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

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Abstract

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

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

1. Introduction

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

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

The terms prefabricated and modular are often used interchangeably in the literature, but it must be clarified that modular construction is one type of prefabricated construction. In the UK, there are four main prefabricated construction methods: i) panelised units constructed to be assembled in on-site; ii) volumetric construction to produce 3D modular units; iii) hybrid techniques of panelised construction in conjunction with volumetric construction; and iv) other methods of floor or roof cassettes, pre-cast concrete foundation assemblies, pre-formed wiring looms, etc. These methods employ precast concrete, steel, timber, or hybrid material-based construction (e.g. combination of precast and in-situ concrete). The term 'modular construction' has persistently been used in the global literature to refer to off-site manufacture of prefabricated building components and units assembled together on-site, and therefore, we adapted this term throughout the article.

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

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

While the UK government and industry have amplified efforts to communicate the potential of modular construction to bring about benefits upstream [26, 31, 32], the usefulness of this method downstream of the system (i.e. at the operational and end-of-life (EoL) stage of buildings), particularly via the disassembly of construction components and reuse in consecutive structure lifecycles has received comparatively little attention. Our proposition is that modular construction is an exemplary way of connecting upstream and downstream construction stages, and thus a means to actively apply sustainability principles in the construction sector. In this article we aim to provide an overview of the advances made in the UK towards improving the productivity in the construction sector via modular construction and digitalisation, and to rationalise the opportunity missed in adopting a whole systems approach for improving the sector's sustainability performance and resource efficiency. To achieve that we first explore the uptake of modular construction in the UK as promoted by the UK government and industry, and organize the information to show where efforts are placed and outline some of the key obstacles in taking up modular construction in the UK (Section 2). We then provide the evidence to support the hypothesis that a digitally enabled modular construction model has the potential to promote sustainability across the entire construction chain. To date digital technologies have been increasingly promoted for improving resource efficiency upstream but their implementation for the end-of-life management of components has been ignored. The rise of the digital economy offers an opportunity to bring business transformation in the construction sector and promote a new way of doing things; effectively enabling transformative change in the system as a whole (Section 3). This can unlock benefits to the society and create impact for the UK government and industry through enhanced productivity, employment, skills development, income distribution, and environmental protection. Finally, conclusions are drawn and avenues for further research are suggested in Section 4.

2. The Future of Modular Construction in the UK

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

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

Achieving efficiency, productivity and sustainability in the way resources are used in the UK economy are key drivers shaping the government's political agenda [33], and construction sector is one of the five key areas[1] identified by the government for improving resource efficiency [34]. It is also one of the sectors represented by the Business in the Community 'Waste to Wealth' commitment to improve the productivity of resources and redesign the way resources are used [35]. The 'Waste to Wealth' Commitment is a programme that supports businesses to define individual and collaborative action plans by identifying challenges and innovative solutions within and across sectors [35]. In the

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

construction sector not much has been reported as of yet, but progress in promoting the better management of resources is suggested to be underway [17]. This progress will build on the efforts achieved by the WRAP's Halving Waste to Landfill commitment that has diverted five million tonnes of construction, demolition and excavation waste per year from landfill, saving £400 million annually [34].

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

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

Homes England suggested that the uptake and development of innovative and modern methods of construction alongside developments such as digitalisation in the design and construction processes, have the potential to transform the construction processes; building on Level 2 Building Information Modelling (BIM) programme that was designed to operationalise this integration using BIM technology mandated in the 2011 Government Construction Strategy [40], and later embraced by Construction 2025 [31] and the Construction Strategy 2016-20 [41]. BIM has the ability to digitally represent the physical and functional characteristics of a built asset, and to enable the coordination of information about the design, construction, and handover to operation/maintenance of that asset [42, 43]. Homes England suggested that the integration of modular construction and digitalisation can be a vital measure for adapting to the changing environment, which demands better management of resources and assets, and higher productivity in the sector [39]. Similar views were endorsed by the construction industry that called for investment in digitalisation and new skills development to break barriers and change traditional construction norms [7, 9]. Both industry and government suggested that these changes could only be made via a range of interventions, e.g., making modular construction the new norm in building lease agreements, making finance provisions for modular construction and digitalisation to developers [13], and building the skills of the future workforce, also supported by the government's Industrial Strategy Construction Sector Deal [44].

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

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

The strategies and plans set out by the government and industry recognise the existence of key barriers in transforming the construction sector, and signal strongly towards the adoption of innovative techniques and technologies for driving change. The shift might be occurring at a slow pace, but key objectives such as the UK Government's commitment to alleviate the housing shortage and deliver one million homes by the end of 2020, as well as the joint government-industry partnership to reverse construction sector's underperformance [13], will drive substantial changes in the short- to medium-term. The Digital Built Britain programme , designed to promote effectiveness and efficiency in the entire life-cycle of built via harnessing the potential of new technologies such as BIM and advanced data analytics [43, 46], reinforces this transition. Up until now, not much has been reported in regards to using modular construction in connecting upstream with downstream practices. While the Building Research Establishment (BRE), the Green Construction Board and others have increasingly placed emphasis on understanding the EoL fate of buildings and their components, to determine key demolition products and make recommendations for their reuse (on and off-site), recycling or final disposal, these efforts appear to be divorced from government ambitions and plans that largely focus on the upstream parts of the construction value chain.

2.2. Working towards Modular Construction Uptake

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

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

Another obstacle is the perception that modular construction is a cheap, ugly, and poor quality alternative to traditional construction processes [49]. The stigma of poor quality and cheapness that developed after the post-war era highlights that changes in construction system need to go beyond technical and economic realms in order to re-establish the perception of modular construction as a high-quality process among the general public. As a result, modular construction was rebranded as Modern Methods of Construction (MMC) in order to break down the misperceptions towards it. With society becoming increasingly aware of the need to promote sustainability, industry and the government have an opportunity to alter past perceptions, and turn society in favour of this modern, sustainable method of construction. One way to achieve this is by showcasing the aesthetic quality and precision achieved via the modular method of construction, the faster construction time (around 20-50% faster), and affordability (around 20% cheaper) compared to traditional methods of construction [49]. Strict quality assurance procedures can be more easily achieved in off-site manufacturing, increasing the durability and reliability of the structure and reducing the risk of defects and delays for the client [10, 18]. In addition, modular buildings may be stronger than conventional ones because each module is engineered to withstand loads independently [15], and offer better airtightness and thermal performance [18]. Moreover, a controlled factory environment reduces site disruption, noise, dust, and risks related to occupational safety and health [18], whilst promoting a reduction in carbon emissions and energy usage at the on-site assembly stage (i.e. due to fewer vehicle movements to site, improved productivity performance, and significantly less material waste compared to site-based construction) [13].

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

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

Finally, wide-scale use of sub-contracting and tiered transactional interfaces makes the construction supply chain highly fragmented, leading to poor project coordination and management, increased resistance to change and fewer opportunities to drive out waste or reduce cost [48, 50, 51]. This is stalling progress towards innovation and thus preventing efforts to promote sustainability in the construction sector [1]. As suggested in our previous work, understanding the performance of modular components across their full lifecycle can support informed decision-making in the construction sector, and improve the ability of stakeholders involved in construction projects to make improvements in modular buildings lifecycle management via repair, recovery and reuse [52]. This knowledge base can be built by the use of smart technologies, which in turn can open up new avenues for stakeholders to leverage multi-various benefits from their activities in the construction sector. The next section delves into exploring and discussing the attributes of employing digital technologies in the construction sector.

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

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

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

In regards to the latter, emerging information technologies that enable data capture and management have been increasingly recognised on their ability to enable the planning of new infrastructure more effectively, building it at lower cost, and operating and maintaining it more efficiently [42]. In light of this information, the UK government and construction industry have been increasingly promoting BIM's use to support the coordination of multi-disciplinary project teams to design and fabricate buildings in a more efficient and effective manner compared to traditional methods of construction. BIM can utilise information (e.g. building geometry, geographic information, quantities and properties of the building components and the materials used) to design a structure and virtually represent the components that will be used at the construction stage, and their attributes (e.g. characteristics, properties, functionalities). This tool facilitates the communication and collaboration between all stakeholders' involved in a construction project [54]. This co-operative use of shared information models has realised resource efficiency in the construction stage (upstream) and significantly contributed to construction cost savings [43, 55].

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

RFID with its automatic data collection ability, information storage capability, ease of handling, durability, and affordability, can enable the transmission of valuable information throughout the components' lifecycles. The use of this technology in the construction sector is not new. It has traditionally been used to track and trace construction materials and components, equipment and tools during on-site construction, and even on the track and trace of workforce as a way of increasing the productivity and cost efficiency of construction projects [60-65]. Recently, RFID has gained prominence in the construction research field due to its ability to facilitate the storage and accessibility of data on building components over their entire life-cycle [66-68]. RFID can capture information over long periods of time, creating 'components passports', and enabling the real-time assessment of components' technical properties and quality over time [8]. This seamless transfer of whole-life data, shown in Figure 1, provides the ability to track, access and update information on modular components properties (e.g., loading history, environmental conditions, and damage or refurbishment events) and trace their performance over their entire lifecycle; allowing good quality modular components to be reused in new designs [69-71]. The benefits of RFID do not end here; it also has the capacity to create a dynamic data repository system that allows the transparent exchange of life-cycle information, providing insights into the design, installation, performance and recovery, as well as on ownership and geographical location [42, 50, 72].

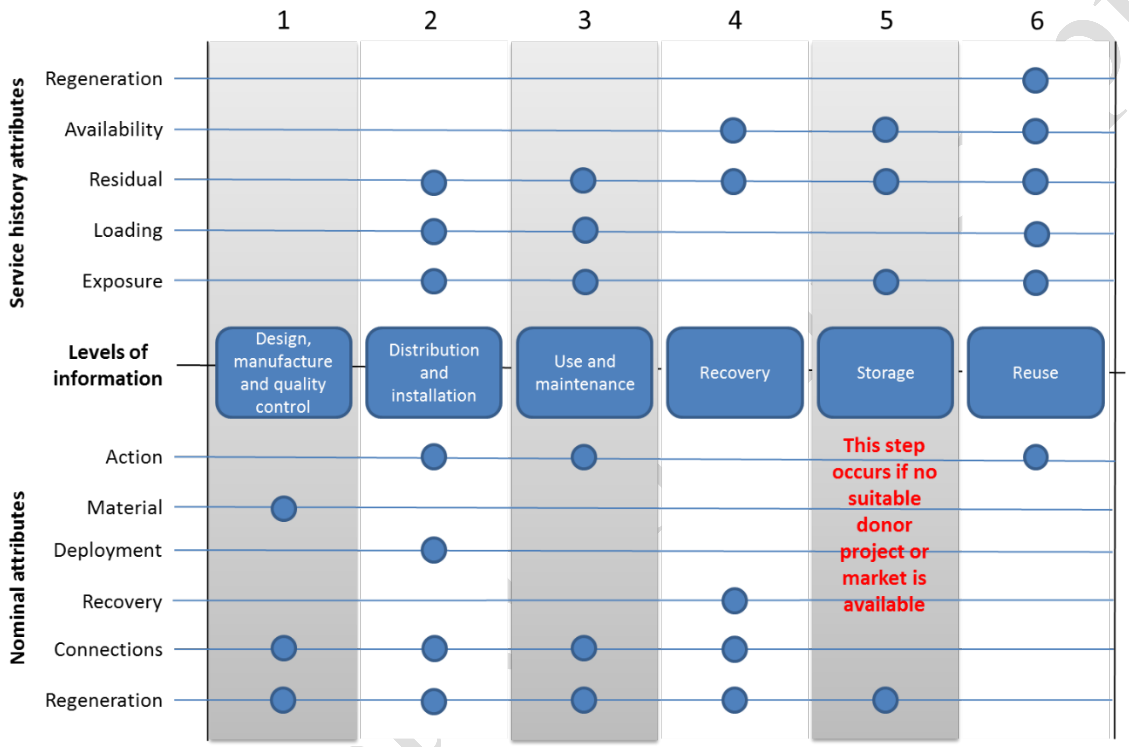

Figure 1. Nominal and service history attributes captured via RFID-BIM for promoting construction components reuse.

The idea of ‘components passports’ is very powerful, because it places thinking about the ‘end’ of the process right at the very beginning of the construction system. These digital passports provide evidence on modular components’ performance over time and generate insights into how different conditions, internal or external, might have affected their functionality and quality [42, 50]. This information can be logged and archived into BIM databases, allowing good quality modular components to be successively reused in new designs [42]. Akinade at el. (2017) suggest that BIM can play a key role in ensuring that all stakeholders are committed and actively involved to making deconstruction related decisions early at the planning process [57]. This stipulates that BIM could also help to empower and ensure integration of the RFID passports in modular components right from the design stage. This almost mandates that the design of modular structures should include a plan for recovering and reusing modular components where feasible, and this plan can only become realised via the integrated use of RFID-BIM.

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

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

In the long-term, this could promote the implementation of a reverse supply chain system (known as reverse logistics (RL) system), in which the client returns salvaged modular components back to the contractor, supplier or manufacturer. In a reverse supply chain system, companies will be expected – or indeed legally required via implementation of extended producer responsibility (EPR) policies – to take responsibility for their assets and components thereof during their entire life-cycle. This can be an effective strategy in promoting disassembly and reuse over recycling and disposal, in order to minimize EoL management costs [74]. It can facilitate coordination of activities across the sector, harmonise tasks at each stage of construction and among stakeholders, and improve the monitoring of construction components production, use and EoL management. Nevertheless, for a reverse supply chain system to succeed in its quest of enabling resource efficiency in the entire construction value chain, it requires the collective responsibility of, and communication between all stakeholders in the construction system [75].

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

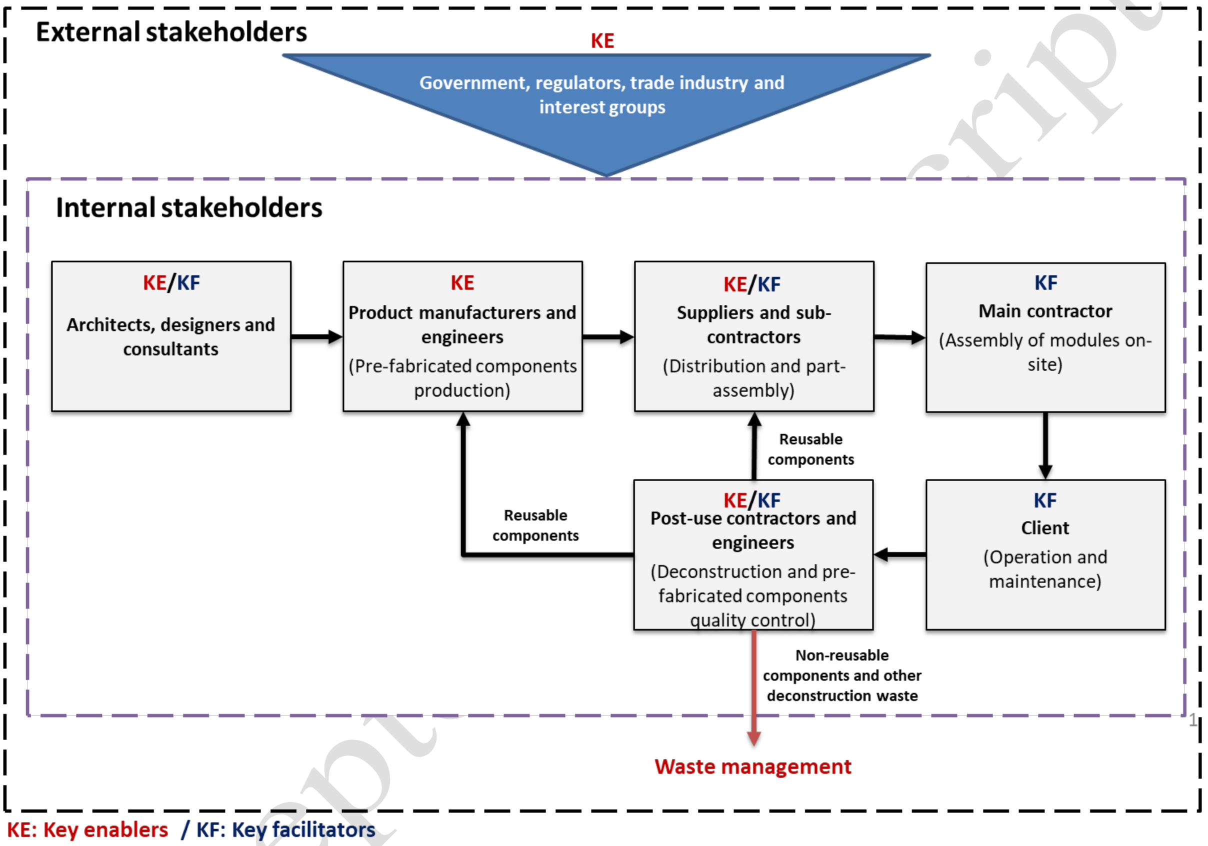

Figure 2. Key construction sector stakeholders (external and internal) platform and their responsibility in promoting reuse of construction components.

Briefly, *key enablers* (KEs) are the stakeholders responsible for enabling the seamless transition to modular construction and digitalisation. They have the power to call for strategic innovative changes in the construction value chain, and they can also promote modular components reuse by integrating thinking of the 'end' right at the design stage of the construction value chain. KEs can bring changes via pioneering new designs, reforming regulations and making changes in specifications and standards (or reforms to existing ones) [32, 77-80]. When it comes to implementing these initiatives and changes, KEs should lead by example making it mandatory for all stakeholders to coordinate their activities and begin transitioning to modern methods of construction and life cycle management of assets. This aptitude can create a thriving environment that will boost competitiveness and increased innovation. Improved information capture and management via modular components passports monitored and controlled either by themselves or by the KFs, can help KEs to understand the legitimacy of modern practices, and break down decision-making and planning that occurs in silos [51]. This will fulfil the vision of digitally enabled modular construction across the entire spectrum of the construction value chain, promoting increased resource efficiency and productivity via an improved and sustainable life cycle use of modular assets.

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

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

4. Discussion

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

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

Innovation is often associated with inherent uncertainty, yet this should not diminish efforts to promote circularity in the construction sector via radical transformations. Some negative outcomes related to service life and datafication issues, trust and security, property rights, competition, commercial and financial arrangements may also occur in the system; an inevitable consequence of using technologies that are not yet well understood and having many stakeholders involved each representing their own interests and values. Further research needs to look into the way these aspects will pan out in the system, and their impacts and trade-offs that are likely to create in the short- to long-term. Generation of pilot studies whereby RFID-BIM is applied to different modular structures including short- and long-lived projects could help us gain an insight into the benefits and side-effects of such projects. These could provide guidance to different target audiences such as manufacturers, policymakers, procurement specialists, contractors, security analysts, etc. to overcome shortcomings and help refine or dismiss such models for promoting efficiency and sustainability in the construction sector.

5. Conclusions

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

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

6. Acknowledgements

The authors would like to acknowledge Brunel University London, University of Leeds and Northumbria University for the financial support and research facilities. Some outputs of the work were part-funded by the UK Engineering and Physical Sciences Research Council (EPSRC) and the UK Economic and Social Research Council (ESRC) under Grant No. EP/K012398/1, in the context of Infrastructure Business models, valuation and Innovation for Local Delivery (iBUILD) project.

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