4.Zero waste

Refocusing modern methods of construction on the climate emergency: a ‘five capitals’ model for action

Adrian Campbell, Robert Hairstans and Giulia Jones explain how natural, human, social, manufactured and economic capital can all benefit from a sustainability-focused approach to off-site manufacturing.

Introduction

Modern methods of construction (MMC) is a catch-all term used to describe improvements in construction industry methods and technologies both on and off site. There are a lot of other terms (industrialised, prefabricated, pre-manufactured, precision-manufactured, manufacturing-led, kit-of-parts, modular, platform-based, etc.) used to describe supposed non-traditional and less labour-intensive construction methods.

Some degree of off-site manufacturing (OSM) is inherent in almost all projects and has historically been adopted to best suit available and efficient production methods. Timber, cast or wrought iron, precast concrete, and standardised steel framing systems such as CLASP, all have a long history of use in construction and so aren’t strictly ‘modern’.

This paper, however, focuses on current and more advanced OSM methods, as a subset of the MMC ambition, and a smarter way of building to improve sustainability, maximise benefits to the user and minimise whole-life costs[1].

As noted by CIRIA recently[2], these benefits are not always clearly substantiated. Important environmental and social benefits metrics for OSM are also often downgraded to ‘broader’ or ‘wider’ issues, maintaining ‘direct’ commercial drivers as the principle focus. There is little about how OSM will need to respond to the changed reality of the climate emergency.

This paper therefore sets out what this refocused method of response might be. It uses the ‘five capitals’ model for sustainability[3] to identify how natural, human and social capital, not just manufactured and economic capital, could be enhanced in the use of OSM.

We use the term OSM to mean the factory-based manufacture and

TABLE 1: What is off-site manufacturing?

		Basic materials	Improved on-site methods		Off-site systems		
Common construction definition[7]		Labour intensive	Efficient site methods	Site automation	Elements/ components	Sub-assemblies	
Increasing level of complexity[8,9]	Structure only						
	Limited fixtures						
	Fully functional						
Associated MMC definition (MHCLG)[6]			(Category 6) Traditional building product-led site labour reduction/productivity improvements	(Category 7) Site process-led labour reduction/productivity improvements	(Category 3) Pre-manufacturing – non systemised primary structure	(Category 5) Pre-manufacturing – non-structural assemblies and sub-assemblies	
Examples		No OSM content Basic materials for intensive on-site construction	Large format masonry products Modular wiring Brick slips Flexible pipework Insulated concrete formwork	AR/VR Site robotics	Screw piles Roof truss Precast staircases	Windows Cladding panels Services pods Pre-assembled service risers	

pre-assembly of components, elements or modules away from the construction site before final transport and assembly (deployment) in their final location. OSM uses product standardisation and increasingly automated industrialised production methods to manufacture major parts, or even whole buildings, in more efficient, safe and attractive working environments.

The UK government recognises the importance of this shift, and its announcement in 2017 in favour of off-site methods[4] was aimed at supporting investment. Equally, the construction industry's ambition for 33% lower costs, 50% faster delivery and 50% lower emissions[5] will require more OSM.

A basic introduction to the major forms of OSM and their relationship to the standardised descriptions of MMC[6] is set out in **Table 1**, along with suggested further reading.

Different levels of product complexity ('pre-manufactured added value') can be delivered depending on the production methods. In many cases, buildings will adopt multiple or hybridised approaches to suit the particular project requirements.

For the structural engineer, however, the choice is still principally between the use of different components, standardised 2D (panel) systems, or 3D volumetric methods. This choice should be made early in the design process to allow the systems to be optimised within the design. This can be done by procuring for performance, not system delivery, or acknowledging that early system selection reduces future design and procurement options.

OSM construction as part a more regenerative system culture

The climate emergency will require responses that go beyond established and somewhat formulaic approaches to sustainability. To make the scale of reductions needed, more restorative and regenerative systems strategies, which repair – not just minimise – impacts on our environment, will be required. There are emerging ideas that help understand this ambition[10]. Although they need further development, they are a useful basis to identify the sort of approaches that can be taken.

Rather than simply focus on the technologies, **Table 2** recognises the interconnectedness of different types of capital, and aims to demonstrate how a broader systems view could benefit human, social and planetary health, as well as the quality and economy of built projects.

Many of these actions are not exclusive to OSM, but do show how manufacturing-led construction might help deliver the buildings we need, in a way that is more aligned to construction in the context of the climate emergency.

More detail on these approaches and their possible benefits and limitations is now provided.

> **"THE AMBITION FOR 33% LOWER COSTS, 50% FASTER DELIVERY AND 50% LOWER EMISSIONS WILL REQUIRE MORE OSM**

How to implement more regenerative OSM methods

This requires a different approach and ambition. Methods both to embed OSM successfully and change the ambition to more regenerative design principles need to start at the beginning of a project and not simply be considered as a contractor delivery alternative. This includes influencing the client's investment strategy and the brief, identifying new system methods, and suggesting alternative procurement options consistent with those systems. If adopted late, bespoke rather than standardised systems are entrenched into the design, leaving little opportunity for modification without major programme implications.

Traditional competitive tendering methods in particular make it harder to influence the project design and specification at that late stage. Project teams hoping to adopt OSM can informally engage with suppliers to understand new options and optimal production requirements, not just manufacturing limits. Alternatively, supplier design input can be formally obtained under a preconstruction service agreement (PCSA) to arrive at a more developed solution with greater design and cost certainty, even if this does lock in certain aspects of the design.

Although OSM is used on many

2D panelised	3D volumetric ('modular')	Hybridised	Whole building	Automated production
Basic structural wall/floor panel	Structural chassis		Complete structure	
Pre-finished wall/floor panel	Pre-finished room		Pre-finished building	
Fully finished and serviced wall/ floor panel	Fully finished room		Fully serviced and finished building	
(Category 2) Pre-manufacturing – 2D primary structural systems	(Category 1) Pre-manufacturing – 3D primary structural systems			(Category 4) Additive manufacturing – structural and non-structural
Platform and balloon frame housing construction Precast wall and floor panels Open or closed-panel timber or LGS frame, CLT, SIP Insulated roof cassette with applied waterproofing	Uninsulated volumetric chassis with internal boarding Modular housing systems with applied external finish Finished plant room module	Mixed system comprising various typologies, e.g. 2D plus 3D or mix of DfMA approaches providing customised approach Platform-based (P-DfMA) standardised system[9]	Out-of-town hotels/ restaurants	3D printed concrete elements or buildings

TABLE 2: OSM and five-capitals model of sustainability

NATURAL CAPITAL	HUMAN CAPITAL	SOCIAL CAPITAL	MANUFACTURED CAPITAL	FINANCIAL CAPITAL
Building less Using OSM as part of enabling building reuse with lightweight system or with logistics-constrained refurbishment	**Multi-skilled workforce** Ability to engage both skilled and semi-skilled workers providing more flexible career pathway	**Reskilling and apprenticeships** Cross-industry skills transfer with new opportunities to attract more people to a high-quality industry with a broader purpose	**Reduced whole-life impacts** Improved airtightness and thermal efficiency Extend building use through durability	**Faster delivery** Earlier return on investment and better cashflows
Using biogenic materials Working with renewable natural materials to reduce non-renewable resource consumption, reduced extraction impacts on biodiversity, and enhanced carbon pools	**Improved and regular working conditions** Safer and healthier working environments More regular and local work Shift patterns and flexible working for more inclusive employment across all ages	**Diverse routes to delivery** Alterative models for small and self-build to diversify opportunities	**Optimised products** Product optimisation and production waste reduction particularly with platform-based systems	**Route to embodied carbon reductions** Optimisation for net-zero-carbon materials and limitation of future carbon pricing or governance impacts
DfMA+D Disassembly within the product design and greater standardisation allows for greater material reuse	**Digitalisation uptake** Increased adoption of innovative digital processes for manufacturing simulation and supplier coordination via platform systems Digital twin benefits maximised through end of first use and then reuse with retained information	**Design quality** Avoiding 'sameness' in the built environment through design quality, mass customisation and digitally enabled flexible manufacturing	**User-focused** Designed to suit changing user needs and adaptability over time, including climate resilience and lifestyles	**Reduced rework** Remedial costs reduced by right first time approach

projects with easily identifiable and repeating modules – such as in forms of housing – its use is not always as clear cut. Options should be explored with contractors/manufacturers to identify what suits each project. The new RIBA Plan of Work 2020[11] reasonably suggests Stage 2 (concept design) as an appropriate time to start this engagement. As OSM also necessitates different transport and assembly methods, getting advice early on logistics is critical to ensuring OSM is easily deliverable.

Focusing on five capitals

Using a systems-based approach across all five capitals will help ensure a more ambitious and balanced agenda for design and procurement.

Preserving and restoring natural capital

If we are to produce more restorative solutions, we must first avoid consuming more materials by refurbishing more buildings, reusing more components and using bio-based materials.

Build less

The UK already has 80% of the buildings that it will have in 2050[12]. The value of OSM, as with any other construction approach, is therefore as much how it will benefit retrofit and refurbishment of existing buildings, as new construction.

By using preassembled and lightweight systems, obstacles to building reuse can be overcome, unlocking any additional capacity of existing structures. Assemblies can be used to overcome access issues, or whole new units can be installed on roof extensions.

There are now many more examples of the use of all-timber or hybrid steel and cross-laminated timber (CLT) frames as a means to provide lighter-weight and lower-impact refurbishment options for offices, such as the Export Building by Studio RHE and Heyne Tillett Steel[13], or the Green House project by Waugh Thistleton Architects and Ramboll[14] **(Box 1)**.

Adopt circular principles

OSM lends itself to an approach more aligned to a circular economy, by standardising systems and managing resources better during the manufacturing (making) phase, and can be extended to consider all the output flows (re-making) and potential impact of a system throughout its full lifecycle[15].

> “ IF WE ARE TO PRODUCE MORE RESTORATIVE SOLUTIONS, WE MUST FIRST AVOID CONSUMING MORE MATERIALS

The principles of a more circular approach are clear, but there are still many practical issues with its implementation in the industry. Critical in the success of this approach will be extending design strategies to include disassembly, as now noted in both BREEAM (credit Wst 06) and the Draft New London Plan (cl. 3.1B.10)[16], into a whole-life aspiration within OSM methods for Design for Manufacture, Assembly and Disassembly (DfMA+D)[17].

One key issue is balancing the initial efficiency provided by composite systems and the difficulty of then disassembling and reusing these later. Demountable precast systems that do not require screed topping have been developed by Laing O'Rourke, which is also experimenting with very low-carbon precast systems for their production **(Box 2)**.

Use natural materials where possible

Using bio-based materials can significantly reduce the embodied impacts of buildings. This must be balanced with an understanding of overall required building performance, including fire – particularly when used in taller structures – durability, and

Box 1. The Green House: OSM in refurbishment and extension projects

This project in London uses all-timber and hybrid CLT and steel framing to extend an existing concrete-framed structure, exposing both the original and timber materials.

CLT panels weigh about one-quarter of a traditional concrete deck, but are usually designed non-compositely with steel framing.

Reusing the existing structure and adopting timber for the floors produces a low-carbon solution while being a fast and efficient framing option.

© JIM STEPEHENSON / WAUGH THISTLETON ARCHITECTS

↗FIGURE 1:
Green House, Cambridge Heath Road, London

end-of-life disposal **(Box 3)**.

CLT is again an increasingly popular and standardised option. It is relatively simple to design with, provides comparable if not improved commercial benefits, and lends itself to machining for more customisation of geometries. Other material options are also emerging alongside timber products, including advanced bamboo, hemp, straw and even fungal mycelium[19].

Developing the human-focused construction workplace

While the focus for engineers is often on the materials and methods of fabrication, the benefits in the conditions of work could be enormously significant in redeploying manufacturing skills into construction, providing more stable, settled and local work, allowing greater diversity in the industry, and providing safer and more attractive working conditions.

OSM provides opportunities to develop safe, healthy and stimulating workplaces to attract more diverse talent into construction. Shift patterns, flexible working, mechanisation and higher levels of automation all facilitate diversification of the workforce.

Improved working methods and safety are critical to the industry and enhanced through clear, systemised approaches inherent to OSM. In some cases, as with MACE's 'jump factory' approach, these methods can also be integrated in site-based factories[20], challenging the notion of factory location.

Enhancing social value in the built environment

There is a misconception that good architecture cannot be achieved via OSM. Successful OSM requires a change in mindset towards the capabilities of a digitally integrated supply chain and advanced manufacturing techniques to encourage mass customisation rather than over-standardised design.

Housing projects using volumetric units, such as the Y:Cube by Rogers Stirk Harbour + Partners[21], provide a transition between sheltered and market housing, and 'meanwhile' projects, such as the modified shipping containers at Pop Brixton by Turner Works[22], can provide important opportunities for small business and start-ups, even if temporarily.

Making buildings better

This is normally the focus for most structural engineers, using OSM to help optimise resource use and lower waste and transport impacts.

Box 2. D Frame: standardised and disassemblable precast concrete

↗FIGURE 2:
D Frame precast framing solution

© LAING O'ROURKE CONSTRUCTION

Laing O'Rourke Construction has developed a precast framing solution that does not require a screed topping to provide diaphragm action and can be disassembled by unbolting connections as a reverse of the erection process.

Embedded pipes in the panels allow for integrated heating and cooling. Precasting methods have been developed to allow the use of concrete mixes with very low embodied carbon, using alkali-activated cementitious material (AACM) cements such as Cemfree, with high slag content to significantly reduce material carbon impacts compared with traditional precast concrete.

TABLE 3: Levels of manufacturing enhancement

Approach	Description
Made to stock (MTS)	Where standard components are produced in advance of consumers buying them off the shelf, e.g. standard door, lintel, or catalogue systems
Assembled to stock (ATS)	Products that have set designs and established standards but that can be customised as long as the relationship of elements to one another is maintained, e.g. CLT panels
Made to order (MTO)	Non-standard customisable products often with longer lead-in times that are then brought to site, e.g. custom plant sub-assemblies
Engineered to order (ETO)	Fully bespoke system using a non-DfMA approach with little or no standardisation e.g. bespoke facade elements.

Box 3. HeimdalsPorten: using bio-based materials

HeimdalsPorten is a modular residential project in Trondheim, Norway comprising two seven-storey and two eight-storey towers. Each tower is constructed with volumetric units of sizes approx. 4.2m wide × 3.5m high × 10m long, arranged around a central reinforced concrete service/stair core and connected with a new bespoke connection.

Each module was optimised in a mix of solid C24 timber sections, and glulam and LVL.

The bespoke modules were designed by timber specialist Ergodomus and manufactured in Poland by Unihouse[18].

Modules were transported by sea before subsequent assembly on site in about 10 days per tower.

FIGURE 3: HeimdalsPorten residential project, Trondheim, Norway

© UNIHOUSE

Design with standardised systems, not just to standards

To unlock these benefits, there is a need for standardisation of requirements and specification in order pull pre-manufactured solutions through the supply chain using DfMA methods.

There are various levels of customisation that can be explained using descriptions of types of manufacturing[23,24] and their associated level of enhancement **(Table 3)**.

Engineers therefore should try and work within the constraints of a standardised system, but balance this with a view on whether material use and embodied carbon is optimised using stock items or standard systems. This can be reviewed for each project against material use benchmarks such as those suggested in the RIBA 2030 Climate Challenge[25].

Reduce waste in delivery

Material and transport emissions can be substantially reduced through the use of OSM[2,26] and those benefits should be included in embodied carbon assessments. It is suggested that lifecycle modules A4 and A5 are based on the values in **Table 4** when following the calculation method used in both *A brief guide to calculating embodied carbon*[27] and the Institution's forthcoming guide, *How to count embodied carbon*.

While waste and transport movement reductions are important, they are of the order of 10% of overall material impacts to practical completion, and therefore relatively small compared with the material manufacturing impact itself. Waste reduction therefore has to be balanced against the impacts of designing for loads induced during deployment, system assembly detailing that can duplicate both floors and wall elements, and ensuring in-service adaptability, and end-of-life reuse in a whole-life approach.

This whole-life approach has been

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FIGURE 4: Orca light-gauge steel frame

© ORCA LGS SOLUTIONS

Box 4. Orca light-gauge steel frame: standardised components and in-use adaptability

The ORCA light-gauge steel frame is 100% recyclable and has been designed with pre-determined adaptability for future use.

Simple allowances can be made which allow additional floors or extensions to be added to the existing LGS frame interface, without the owner having to make changes to the existing structural elements.

On the high-quality housing development illustrated here, the superstructure build was completed in just 16 days.

adopted in thinking around steel-framed system use, such as by Orca housing **(Box 4)**[28].

Delivering better financial returns

When incorporated well from the start of projects, OSM can produce significant savings in costs and programme, better cash flows, and a reduction in defects and hence re-work compared with traditional construction.

By stabilising the flow and type of work, it should also allow better payment practices.

Through product standardisation and system optimisation, it should also be possible to start targeting savings in embodied carbon at scale, which will likely become linked to carbon pricing mechanisms in the future to more accurately represent the true costs of materials.

Conclusions

OSM can have major benefits over traditional construction when assessed across conventional metrics of cost, quality and time. These are necessary but not sufficient in the face of the current climate emergency, which calls for a different, more radical and systems-based approach.

This paper has set out actions based on the five-capitals model for sustainability to show how OSM might be refocused for the benefit of natural, human and social value, not just the productivity and economy that dominate current thinking.

It is hoped the examples show how various OSM approaches can be adopted, the benefits they bring, and will encourage others to develop metrics

TABLE 4: Suggested construction-stage values to be used in embodied carbon assessments

	Potential benefit[23]	Typical values compared with traditional	Suggested working basis for embodied carbon assessment
Transport (module A4)	Up to 60%	20% net reduction	Same as typical / km
Energy on site (A5a)	Up to 80%	30% net reduction	500kgCO_2e / £100 000
Waste (A5w)	Up to 90%	1–2% by volume	DWF = 0.010
Re-work (A5w)	Up to 80%		Exclude from A5w

and methods for regenerative systems cultures as those ideas become more understood and accepted.

While it would be facile to suggest that it is possible to somehow manufacture your way out of a crisis, what we hope has been shown is that we stand a far greater chance of responding to the climate challenges we face using OSM than traditional forms of delivery.

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FURTHER READING

The following suggested reading provides additional insight on OSM history and methods:

Buildoffsite website (www.buildoffsite.com)

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