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1 **Digitally Enabled Modular Construction for Promoting Modular Components Reuse: A UK View**

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11

12 **Abstract**

13 The UK construction sector is facing multiple challenges associated with low productivity, unreliable
14 project delivery, poor performance, skilled labour shortages, and resource inefficiency. Modular
15 construction has been increasingly promoted by the UK government and industry to address those
16 challenges, and improve efficiency and productivity in the construction sector. While modular
17 construction can help deliver sustainability credentials in the sector by improving resource efficiency
18 at all stages of the construction process upstream, i.e. at the design, manufacture and construction, it
19 appears to be divorced from the construction stages occurring downstream (i.e. disassembly and end-
20 of-life management). This could shift resource inefficiency elsewhere in the system, creating future
21 problems for the sector to deal with. In this article we provide an overview of the current state of
22 modular construction and digitalisation in the UK as promoted by the government and industry, and
23 outline key obstacles in modular construction's mainstream use. We argue that there is a real
24 opportunity in using modular construction to promoting resource efficiency and productivity in the
25 construction sector as a whole, via integrating innovation upstream and downstream of the construction
26 system. This could be achieved via a digitally enabled modular construction, whereby smart
27 technologies are combined with modular construction, to promote the maintenance, recovery and reuse
28 of modular components and reduce waste generation in the sector. For this to take precedence we need
29 to think of the 'end' right at the beginning of the design stage. Integrating smart technologies in modular
30 components can operationalise the collection and storage of components' lifecycle information and
31 build the capability needed to support such activities via an improved collaboration between all
32 stakeholders involved in the construction value chain.

33

1 **Keywords:** modular construction; RFID-BIM; resource efficiency; sustainability; digitalisation; reuse

2 **1. Introduction**

3 The UK construction sector is currently facing multiple challenges associated with low productivity,
4 unreliable project delivery, poor performance, aging workforce, skilled labour shortages, lack of
5 lifecycle information/ data management and performance transparency, and an ever increasing need to
6 reduce the sector's environmental impact [1-4]. The latter is particularly important given that
7 construction, demolition and excavation activities account for 59% of all solid waste generated in the
8 UK [5]. To help the construction sector deal with these challenges the UK government has pledged to
9 provide a multi-million pound investment in technological improvements and innovation in the
10 construction sector [6].

11 Investments in technological improvement and innovation in the construction sector have paved the
12 way towards uptake of modern techniques for construction, signifying a departure from over-reliance
13 on traditional linear design and procurement relationships [7]. New construction techniques that are
14 gradually being promoted in the UK, include: design for deconstruction (DfD), design for reuse (DfR),
15 design for manufacture and assembly (DfMA)) [8]. Of these techniques, DfMA has gained momentum
16 as a response to some of the construction industry's challenges [9]. It can bring higher quality and
17 precision in the manufacturing stage, better quality control, speedier construction and installation
18 compared to traditional methods, reduced costs and improved resource efficiency [7, 10-16]. For
19 example, around 35% to 45% steel savings can be achieved when the DfMA technique is used [17].
20 The main principle of DfMA is the pre-fabrication of volumetric or three-dimensional elements of a
21 building (e.g. rooms, corridors, or even complete small buildings) rather than prefabricated mechanical
22 systems, kitchen/bathroom pods or wall assemblies, that are manufactured off-site and are then
23 assembled together on-site. It also refers to the prefabrication of structural components (e.g. columns,
24 floor slabs, beams, flat panelled walls) off-site and their assembly at the final building site [7, 9-11, 13].
25 This form of off-site manufacture for construction (OSM), i.e. the manufacture of pre-engineered
26 building components and units that are delivered and assembled on-site, is often called prefabricated or
27 modular construction. It must be noted, that there is another form of modular construction such as
28 shipping container (steel) manufacture, but this will not be discussed further in this article.

29 The terms prefabricated and modular are often used interchangeably in the literature, but it must be
30 clarified that modular construction is one type of prefabricated construction. In the UK, there are four
31 main prefabricated construction methods: i) panelised units constructed to be assembled in on-site; ii)
32 volumetric construction to produce 3D modular units; iii) hybrid techniques of panelised construction
33 in conjunction with volumetric construction; and iv) other methods of floor or roof cassettes, pre-cast
34 concrete foundation assemblies, pre-formed wiring looms, etc. These methods employ precast concrete,
35 steel, timber, or hybrid material-based construction (e.g. combination of precast and in-situ concrete).

1 The term ‘modular construction’ has persistently been used in the global literature to refer to off-site
2 manufacture of prefabricated building components and units assembled together on-site, and therefore,
3 we adapted this term throughout the article.

4 The concept of modular construction has been gaining traction since the 1950’s, and in 1998 enthusiasts
5 claimed that the quality, speed and cost savings achieved with the OSM of modular components could
6 offer irresistible benefits to the building industry [18]; e.g., helping to deal with increasing labour costs
7 and the demand for sustainable development [19]. In 2016, the use of modular construction had a share
8 of less than 5% of the global construction market. Europe was an important market of modular
9 components with a share of 15.1% [20], of which a large proportion is represented by Scandinavia
10 where around 80% of new houses are manufactured off-site [20]. The largest market share of modular
11 components is held by the Asia-Pacific region (46.3%), followed by North America (27.6%), due to
12 consumer preference for green buildings and sustained investments in commercial real estate [20]. The
13 share of offsite modular housing construction in the UK is around 5%-7% [21, 22], equating to project
14 financial savings of over 7% against traditional methods of construction [23].

15 Modular construction has been practised in the UK in various forms since the eleventh century, with its
16 use being expanded considerably in the immediate post-war period when the replacement of housing
17 was in great demand [24-27]. During the period 1940-1060 the use of prefabricated elements were
18 gaining popularity in buildings and in high rise flats construction [28]. However, low quality design
19 and failures in the performance of such systems in the 1970s (following the 22-storey prefabricated
20 Ronan Point block collapse in 1968 in East London) questioned the durability and structural integrity
21 of prefabricated buildings and created negative public perception [28, 29], which coupled with the
22 pervasion and persistence of the ‘on-site’ trades (masons, bricklayers, plasterers etc.) have reduced
23 preference to prefabricated construction [24]. According to Hashemi (2013) in the 20th century there
24 was around one million prefabricated homes built in the UK [28]. In recent years the government’s
25 commitment to improve resource efficiency and innovation in the construction sector, alongside efforts
26 to alleviate the housing, schools, and offices shortage, has re-introduced the concept of modular
27 construction. Around 15,000 modular homes are now constructed in the UK each year, and another
28 100,000 modular homes are in the pipeline [13]. Modular construction benefits include ease of
29 constructability, quality and time of construction, capacity to cope with labour shortage, and safe work
30 environments, and particularly, the substantial waste reduction and resource efficiency achieved by the
31 controlled manufacture and construction stages (upstream of the construction system) [14, 30].

32 While the UK government and industry have amplified efforts to communicate the potential of modular
33 construction to bring about benefits upstream [26, 31, 32], the usefulness of this method downstream
34 of the system (i.e. at the operational and end-of-life (EoL) stage of buildings), particularly via the
35 disassembly of construction components and reuse in consecutive structure lifecycles has received
36 comparatively little attention. Our proposition is that modular construction is an exemplary way of

1 connecting upstream and downstream construction stages, and thus a means to actively apply
2 sustainability principles in the construction sector. In this article we aim to provide an overview of the
3 advances made in the UK towards improving the productivity in the construction sector via modular
4 construction and digitalisation, and to rationalise the opportunity missed in adopting a whole systems
5 approach for improving the sector's sustainability performance and resource efficiency. To achieve that
6 we first explore the uptake of modular construction in the UK as promoted by the UK government and
7 industry, and organize the information to show where efforts are placed and outline some of the key
8 obstacles in taking up modular construction in the UK (Section 2). We then provide the evidence to
9 support the hypothesis that a digitally enabled modular construction model has the potential to promote
10 sustainability across the entire construction chain. To date digital technologies have been increasingly
11 promoted for improving resource efficiency upstream but their implementation for the end-of-life
12 management of components has been ignored. The rise of the digital economy offers an opportunity to
13 bring business transformation in the construction sector and promote a new way of doing things;
14 effectively enabling transformative change in the system as a whole (Section 3). This can unlock
15 benefits to the society and create impact for the UK government and industry through enhanced
16 productivity, employment, skills development, income distribution, and environmental protection.
17 Finally, conclusions are drawn and avenues for further research are suggested in Section 4.

18

19 **2. The Future of Modular Construction in the UK**

20 The purpose of this part of the study is to investigate the UK government's position on modular
21 construction, and the way existing or planned changes to policies could increase or diminish innovation
22 and sustainability in the sector. We analysed a number of reports and other documents published by the
23 UK government and industry that describe the ambitions, plans and policies that aim to transform the
24 construction sector. We then outline the progress made in taking up modular construction in the UK
25 drawing upon the literature. Through this analysis we move towards an understanding of what the future
26 may hold for the construction sector, and the degree of innovation we are likely to see.

27 ***2.1. Ambitions, Plans and Policies to Transform the Construction Sector***

28 Achieving efficiency, productivity and sustainability in the way resources are used in the UK economy
29 are key drivers shaping the government's political agenda [33], and construction sector is one of the
30 five key areas¹ identified by the government for improving resource efficiency [34]. It is also one of the
31 sectors represented by the Business in the Community 'Waste to Wealth' commitment to improve the
32 productivity of resources and redesign the way resources are used [35]. The 'Waste to Wealth'
33 Commitment is a programme that supports businesses to define individual and collaborative action

¹ The rest of the five key areas for improving resource efficiency are: chemicals, food, metals and textiles.

1 plans by identifying challenges and innovative solutions within and across sectors [35]. In the
2 construction sector not much has been reported as of yet, but progress in promoting the better
3 management of resources is suggested to be underway [17]. This progress will build on the efforts
4 achieved by the WRAP's Halving Waste to Landfill commitment that has diverted five million tonnes
5 of construction, demolition and excavation waste per year from landfill, saving £400 million annually
6 [34].

7 At the Autumn Budget 2017 the government announced an investment of £170 million to support
8 innovation and skills in the industry via a platform approach to design for manufacture and assembly,
9 called "P-DfMA" [36]. The P-DfMA was developed to support off-site construction and build on the
10 progress already made by a number of sectors that use offsite construction [36]. Since then, assets such
11 as schools, hospitals, and prisons have been constructed using modular construction methods, giving
12 suppliers confidence to expand into the market while supporting the delivery of high quality, energy
13 efficient buildings [7, 37]. Yet a number of barriers such as lack of integration across the construction
14 supply chain, lack of demand for modular structures, the risk averse culture nurtured by traditional
15 construction, and skills shortages [38], have stalled progress and the government has sought to tackle
16 those barriers by coming up with yet another set of ambitions and plans.

17 In the Accelerated Construction Programme, administered through the Homes and Communities
18 Agency in England, and the Home Builders' Fund, the government has promoted the uptake of modular
19 construction as the way forward both for boosting productivity in the construction sector and meeting
20 housing demand [37]. They supported this ambition via a £450 million grant programme for local
21 authorities to unlock sites for housing delivery and made it a condition of funding for a proportion of
22 new structures to be built via modular construction. Also, in 2018 the Small Sites Fund was launched
23 giving £630 million grant funding to support and proliferate smaller building firms, which in 2017 were
24 estimated to number only 2,500 (building 12% of new homes), 79% lower than reported in 1988 [39].
25 According to the Strategic Plan 2018/19 - 2022/23 published by Homes England the drop in smaller
26 building firm's numbers was suggested as a reason for stalling competition and innovation in the sector.
27 As a result they have committed to support smaller builders, in order to create the stimulus for speeding
28 up innovation in the construction sector via the promotion of modern construction methods [39].

29 Homes England suggested that the uptake and development of innovative and modern methods of
30 construction alongside developments such as digitalisation in the design and construction processes,
31 have the potential to transform the construction processes; building on Level 2 Building Information
32 Modelling (BIM) programme that was designed to operationalise this integration using BIM technology
33 mandated in the 2011 Government Construction Strategy [40], and later embraced by Construction
34 2025 [31] and the Construction Strategy 2016-20 [41]. BIM has the ability to digitally represent the
35 physical and functional characteristics of a built asset, and to enable the coordination of information
36 about the design, construction, and handover to operation/maintenance of that asset [42, 43]. Homes

1 England suggested that the integration of modular construction and digitalisation can be a vital measure
2 for adapting to the changing environment, which demands better management of resources and assets,
3 and higher productivity in the sector [39]. Similar views were endorsed by the construction industry
4 that called for investment in digitalisation and new skills development to break barriers and change
5 traditional construction norms [7, 9]. Both industry and government suggested that these changes could
6 only be made via a range of interventions, e.g., making modular construction the new norm in building
7 lease agreements, making finance provisions for modular construction and digitalisation to developers
8 [13], and building the skills of the future workforce, also supported by the government's Industrial
9 Strategy Construction Sector Deal [44].

10 The Construction Sector Deal, which builds on the Construction 2025 [31] and the Farmer Review [1]
11 published in 2013 and 2016 respectively, recognises the need for understanding the symptoms of, and
12 devising solutions for addressing, the skills shortage, training and data transparency and interoperability
13 between stakeholders in the construction supply chain. The Construction Sector Deal seeks to optimise
14 the performance of the construction sector, and enable its transformation via a joint investment of up
15 to £420 million by the industry and Government to accelerate progress in modern methods of
16 construction and digital technologies [44]. The focus on transforming construction involves the
17 development of off-site manufacturing of building components, and the use of digital technologies: a)
18 for supporting the development of an integrated supply chain and b) for improving the whole life
19 management of assets, with an opportunity to minimise waste upstream and increase productivity and
20 efficiency in the sector. Likewise, the Infrastructure and Projects Authority (IPA) in their latest report
21 have stressed that merging modern methods of construction with smart technologies can be an effective
22 way to deal with the failures in the system.

23 The IPA committed to build on the use of best practices in their projects via their Transforming
24 Infrastructure Performance (TIP) plan. This ten-year plan seeks to improve and increase productivity in
25 the design, build and operational stages of assets, in an effort to tackle systemic issues that slow down
26 the take up of innovative and transformative solutions in the construction section, and help the UK
27 Government meet the targets set in the Industrial Strategy. Most importantly TIP places a focus on the
28 whole life performance of assets via the use of new technologies, as a way to improve productivity in
29 delivery and maximise the overall benefits of infrastructure [45]. To reinforce these ambitions the Green
30 Construction Board developed guidance for increasing resource efficiency and reducing waste in the
31 sector, through the adoption of circular economy principles and the development of an ambitious
32 roadmap by 2020 setting out how this can be achieved [34]. Yet these ambitions are largely focused on
33 upstream processes, with little (if any) reference on downstream stages in the construction value chain.

34 The strategies and plans set out by the government and industry recognise the existence of key barriers
35 in transforming the construction sector, and signal strongly towards the adoption of innovative
36 techniques and technologies for driving change. The shift might be occurring at a slow pace, but key

1 objectives such as the UK Government's commitment to alleviate the housing shortage and deliver one
2 million homes by the end of 2020, as well as the joint government-industry partnership to reverse
3 construction sector's underperformance [13], will drive substantial changes in the short- to medium-
4 term. The Digital Built Britain programme, designed to promote effectiveness and efficiency in the
5 entire life-cycle of built via harnessing the potential of new technologies such as BIM and advanced
6 data analytics [43, 46], reinforces this transition. Up until now, not much has been reported in regards
7 to using modular construction in connecting upstream with downstream practices. While the Building
8 Research Establishment (BRE), the Green Construction Board and others have increasingly placed
9 emphasis on understanding the EoL fate of buildings and their components, to determine key demolition
10 products and make recommendations for their reuse (on and off-site), recycling or final disposal, these
11 efforts appear to be divorced from government ambitions and plans that largely focus on the upstream
12 parts of the construction value chain.

13 ***2.2. Working towards Modular Construction Uptake***

14 The UK Government and industry agree that the take up of modular construction is currently being held
15 back due to a number of challenges, including fragmentation in the supply chain and skills capacity [7,
16 36, 37, 39, 44]. Yet there are further technical, economic, political and social obstacles to the uptake of
17 modular construction.

18 In traditional methods of construction, where each stage of construction takes place on site, it is common
19 for the design to overlap with construction, allowing minor modifications to the design of a building to
20 be made during the construction phase [47]. The lack of early and firm decisions at the design stage
21 provides freedom and flexibility to the client to make changes in their building [48]. In modular
22 construction, this freedom is not readily available. Changes in the factory can be challenging as they
23 can disrupt the pre-fabrication process, lead to waste generation, inefficiency and high cost of
24 manufacture; affecting all parties involved in the process [18]. Encouraging clients and their teams to
25 complete their decisions early on the design process can significantly improve the popularity of modular
26 construction, as well as the resource, time and cost efficiency levels during construction [48]. Incentives
27 to promote early decisions at the design stage include shorter construction time, lower costs of
28 construction (as a result of improved site management and efficient use of labour) [18], and greater
29 certainty on project delivery [13].

30 Another obstacle is the perception that modular construction is a cheap, ugly, and poor quality
31 alternative to traditional construction processes [49]. The stigma of poor quality and cheapness that
32 developed after the post-war era highlights that changes in construction system need to go beyond
33 technical and economic realms in order to re-establish the perception of modular construction as a high-
34 quality process among the general public. As a result, modular construction was rebranded as Modern
35 Methods of Construction (MMC) in order to break down the misperceptions towards it. With society

1 becoming increasingly aware of the need to promote sustainability, industry and the government have
2 an opportunity to alter past perceptions, and turn society in favour of this modern, sustainable method
3 of construction. One way to achieve this is by showcasing the aesthetic quality and precision achieved
4 via the modular method of construction, the faster construction time (around 20-50% faster), and
5 affordability (around 20% cheaper) compared to traditional methods of construction [49]. Strict quality
6 assurance procedures can be more easily achieved in off-site manufacturing, increasing the durability
7 and reliability of the structure and reducing the risk of defects and delays for the client [10, 18]. In
8 addition, modular buildings may be stronger than conventional ones because each module is engineered
9 to withstand loads independently [15], and offer better airtightness and thermal performance [18].
10 Moreover, a controlled factory environment reduces site disruption, noise, dust, and risks related to
11 occupational safety and health [18], whilst promoting a reduction in carbon emissions and energy usage
12 at the on-site assembly stage (i.e. due to fewer vehicle movements to site, improved productivity
13 performance, and significantly less material waste compared to site-based construction) [13].

14 Changing the public's perception and mind-set in regards to modular buildings would help this method
15 of construction to gain traction in the future. This can enable changes to traditional contracting roles,
16 and empower both small and large builders to build up the capabilities, skills and knowledge needed to
17 adapt to the new market demands [48] and offer a new, modern approach to construction that can attract,
18 retain and inspire a new generation of workers [13]. In the UK where labour shortages and large-scale
19 unmet demand for housing intersect, this is particularly important for driving change and establishing
20 a market for modular construction [49]. However, demand for on-site construction will still be needed,
21 as different projects may have different off-site and on-site construction demands. This is likely to create
22 some disruption in the market in regards to the percentage of offsite construction that is considered
23 appropriate for different projects.

24 Establishing a market for modular construction may also help to overcome barriers related to
25 procurement. At present, pre-fabricated components are made by a small number of suppliers, which
26 means that if a particular supplier fails to deliver, this creates risks in the project delivery time, budget
27 and quality. In addition, most UK suppliers use simple traditional forms of construction, largely because
28 the prefabricated component industry is still stifled, and as such they are reluctant to invest heavily in
29 automated fabrication systems without feeling secure for their return on investment [18]. A modular
30 construction market growth would increase demand, create competition and bring up the pace for
31 innovation and multiple forms of pre-fabrication.

32 Finally, wide-scale use of sub-contracting and tiered transactional interfaces makes the construction
33 supply chain highly fragmented, leading to poor project coordination and management, increased
34 resistance to change and fewer opportunities to drive out waste or reduce cost [48, 50, 51]. This is
35 stalling progress towards innovation and thus preventing efforts to promote sustainability in the
36 construction sector [1]. As suggested in our previous work, understanding the performance of modular

1 components across their full lifecycle can support informed decision-making in the construction sector,
2 and improve the ability of stakeholders involved in construction projects to make improvements in
3 modular buildings lifecycle management via repair, recovery and reuse [52]. This knowledge base can
4 be built by the use of smart technologies, which in turn can open up new avenues for stakeholders to
5 leverage multi-various benefits from their activities in the construction sector. The next section delves
6 into exploring and discussing the attributes of employing digital technologies in the construction sector.

7 8 **3. Promoting a Digitally Enabled Modular Construction for Connecting Upstream with** 9 **Downstream Parts of the Construction Supply Chain**

10 In the spirit of moving forward, the UK Government and construction industry have started to develop
11 an implementation strategy for aligning policy objectives with industry efforts to promote innovation
12 and efficiency in the construction sector. These efforts have placed a lot of emphasis in tackling the
13 obstacles that currently hold back the uptake of modular construction, and in promoting digitalisation
14 as a way to monitor and assess infrastructure use and performance, and allow for improvements in the
15 design, construction and operation/maintenance practices [43]. However, little attention has been given
16 to the fact that a major innovation in modular construction is the ability of modular structures to be
17 repaired when damaged, and dismantled (deconstructed) when no longer needed. This can effectively
18 maintain modular components' (and assets') functionality— rather than simply recovering the materials
19 from which they are made. It can also recapture the value of modular components by retaining them in
20 the system for longer when feasible, thereby meeting the principles of the circular economy.

21 At present, the recovery (as in removal) and reuse of prefabricated components is not actively promoted
22 for achieving resource efficiency downstream of the system. The reason is twofold: 1) due to the largely
23 pervasive linear way of managing our resources that has placed little emphasis on recovering value at
24 the end of structures service (but not functional) life in the past, and which is still practiced today; and
25 2) the lack of confidence on the quality of structural modular components and their remaining
26 functionality which demand both money and time-investment (for quality control, etc.). As reported in
27 the study of Whittaker et al. (2021) additional challenges related with the recovery and reuse modular
28 components such as beams, columns, slabs, include: compliance with existing building regulations;
29 availability of mechanical connections to facilitate assembly and disassembly; number of modular
30 components used; transportation, cost and time; lifespan and repairability potential; and traceability
31 [53].

32 In regards to the latter, emerging information technologies that enable data capture and management
33 have been increasingly recognised on their ability to enable the planning of new infrastructure more
34 effectively, building it at lower cost, and operating and maintaining it more efficiently [42]. In light of
35 this information, the UK government and construction industry have been increasingly promoting

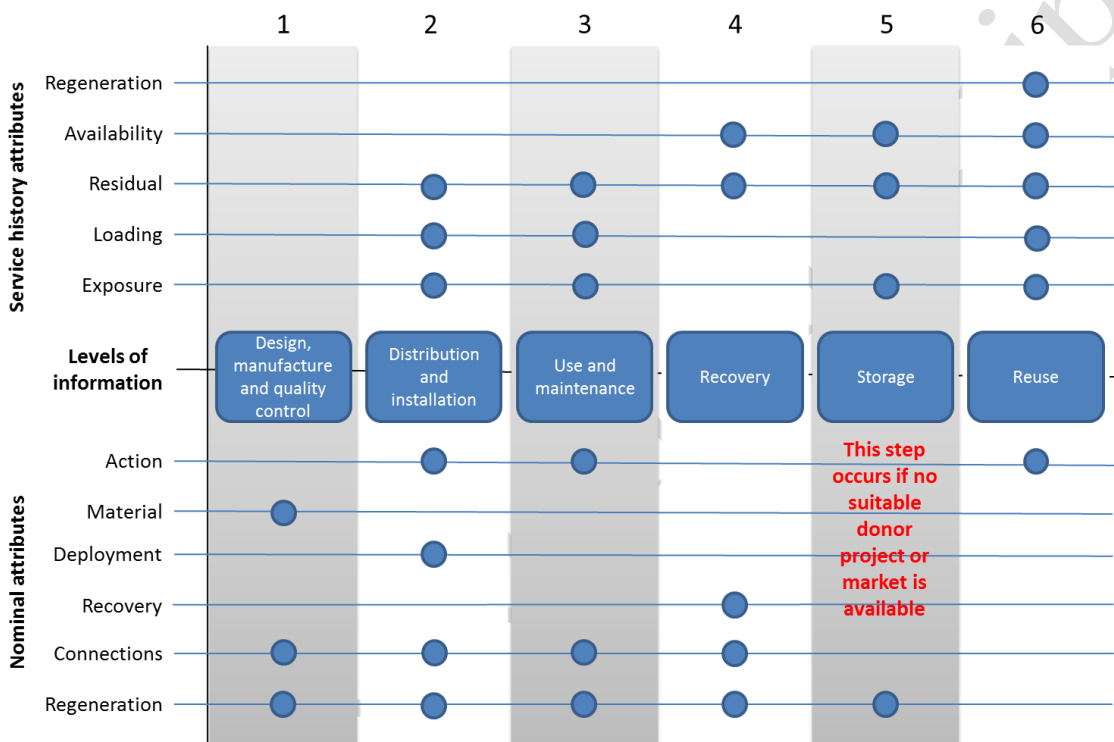
1 BIM's use to support the coordination of multi-disciplinary project teams to design and fabricate
2 buildings in a more efficient and effective manner compared to traditional methods of construction.
3 BIM can utilise information (e.g. building geometry, geographic information, quantities and properties
4 of the building components and the materials used) to design a structure and virtually represent the
5 components that will be used at the construction stage, and their attributes (e.g. characteristics,
6 properties, functionalities). This tool facilitates the communication and collaboration between all
7 stakeholders' involved in a construction project [54]. This co-operative use of shared information
8 models has realised resource efficiency in the construction stage (upstream) and significantly
9 contributed to construction cost savings [43, 55].

10 BIM is now widely adopted by the UK construction industry, because it provides construction speed,
11 cost savings, efficiency, and safety [19, 43, 56]. However, its use in promoting the deconstruction and
12 reuse of modular construction components has been significantly less prominent [57, 58]. This is owing
13 to the fact that to a large degree, only digital *nominal attributes (static and essential)* of construction
14 components are readily available via BIM, creating an information gap when components reach the end
15 of their lifecycle [42, 59]. Detailed tracking and storing of modular components' lifecycle information
16 is required to generate the evidence needed to support the sound reclamation and reuse of modular
17 components [42]. This evidence takes the form of attributes related to modular components performance
18 i.e. *service history attributes (dynamic and desirable)*. These attributes provide insight into the changes
19 occurred in the condition, performance, and ownership of modular components during their life cycle.
20 The collection of these (*service history*) attributes is not currently routinely practiced (except for high-
21 profile or heritage infrastructure such as suspension bridges or historic buildings) yet the use of radio
22 frequency identification (RFID) technology is gaining traction as a useful means to enable *service*
23 *history* attributes collection in everyday structures. RFID as defined by many studies that have explored,
24 and/or discussed its potential, is "a wireless sensor technology operating based on the transmission of
25 data via radio frequency (RF) signals to and/or from physical 'tags' attached to products and
26 components" [52].

27 RFID with its automatic data collection ability, information storage capability, ease of handling,
28 durability, and affordability, can enable the transmission of valuable information throughout the
29 components' lifecycles. The use of this technology in the construction sector is not new. It has
30 traditionally been used to track and trace construction materials and components, equipment and tools
31 during on-site construction, and even on the track and trace of workforce as a way of increasing the
32 productivity and cost efficiency of construction projects [60-65]. Recently, RFID has gained
33 prominence in the construction research field due to its ability to facilitate the storage and accessibility
34 of data on building components over their entire life-cycle [66-68]. RFID can capture information over
35 long periods of time, creating 'components passports', and enabling the real-time assessment of
36 components' technical properties and quality over time [8]. This seamless transfer of whole-life data,

1 shown in Figure 1, provides the ability to track, access and update information on modular components
 2 properties (e.g., loading history, environmental conditions, and damage or refurbishment events) and
 3 trace their performance over their entire lifecycle; allowing good quality modular components to be
 4 reused in new designs [69-71]. The benefits of RFID do not end here; it also has the capacity to create
 5 a dynamic data repository system that allows the transparent exchange of life-cycle information,
 6 providing insights into the design, installation, performance and recovery, as well as on ownership and
 7 geographical location [42, 50, 72].

8



9

10 **Figure 1.** Nominal and service history attributes captured via RFID-BIM for promoting construction
 11 components reuse.

12

13 The idea of ‘components passports’ is very powerful, because it places thinking about the ‘end’ of the
 14 process right at the very beginning of the construction system. These digital passports provide evidence
 15 on modular components’ performance over time and generate insights into how different conditions,
 16 internal or external, might have affected their functionality and quality [42, 50]. This information can
 17 be logged and archived into BIM databases, allowing good quality modular components to be
 18 successively reused in new designs [42]. Akinade et al. (2017) suggest that BIM can play a key role in
 19 ensuring that all stakeholders are committed and actively involved to making deconstruction related
 20 decisions early at the planning process [57]. This stipulates that BIM could also help to empower and
 21 ensure integration of the RFID passports in modular components right from the design stage. This

1 almost mandates that the design of modular structures should include a plan for recovering and reusing
2 modular components where feasible, and this plan can only become realised via the integrated use of
3 RFID-BIM.

4 An integrated use of RFID-BIM can enable contractors and service providers to access information
5 readily, coordinate their activities and manage their assets more effectively. It can also support them in
6 optimising guidance on how to capture appropriate data more effectively, and approach data limitations.
7 This can raise confidence in asset procurement and management across its entire life cycle, promote the
8 use of DfD, and adapt components to new uses via the use of DfR when assets are no longer needed. In
9 essence, improved data capture and management can facilitate communication and exchange of
10 information on modular components throughout the construction value chain, and can create the space
11 for partnerships to flourish based on data and information capture and sharing. This may open up
12 opportunities for new business paradigms based on information management and data analytics among
13 various stakeholders, creating a platform where architects, contractors, and clients (including building
14 operators and asset management companies). A number of studies have now stressed these potential
15 benefits accrued from the RFID-BIM integration [42, 50, 73]. Ness et al. (2019) have gone a step further
16 to suggest the use of an ICT-enabled cloud-based data platform to log and manage data and support a
17 product-service systems (PSS) relationship between suppliers/providers and users/clients. This can
18 bring productivity improvements in the construction sector, and maximise the recovery of multi-
19 dimensional value (i.e. environmental, economic, social and technical value).

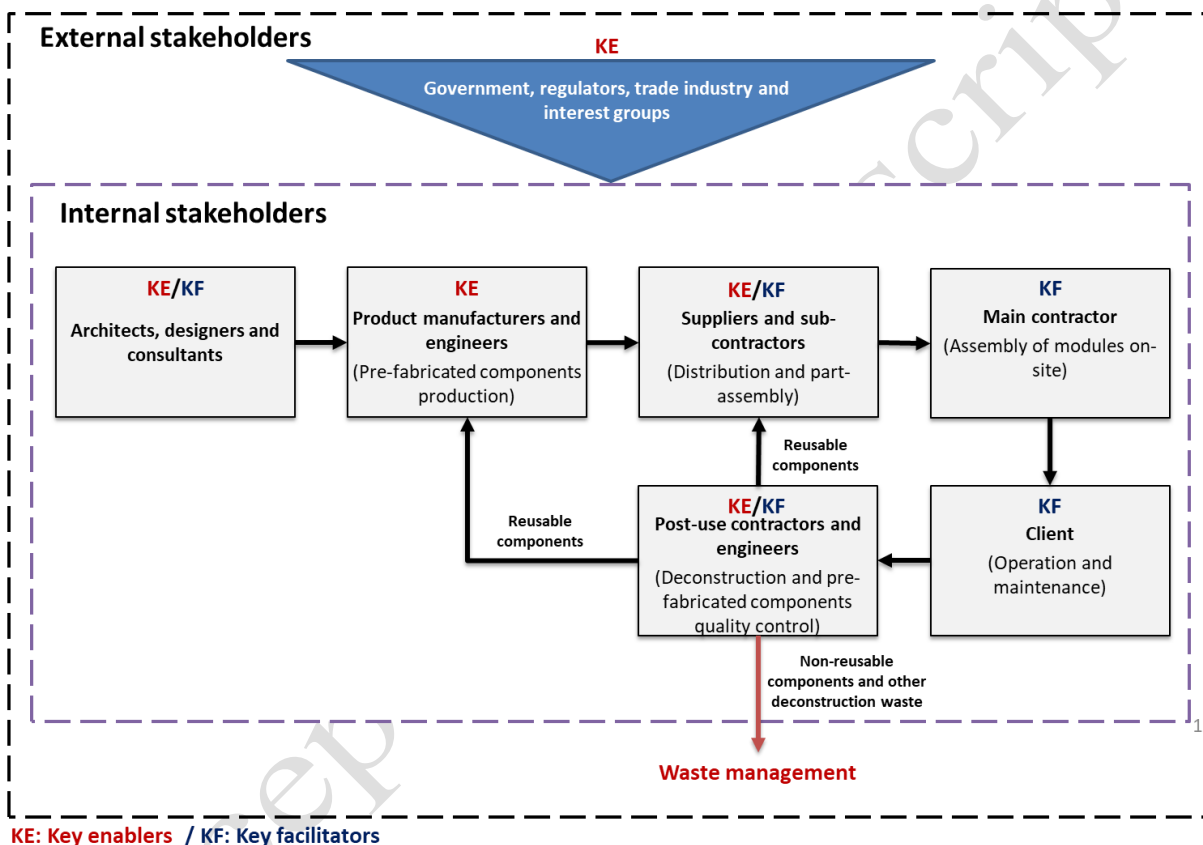
20 Other platforms may take the form of publicly accessible data spaces that all building firms, small or
21 large, can use [50, 57] or it may involve a closed and privately owned platform used by specific
22 companies that operate at large scale. In the latter case manufacturers or third-party firms will be able
23 to fashion new business models based on modular components stewardship, whereby the function
24 provided by modular components – i.e. load resistance – will be provided as a service, but ownership
25 and traceability of components and materials over time will remain with the manufacturers. This could
26 shift the focus from modular components purchase to a service provision capable of fulfilling specific
27 client demands [72, 73].

28 In the long-term, this could promote the implementation of a reverse supply chain system (known as
29 reverse logistics (RL) system), in which the client returns salvaged modular components back to the
30 contractor, supplier or manufacturer. In a reverse supply chain system, companies will be expected – or
31 indeed legally required via implementation of extended producer responsibility (EPR) policies – to take
32 responsibility for their assets and components thereof during their entire life-cycle. This can be an
33 effective strategy in promoting disassembly and reuse over recycling and disposal, in order to minimize
34 EoL management costs [74]. It can facilitate coordination of activities across the sector, harmonise tasks
35 at each stage of construction and among stakeholders, and improve the monitoring of construction
36 components production, use and EoL management. Nevertheless, for a reverse supply chain system to

1 succeed in its quest of enabling resource efficiency in the entire construction value chain, it requires the
 2 collective responsibility of, and communication between all stakeholders in the construction system
 3 [75].

4 Understanding the role of the different stakeholders involved in the construction supply chain system,
 5 i.e. from the transforming of raw materials into finish products (e.g. assets) for use by a client, the
 6 depiction in Figure 2 can be particularly useful. A reverse supply chain begins when the client returns
 7 the product back to the contractor [76].

8



9

10 **Figure 2.** Key construction sector stakeholders (external and internal) platform and their responsibility
 11 in promoting reuse of construction components.

12

13 Briefly, *key enablers* (KEs) are the stakeholders responsible for enabling the seamless transition to
 14 modular construction and digitalisation. They have the power to call for strategic innovative changes in
 15 the construction value chain, and they can also promote modular components reuse by integrating
 16 thinking of the ‘end’ right at the design stage of the construction value chain. KEs can bring changes
 17 via pioneering new designs, reforming regulations and making changes in specifications and standards
 18 (or reforms to existing ones) [32, 77-80]. When it comes to implementing these initiatives and changes,

1 KEs should lead by example making it mandatory for all stakeholders to coordinate their activities and
2 begin transitioning to modern methods of construction and life cycle management of assets. This
3 aptitude can create a thriving environment that will boost competitiveness and increased innovation.
4 Improved information capture and management via modular components passports monitored and
5 controlled either by themselves or by the KFs, can help KEs to understand the legitimacy of modern
6 practices, and break down decision-making and planning that occurs in silos [51]. This will fulfil the
7 vision of digitally enabled modular construction across the entire spectrum of the construction value
8 chain, promoting increased resource efficiency and productivity via an improved and sustainable life
9 cycle use of modular assets.

10 *Key facilitators* (KFs) are the stakeholders responsible for practicing reuse (e.g. specialised technical
11 experts) and retaining data records and/or accessing and assessing modular components properties. To
12 carry out their tasks KFs need to attain the new, crucial skillsets required for the installation and use of
13 smart technologies, and the collection, analysis and management of data effectively throughout the
14 components life cycle. This is fundamental in order to carry out the dismantling (deconstructing) and
15 reuse operations. As assets may have varying service lifecycles that range from 10 to over 50 years, the
16 challenge for KFs is not only to track, trace and archive the appropriate data, but to also preserve them
17 and transfer them through the assets (and modular components) lifecycle. Preserving this information
18 with an appropriate level of transparency, trust and security is fundamental in promoting their reuse
19 [47]. The absence of useful information and data, and/or the lack of trust can result to inefficiencies in
20 the system. Therefore, building the capability to perform a digitally enabled modular construction
21 across the entire sector and be able to respond to technical changes due to technological advances over
22 time is a key prerequisite to achieving the multi-objective optimisation (e.g., whole life cost, energy
23 consumption, safety, health, comfort) of construction processes. The latter is particularly important
24 especially as data capture and storage technologies can become outdated (or even obsolete) at a faster
25 rate than building systems and components, which can generally last for a few decades.

26 The challenge of handling decades' worth of data requires both KEs and KFs to collaborate and
27 coordinate their actions in order to preserve the ability to read data on components life-cycle
28 performance. They will also need to remain ahead of technological advancements and upgrade the
29 digital solutions used across the construction value chain in order to maintain continuity of information
30 access and interoperability, especially as they will become increasingly reliant on data collection,
31 storage, and management in the future. Clearly, KEs will complement and support the activities of KFs
32 via changes in policy instruments needed to ensure that whatever progress has been made in improving
33 resource efficiency and productivity in the sector is maintained over time.

34

35

1 4. Discussion

2 Modular construction and digitalisation are increasingly promoted by the UK government and
3 construction industry as a means to address the inefficiencies in the construction sector and enable its
4 transformation to increase productivity, and improve economic and social outcomes. To date, the focus
5 of the UK Government and industry's ambitions has been largely placed on the upstream parts of the
6 construction system. In our view this is a narrow way of promoting efficiency and sustainability in the
7 construction system. It is narrow in scope and can result in incremental improvements in the
8 construction system. Resource efficiency is not just about doing more with less, but it is about
9 preserving the resources and their embedded value in the system for longer. As a result, modular
10 (prefabricated) construction supported by digitalisation across the full life cycle of infrastructure can
11 optimise efficiency, maximise value (i.e. positive environmental, economic, social and technical
12 impacts) recovery and promote circularity in the sector.

13 At present, reclamation of construction components is limited due to the lack of information and
14 confidence in the ability of reclaimed components to be used in their original form for the same or
15 similar function, and this result to massive amounts of waste. Waste is a sign of system inefficiency.
16 The data generated by smart technologies such as RFID can be extremely useful in the improved
17 management of modular components and structures promoting resource efficiency and sustainability in
18 the construction sector. A digitally enabled modular construction via the integrated use of RFID-BIM
19 that has the potential to connect upstream and downstream parts of the construction system (i.e., EoL
20 management) [42], can be a means to preserving valuable data and fostering communication between
21 key enablers and facilitators in the construction value chain. It can promote interoperability, improve
22 resource efficiency and sustainable asset management in the long-term, maximising value and
23 productivity in the construction sector. In turn, this can stimulate green building design and promote
24 the development of new business opportunities. At present, recovery and reuse of modular components
25 is not a mainstream practice, due to the lack of reuse markets and supply chains; time constraints; and
26 associated costs [81]. However, with government's renewed focus on decarbonising industry [82], and
27 promoting resource efficiency [34], the reuse of reclaimed components may soon become an
28 increasingly attractive practice [83].

29 Innovation is often associated with inherent uncertainty, yet this should not diminish efforts to promote
30 circularity in the construction sector via radical transformations. Some negative outcomes related to
31 service life and datafication issues, trust and security, property rights, competition, commercial and
32 financial arrangements may also occur in the system; an inevitable consequence of using technologies
33 that are not yet well understood and having many stakeholders involved each representing their own
34 interests and values. Further research needs to look into the way these aspects will pan out in the system,
35 and their impacts and trade-offs that are likely to create in the short- to long-term. Generation of pilot
36 studies whereby RFID-BIM is applied to different modular structures including short- and long-lived

1 projects could help us gain an insight into the benefits and side-effects of such projects. These could
2 provide guidance to different target audiences such as manufacturers, policymakers, procurement
3 specialists, contractors, security analysts, etc. to overcome shortcomings and help refine or dismiss such
4 models for promoting efficiency and sustainability in the construction sector.

5 6 **5. Conclusions**

7 As modular construction is being picked up by the construction industry to build affordable and efficient
8 homes, to meet housing demand and promote resource efficiency and productivity in the sector, there
9 is an increased likelihood that EoL considerations may take precedence. The reclamation and reuse of
10 modular components in new designs depends on the successful dialogue and improved collaboration
11 amongst the key enablers and facilitators involved and operating in the construction value chain. In
12 turn, this is tied to the dynamic information capture and management that makes the recovery and reuse
13 of modular components possible. Digitalisation can tackle both these tasks and help provide more
14 clarity and transparency in the activities and processes in the construction value chain and shed light on
15 the stakeholders' interests that drive them, rendering the sustainable EoL management of assets an
16 inevitable causality in the long-term.

17 The use of RFID-BIM may currently be limited, but their strength in promoting interoperability between
18 different stakeholders in the construction value chain while improving project lifecycle management
19 monitoring, makes RFID-BIM particularly attractive in promoting innovation and unlocking multiple
20 technical, environmental, economic, and social benefits. A transition to off-site manufacture and
21 modular construction and digitalisation upstream in the construction system, is likely to roll-out changes
22 downstream of the system, making the digitally enable modular construction a trend, and the EoL
23 management of assets an inevitable causality in the long-term.

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