investment will need to be developed.

Substantial new and additional laboratory testing facilities are required for all parameters considered in certification and regulation, including acoustic, thermal, structural, fire and moisture properties. These facilities should also be available for product and process development, including research and prototyping activities addressing new construction and end-of-life disassembly. Laboratory expertise will need to be maintained by consistent engagement in certification, development, research and education activities, and be available to provide advice on testing requirements based on previous experience with certification, building regulations expertise and scientific knowledge. The available laboratory space and equipment should support the efficient turnover of experimental programmes required to provide a reliable and efficient service to industry.

6.4 Operational Systems & Knowledge Transfer

A well-developed national ecosystem including guidelines, standards, training, research, innovation and enterprise will enable widespread adoption of MMC

Condition: Research, development and innovation activities complemented by effective knowledge transfer will support DfMA by offering multiple MMC solutions to emerging design requirements including DfR. This will take place in a strong ecosystem encompassing education, training and enterprise support, expert input for standards and regulations and comprehensive guidance for construction professionals. Knowledge-sharing including open source digital resources, MMC technology databases and online libraries of case studies will enable sectoral collaboration and excellence in construction practice.

Recommendations: The construction sector in Ireland has experienced little public or private investment in research, and the existing research and innovation ecosystem needs to strengthened if it is to play a strong role in industrial capacity development. There is generally limited relevant R&D capacity within and supporting industry, and this should be expanded to provide the guidelines, standards and affordable technologies needed to enable widespread adoption of MMC enabled by DfMA and to facilitate DfR.

The recently established centres of excellence at Construct Innovate, the MMC Demonstration Park and the Build Digital Project can act as focal points for this expansion if they are adequately resourced with long-term funding commitments, and if the construction and built environment sector engages fully in their activities. The Construct Innovate AIMDays which serve to support and empower industry members to align the centre's research, development and innovation activities with the business challenges faced by their organisations is an example of the collaboration required to build a strong ecosystem. Similar collaboration and knowledge transfer can take place in the context of education programmes and conferences organised by professional and industry bodies.

The above centres of excellence can contribute to MMC adoption in housing delivery by showcasing and demonstrating MMC products, systems and technologies to industry stakeholders including clients, manufacturers and construction professionals, and through the dissemination of research results throughout the sector through publications, events and online tools. The sharing of knowledge and information including open databases of MMC system test results and interoperable digital technical content will improve sectoral productivity. Guidelines and standards can be used to co-ordinate technical knowledge and procedures amongst diverse industry partners.

The design, manufacturing and construction methods required to apply MMC in residential construction will be well developed and widely available in Ireland

Condition: The available methods will include those required to execute the tasks related to design development, sustainability and digital delivery outlined for each project work stage in the RIAI DfMA Overlay. These involve selecting the right solution between candidate MMC options, optimising the choice of materials, and overcoming challenges related to design, manufacturing, technology, logistics and assembly, amongst others. They will also include the methods required for disassembly and component reuse within DfR. New workflows will feature the co-ordinated adoption of new BIM modelling and verification tools to automate design and assembly, and new on-site construction methods will address materials handling, component assembly, the use of specialised equipment and record keeping. The development and learning of these new methods will require investment in human capital and knowledge exchange.

Recommendations: DfMA and DfR with MMC will require the development of new methods in design, manufacturing and construction, and these methods will need continuous updating as MMC technology evolves. Regular training and CPD activities will be required to disseminate and learn these new methods. Technological advances will feature strongly in these new methods, especially on-site technology for identifying and checking MMC components for assembly or disassembly and BIM modelling for co-ordination and lifecycle documentation, building on the recent Digital Construction Pack and other planned supports for BIM adoption. Improved methods and skills in documentation will be required for DfR. Both DfMA and DfR are strongly dependent on the form of connection employed between assemblies and components and specific methods will be required for their planning, design, execution and verification. New methods will be required to address environmental sustainability goals including waste and climate impacts and in supply chain and logistics.

Accessible education and training programmes in MMC will meet the needs of the Irish construction sector workforce and wider stakeholders

Condition: A comprehensive range of education and training programmes will support many of the above conditions for MMC adoption. Appropriate programmes addressing the different skills and knowledge required for MMC projects will be provided for all stakeholders including the construction workforce, professionals and clients. High quality education and training facilities will be employed in online, in-person and hands-on environments. Experienced education providers have begun to offer courses in this field, but these will need to be expanded with additional supports, especially funded participation by construction workers and professionals. Curricula will be designed in collaboration with industry stakeholders and the programmes and facilities will be closely integrated with applied research, development and innovation activities.

Recommendations: Industry-focused education, training and CPD programmes will be required in:

- MMC technologies and their application in housing delivery.
- DfMA procedures, including the RIAI DfMA overlay and the tasks encountered in each of its work stages.
- Sustainability and circularity in construction, including climate impact assessment, material properties and guidance on the implementation of DfR with different forms of construction.
- Digital technologies, including BIM, that take account of the dual manufacturing-construction requirements of MMC.
- Organisational structures including collaboration, project management, co-ordination, and communications skills for construction professionals in DfMA-based projects.
- Contractual frameworks encompassing procurement and contractual procedures to enable MMC including DFMA, D&B and IPD,
- Certification and building control procedures for MMC including testing and inspection.
- On-site construction methods and technologies for logistics, materials handling, component assembly, use of specialised equipment and record keeping.
- Structured research and innovation methods, including the application of testing and modelling in the development of new MMC products and methods and intellectual property creation and protection.

7 Conclusions

7.1 Developing MMC with DfMA and DfR

- There is wide support for the adoption of Modern Methods of Construction (MMC) in Ireland and strong belief that MMCs can improve productivity in the construction sector and help to meet objectives set out in Housing for All, the National Development Plan and the National Climate Action Plan, including those relating to public housing delivery. This support is evidenced by the large number of recent, current and planned related activities across the public and private sectors.

- Design for Manufacture and Assembly (DfMA) can support the adoption of MMC by co-ordinating the design, manufacturing and assembly phases of a construction project in a way that promotes integration of its participants and activities. This integration is essential for optimal use of MMC. The RIAI DfMA Overlay to the Plan of Work provides a structured framework through which this can be achieved in any project by applying the principles of DfMA in a series of construction project work stages.

- Design for Reuse (DfR) seeks to maximise the proportion of material employed in the construction of a new building that can be reused when it reaches the end of its life. As offsite construction employing modular and panelised assemblies can be more amenable to disassembly than many forms of traditional construction, it is expected that MMC can help to enable DfR. By extension, the use of DfMA to facilitate MMC adoption can also help in the application of DfR, and many DfMA principles can be shown to be equivalent to DfR principles.

- However, other important DfR principles, such as the layering of building components, are not represented in DfMA, and need to be considered separately. Compared to the amount of recent MMC-related activity in Ireland, the subject of DfR has received very little attention. A programme of research and knowledge transfer on DfR is required to help the construction and built environment sector meet emerging sustainability obligations.

7.2 Stakeholder Commitment

- Continued industry and client commitment will be required if MMC enabled by DfMA is to make a substantial contribution to the delivery of residential construction projects in Ireland. This commitment will only be given if factual evidence shows that the productivity and cost benefits expected from MMC are realised in Irish construction projects. Detailed data collection, analysis and sharing from a cross-section of case study projects will help to provide this evidence.

- Evidence-based commitments to MMC can create strong and consistent market demand, encourage investment in OSM and promote DfMA-based project delivery in Ireland. This will be necessary to build the market capacity required to satisfy the needs of Irish residential construction. Numerous current activities have been identified that aim to increase market capacity, and continued industry and State support for these will be essential if demand and capacity are to grow together.

- Integrated project delivery such as DfMA can achieve the high levels of stakeholder integration and co-ordination required to realise the benefits of MMC. Compared to traditional forms of project delivery, this often requires different forms of organisational structures, better use of information technology including BIM and an appropriate contractual framework.

- Stakeholder awareness, knowledge and experience of MMC and DfMA should be strengthened through the structured collection of information on relevant products and projects, and the dissemination of this information through a variety of media. These activities can be performed by the National MMC Demonstration Park and Construct Innovate, and should include co-ordinated living laboratory programmes aimed at exploring and demonstrating assembly and disassembly methods applicable in DfR.

7.3 Regulation & Certification

- A robust regulatory environment is necessary to support public and industry confidence in the use of MMC in Irish housing. Regulations including certification and building control will need to evolve rapidly in line with innovations in MMC technologies, for which responsive regulatory structures will be required. There is a clear role for Construct Innovate in co-ordinating wider industry input to the maintenance of regulations through technology foresight activities. Confidence in MMC use will also be strengthened by mitigating end-of-life risks through research and guidance on DfR in Irish housing

- Understanding and navigating the complex certification procedures required for many new MMCs requires support in the form of external advice and technical expertise, which will promote access to and efficient use of the certification process. This support is especially important for SMEs. The unique nature of Ireland's independent national certification system calls for specific relevant advice, linked to access to local testing facilities and understanding of local building inspection procedures.

- It is widely believed that the potential benefits of scalability and repeatability offered by MMC use in residential construction will be easier to realise with standardised building and component designs. Given the importance of this topic for housing delivery in particular, prime responsibility for promoting standardisation should be assigned to a single centre of excellence, charged with growing market capacity, increasing productivity and enabling DfR through standardisation of key forms of construction.

- Substantial investment in construction laboratory testing facilities and expertise will be required to meet future MMC product development, certification and regulatory requirements. Current national testing capacity in Ireland is exceptionally low due to weak prior investment in construction research and innovation. This represents a significant barrier to innovation activities that support national policy goals, including Housing for All, the National Development Plan, and the Climate Action Plan. Removing this barrier will be an essential requirement for the development of a modern construction industry expected to feature certified MMC in most projects. The essential investment in testing facilities should be linked to education, research and demonstration activities supporting the development of new design and construction methods suited to MMC adoption.

7.4 Knowledge Transfer

- A well-developed national ecosystem to enable widespread adoption of MMC can be created by MMC stakeholders in Ireland. A strong ecosystem will develop capabilities and share knowledge in the form of guidelines, standards, training and research to support innovation and enterprise in the public and private sectors. The co-ordination of this ecosystem can be achieved through existing industry-government groups, centres-of-excellence and professional associations. Motivation for increased stakeholder collaboration in the ecosystem should be based on mutual benefits arising from common research, education and knowledge-sharing interests.

- The new work practices and methods required in MMC, DfMA and DfR need to be supported by a comprehensive set of education, training and CPD programmes. Irish universities, vocational education providers and professional associations have already developed and offered courses addressing relevant skills and knowledge requirements, and the national capability to deliver the required programmes has been demonstrated. However, a larger range of programmes will be required to meet the diverse needs of the construction workforce and professionals, both in terms of course content and mode of delivery and accessibility. Supports will be required to ensure that programmes are industry-focused and updated as MMC technology and methods evolve. A key issue will be securing the engagement of the existing workforce, which needs to be resourced from current rather than future activities. This can be linked to the need to demonstrate competence as required by the Building Regulations or incentivised by financial contributions from project budgets.

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