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A Systematic Literature Review exploring the barriers to innovative modular construction methods for the international Hyper-Scale Data Centre sector

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Data centres form the essential global infrastructure relied upon for multiple industries such as the internet, financial services, and telecommunications. Consequently, data centre construction has developed into a buoyant business sector, leveraging increasing global investment. However, traditional means of data centre procurement do not match stakeholder's ambitions or current delivery demands. Thus, there is a need for the adoption of new and innovative construction methodologies in the sector to introduce improvements for the delivery of this essential infrastructure. As a step in that direction, this paper presents a Systematic Literature Review (SLR) that investigates the barriers preventing the implementation of modular construction (MC) techniques on advancing the construction performance for the Hyper-Scale data centre sector. The results of the SLR have identified five main adoption barriers that must be addressed to facilitate the adoption of MC in the sector. Also, despite the many potential benefits of modular construction, the SLR has shown that research into this topic is limited. Thus, we present qualitative findings and recommendations from the study that can act as pointers of future research work.

Keywords: hyper-scale data centre; modular construction; survey; adoption barriers

1. INTRODUCTION

The decision to select one procurement method over another is complex and may be based on numerous factors including geography, site conditions, labour supply, budget, schedule, transport, sustainability, and design criteria [1]. Historically, advancements in productivity within the construction industry have been relatively modest, particularly when compared to other industries such as advanced manufacturing [30]. Research studies suggest that productivity in the construction industry has gradually declined at an average compound rate of -0.6% annually in the past four decades, whereas all non-farming industries have experienced increases as a rate of +1.8% per year over the same duration [1]. More recent developments in the areas of off-site construction, advanced manufacturing, and modular construction methodologies have created an opportunity for improvement in the construction industry. This has been made possible through the adoption of digital manufacturing processes, such as BIM (*Building Information Modelling*), and is motivated by demands for faster and more efficient project delivery [1].

When compared to other industries, the construction industry also does not perform well in the areas of innovation, or the use of new technology. Although 13% of the global Gross Domestic Product (GDP) is attributed to construction spending, and it is expected to grow to 14.7% by 2030, productivity improvements have only increased by 1% per annum over the past two decades [30]. Contrasted against other sectors, such as manufacturing with productivity growth of 3.6%, it is evident that the construction industry is underperforming in these areas [23].

Furthermore, in the area of sustainability, it has been proven that construction activities contribute to environmental hazards, such as global warming and ozone depletion. Conventional in-situ construction methods fare poorly in terms of greenhouse gas (GHG) emissions when compared to more innovative modern modular construction techniques [30]. Comparatively, off-site manufacturing, prefabrication, and modular construction techniques have demonstrated leaner production outcomes and efficiencies, making these innovative solutions increasingly attractive to late adopters of innovative construction practices [10].

Data Centre Construction

Advancements in technology and increasing demand for instantaneous access to digital information has been driven by a vast array of industries and groups reliant on an essential physical data centre infrastructure. This has greatly impacted the delivery of what are considered to be mission-critical data centre facilities, increasing the desire for more rapid methods of deployment [17]. Data centres store a growing global network of inter-connected electronic information equipment within secure, controlled environments. Timelines for facilities to become operational are shortening to meet the demands of data centre facility owners and service users.

In recent years hyper-scale data centre construction has developed into a buoyant business sector leveraging increased global investment intensity in digital infrastructure, against the backdrop of constant innovation and advances in technology [21]. However, the traditional means of procuring mission critical data centre infrastructure does not match the ambition or the demand of the industry is serves. Traditional construction methodologies still dominate this sector while smart data centre clients expect more innovative approaches to support their ambition and the infrastructure that acts as the foundation of global connectivity [8]. Therefore, the challenge presented to the construction sector to meet this demand has never been greater. Adoption of new and innovative construction methodologies offers one possible solution to satisfy this global need [1,21].

Although construction related GHG emissions vary depending on geographical locations of a project, innovative modular building techniques have been shown to reduce GHG emissions by as much as 46.9% for the domestic construction sector when compared to more traditional site-built solutions in recent years [30]. However, despite increased attention given to the negative environmental impact of hyper-scale data centre facilities due to their energy consumption and the commitment of large-scale data centre facility providers to off-set their carbon footprint, the construction aspect of a data centre facility remains highly reliant on conventional in-situ construction methods.

It is also likely that continued growth in digitalisation, reliance on Information and Communications Technology (ICT), and growing global data consumption in these areas will accelerate the requirements for data centre infrastructure worldwide [3,8,9]. Much of the literature explored suggests a growing appetite for modular construction for the sector in tandem with environmental factors such as political, environmental, social, technological, legal, and economic influencers. Providers of hyper-scale data centre solutions are experiencing increasing pressures to aligning with the needs and desires expressed by high profile clients and governments [36].

Off-site modular construction for the data centre sector is identified as a multi-billion-Euro industry, globally [21,36]. As the broader construction industry transitions toward a modular off-site project delivery model across multiple other construction sectors, clients and suppliers alike are showing increasing interested in the advantages of Off-Site Manufacturing (OSM). Some of the benefits associated with this form of delivery include reduced reliance on a broad network of supply chain partners, reduced waste and sustainability, quality control, reduced on-site labour, cost, safety control, speed of delivery, design flexibility resulting in increased interest in modularity [1,14].

The risks of not adopting a modular solution-based approach to serve the needs of clients are numerous. It is possible that off-site construction strategies have the potential to relieve the physical barriers associated with conventional construction that limit international growth and access to developing markets based on geography [15]. Limitations of more traditional construction are identified in terms of supply chain reach and scalability as well as in-situ labour restrictions, legal requirements, logistics, and costs associated with construction in territories where hyper-scale data centre clients are required to build as part of their global expansion plans [8-9,15]. Complete, three-dimensional volumetric modular data centre solutions have been identified as a potential innovative strategy for betterment of delivery and facility performance throughout the entire life cycle.

However, despite the many apparent benefits of modular construction, the apparent limited research into the area of modularity specifically for the DC market indicates that adoption is slow. Empirical evidence within the literature suggests that key decision makers may to be reluctant to change to this innovative form of procurement. Studies relating to the topic of adoption of innovation would suggest that the current client base and constructors responsible for deciding their procurement route can be divided into adopter categories such as innovators, early adopters, early majority, late majority, and laggards [34-35].

In this context, the rate of diffusion of modular construction for the DC sector is arguably limited to willing organisations that can be categorised as 'the early majority' seeking evolution of their procurement methods. Comparatively, other influencers who are reluctant to adopt new techniques may be described as the 'late majority' or 'laggards' who may view the solution as a disruptive change from the established delivery method. For those in the latter category, the migration to a new innovative delivery methodology may take longer and may require proof of concept before they are willing to take on modular construction practices [35].

Research Objective

The above scenario motivates the need of this systematic literature review (SLR), which aims to investigate innovative off-site Modular Construction (MC) techniques, as well as their impact, on advanced construction performance for hyper-scale data centres.

More specifically, this research answers the following research question: *What are the barriers to introducing innovative modular construction methodologies for the international Hyper-Scale Data Centre sector?*

Structure of the Document

The rest of the document describes the performed SLR. Section 2 describes the methodology used, while Section 3 presents the main results and findings. Furthermore, Section 4 describes the identified barriers, while Section 5 describes the limitation of the study. Finally, Section 6 presents the conclusions of this work, including recommendations based on the analysis and findings outlined throughout the SLR.

2. METHODOLOGY

A SLR was conducted and followed an established academic research process, beginning with the specific research question, identifying relevant studies, appraising their quality, and evaluating their results using a scientific methodology [27]. The full extent of relevant accessible research was considered as part of a SLR, utilising a scientific methodology with specific search strategies. Multiple peer-reviewed qualitative and quantitative academic journals were retrieved from a range of peer-reviewed academic journals for the purpose of evaluating the strength of the results as evidence for the identified barriers to modular procurement methods used for data centre construction.

The application of evidence-based practice for studies relating to the built environment can improve research reliability when assessed in the form of an SLR, demonstrating stable, consistent results [11]. Data and evidence obtained to support the theories discussed during the forthcoming SLR have been gathered in accordance with the principles of evidence-based practice, and include information gathered from peer reviewed academic literature [11]. A systematic review of selected academic literature was conducted relating to the research question outlined in the previous section. These data sources form the basis for evaluative insight and evidence-based research to support the findings and a conclusion in response to our research question [11].

Research literature relating to the topic of Modularity within the context of Construction Methodology is broad, with hundreds of journal articles, books and online platforms offering a vast number of research options. Numerous databases were considered when exploring the academic research and selecting the journal articles referenced. A systematic search for reliable literature search was carried out across multiple online databases, including those accessible in the Technological University Dublin online library. The databases identified in Table 1 were chosen for their access to content relating to research question and modular construction as the chosen specialism.

Table 1: Summary of Journal Articles Sourced Per Database

No.	Database	Results	Duplicates	Total Screened	Total Excluded	Total Reviewed	Used
1	Ebsco Host	68	10	58	40	18	16
2	TUD Library	17	8	9	7	2	2
3	Emerald Publishing	14	2	12	8	4	4
4	Other	0	0	0	0	0	0
		99	**20**	**79**	**55**	**24**	**22**

Another criterion used for the selection of these databases was the ability to provide appropriate search management tools which allowed the use of Boolean terms, filters, and formatting to manage the search results more effectively. In accordance with recommended best practices, a number of pilot searches were carried out across a broader number of potential databases to test the quality of the information returned, and to assist in selecting both the databases and the inclusion and exclusion criteria outlined [7]. The search criteria were intentionally limited to peer-reviewed journal articles to maintain a high standard of quality and reliability. Additionally, of the articles considered, each article has carried out research and analysis specific to the areas of MC and, or data centre construction.

Individually, the topics of modular construction, off-site construction, and data centres have been written about extensively and with increased frequency since 2000. Following initial exploratory pilot searches, the time range was intentionally limited to papers published from January 2015 onwards, due to the more rapid growth of the hyper-scale data centre construction projects and advancements in the sector in recent times [8].

An extensive search through peer-reviewed databases was carried out and recorded, as reported in Table 1, showing the number of articles published using the listed search terms shown on Table 2. A detailed table of the search terms per category used when finding, selecting, and reviewing the accessed academic literature during this process was recorded. Initially, the search criteria were limited to the title, inclusive of selected search terms: modular, data center/centre, and construction. However, with no results for articles containing all these terms within the title, the search criteria were refined by separating search terms into different categories. Placing these same search terms in several configurations, within the categories of Title, Abstract, or All Text expanded the search results and number of journal articles retrieved in each database.

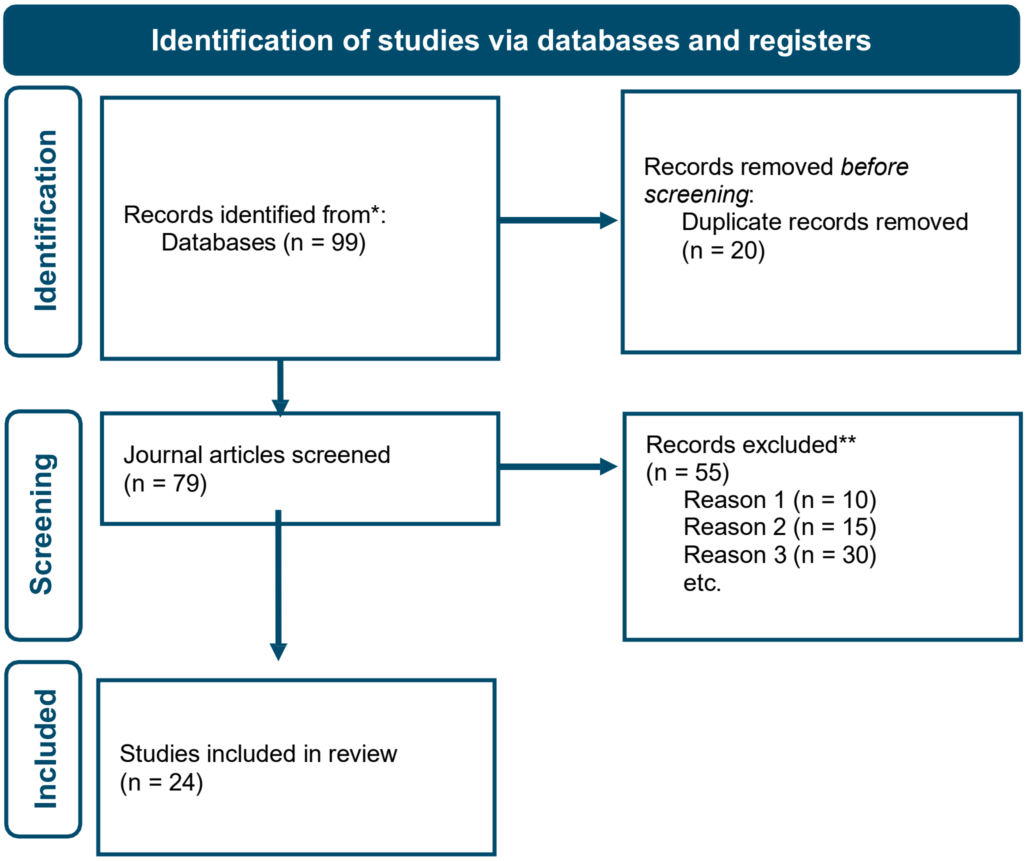
Table 2: Search Terms

No.	Search Term
1	data centre OR data center OR data centres OR data centers
2	modular data centre OR modular data center
3	TI Data centre OR TI Data center
4	((TitleCombined:(modular data centre)) OR (TitleCombined:(modular data center))) AND (Abstract:(modular construction))
5	((TitleCombined:(data centre)) OR (TitleCombined:(data center))) AND (Abstract:(modular construction))
6	(content-type:article) AND (title:"data centre" OR (title:"data center"))

Furthermore, only articles published in English were considered. Duplicate search results were also excluded. From the search results identified through the search criteria explained, only some were deemed relevant to the research question and were identified in the first instance by reviewing the title, and source of the journal. A total of 79 (of a total 99) peer-reviewed journals across all databases were deemed relevant following this initial title screening. Although a large number of the articles related to the Data Centre aspect of the research question, excluding articles from the results was necessary as part of the screening process. Exclusion and inclusion criteria are used as a control measure to ensure that the volume of material is manageable, and the pool of research selected is refined and relevant to the research question and in-scope topics [11].

Following a systematic review of the titles, sources, and abstracts, 55 articles were excluded due to of a distinct lack of linkages between the topic of data centre and the specialism of construction or modularity. Figure 1 uses a flow-chart to demonstrate the identification, screening and inclusion process and results [28-29]. Alternatively, where the initial screening of titles, sources, and abstracts did not conclusively determine if the article was relevant, it was included in the next phase of the screening process to ensure relevant articles were not mistakenly excluded.

Figure 1: SLR Flow Diagram: Article search and selection process. Adapted from: (Page, McKenzie, et al., 2021; Page, Moher, et al., 2021).



The second phase of the screening process involved reviewing the abstract and introduction of each article that passed the first screening phase. Each article was assessed as an indicator for inclusion or exclusion with continual reference to the research question [11]. Where the introduction and conclusion met the needs of the inclusion criteria by expanding on the knowledge relating to data centre construction or modularity, the full article was read before determining its value and suitability for inclusion in the SLR. Substantial methodological shortcomings such as lack of depth and clarity, limitations of the results or research methodology, and lack of relevance to the research question all formed aspects of equally valuable exclusion criteria. Where journal articles were viewed as negligible, these studies were not used for data extraction or assessment in response to the research question. Following the completion of this phased selection and screening process, 24 academic journals were selected as relevant to the research question and form the basis for the findings of the SLR discussed in the following sections.

The next stage in the evaluation of the articles selected involved data extraction through the collation of the results and other information within a table format. This extraction method was based on reading the articles in full and assessing the information contained within. The chosen academic journals were listed in a data extraction table in Microsoft Excel. Key findings were listed, identifying author, year of publication, research design, sample size, limitations, and levels of trustworthiness. Levels of trustworthiness were also identified based on a classification system [25,31]. Additionally, following a full review of each article selected, the key findings of each were summarised and tabled. The methodology used for the SLR is illustrated as a staged process on Figure 2, adapted from a study on Evidence Based Practice for the Built Environment [11].

Figure 2: SLR Methodology Process Diagram, adapted from (Hall et al., 2017):

3. RESULTS AND FINDINGS

As discovered during the literature search process, many articles have been written on the topics of Modular Construction and Data Centres individually. However, for the purposes of this research, a focus has been put on the connections between the two. Therefore, literature reviewed and discussed in response to the research question refers only to the selected studies or portions of selected studies that discuss the linkages between both. When undergoing a search for journal articles under the first set of search terms, 24 peer-reviewed articles were selected as relevant out of a possible universe of 79 articles identified from three separate databases, in line with the search methodologies described in the previous section. The full extent of the search results per database can be seen in Table 1: Summary of Journal Articles Sourced Per Database.

As discussed in the introduction section, the potential benefits of applying innovative Modern Methods of Construction (MMC) and MC to the Data Centre construction sector are substantial [1,21]. Additionally, the apparent desire for improvements in this area is growing [36]. However, the rate of adoption of advanced project delivery techniques within the DC construction sector does not appear to reflect either the need or desire for improvement [14]. In this section, a literature review will determine if there are benefits to MC for the data centre construction sector, and the barriers that prohibit organisations or groups from making the transition from traditional facility procurement methods to MMC and MC. Additionally, where barriers are identified, potential solutions and recommendations to overcome these barriers are outlined.

To gain a suitable understanding of the potential barriers to MC, it is important to first understand what MC is: The phrase MC can be used to describe varying degrees of modularity for construction solutions fabricated in off-site manufacturing facilities [1,14]. At a smaller scale, the phrase MC can also be attributed to a panelised or partially pre-assembled systems that are fabricated in an off-site factory setting. Components such as flat-pack panels, parts or assemblies can also be described as modular. When joined or assembled in-situ, these systems can add up to a complete building solution. However, for the purposes of this study, this on-site assembly process is considered to be more of a modular/construction hybrid and not fully modular.

Henceforth, in the case of this study, the term Modular Construction refers to fully modular 3D volumetric building blocks that, when stacked or placed side-by-side create a complete building format. Modular construction in this context involves the production of 3D volumetric building modules, typically manufactured inside controlled environments or factories before transport and integration on a building site [14,33]. Additionally, in using the term modular within the context of this study, it is intimated that the modular unit described has been brought to a high level of completion, internally as well as externally. An example of this could be described as a modular office, where internal walls and architectural finishes as well as integrated first and second fix electrical elements are complete inside the module, before it is transported to site. Another example, specific to data centres can be described as a modular portion of a data hall which may include server racks, aisle containment, and internal and external architectural finishes as well as services [19].

Furthermore, the following subsections describe the main themes found in the analysed literature with respect to our research question:

Hyper-Scale Data Centres

Data centres (DC) centrally locate electronic information equipment within a secure, controlled building environment. Typically, DCs are formed by one or more buildings, or as part of a building and include a range of facilities including server halls, support areas and habitable administrative spaces for personnel. Additionally, these buildings are supported by a complex technical network of utilities such as power, cooling, security, and performance monitoring infrastructures to ensure performance and reliability [2,24]. Some of the largest hyper-scale cloud facilities host in the region of 10,000 servers, offering varying services uses. These facilities are more efficient energy consumers than multiple smaller facilities. In recent years, DC numbers worldwide decreased from circa 8.55 million in 2015 to 8.4 million in 2017, and are expected to decrease further, to 7.2 million due to the evolution of hyper-scale DCs and the migration of data to a cloud-based infrastructure [8]. Cloud-based DC facilities absorbing the market are built and managed by global information traders and internet giants such as Amazon, Apple, Facebook, Google, and Microsoft, and are ranked among the top companies by market capitalisation [19,21,36].

In 2018, Optics Communications published a peer-reviewed study stating that the data generated by business, globally, had reached 7,000 ExaBytes in 2016 and was expected to grow annually by an average of 24.7% [40]. This prediction is further supported by the theory that the transformation to digital societies is accelerating with internet traffic expected to triple between 2020 and 2025 [2]. Data centres form an essential global infrastructure providing stable, continuous IT services for varying individuals, groups, and multiple industries including internet, banking, telecommunications, broadcast, finance, stock market, amongst others. IT and technology development has significantly increased reliance on data consumption, and data centres. As a result the demand for a reliable data centre infrastructure to support a vast digital economy has increased, globally [2-3,5,8-9,12,16-17,20-21,24,39-40].

Hyper-Scale Data Centre Construction

According to academic literature published within the Arctic and North journal in 2021, investment from some of the largest data centre end-users can reach hundreds of millions, generating tax revenue and employment for thousands of people on construction sites [5,36]. This is also evident in the project delivery phase in multiple regions such as the Nordics, where active data centre construction sites see the highest levels of employment during the construction phase. It is observed that productivity can continue for years on sites where end-users invest in expanding their facilities as part of a phased delivery model [36]. For the data centre construction sector, this has generated significant growth potential.

A critique of conventional construction and design methods suggests they are more focused on Key Performance Indicators (KPI's) such as schedule and cost of delivery, rather than quality of outcome which affects the operational performance of a DC, post-construction [3]. This is further supported by the theory that there are limited numbers of academic studies covering the integrated best practice frameworks for the entire life cycle of DC buildings [2]. This also raises questions around the inter-dependency of back-end facility performance and front-end design and construction methodology, presenting potential future research opportunity in this area. However, the fractured nature of the design process which involves multiple transdisciplinary specialists, and the lack of shared information among cloud providers, obstructs discursive competence that may help end-users to learn from data gathered at the facility performance level.

Combined time and financial constraints, along with demands for quality of execution are placing heightened expectations on constructors and owners of DC properties as well as the service providers who utilise their capabilities. This is contributing to the need for DCs to be constructed in ever-shorter cycles. The penalties for latency or system unavailability include loss of service capacity incurring additional costs, delayed revenue, damage to brand, insurance costs or even legal fees. Synergies throughout the SLR process also suggest that legal requirements and international policy will also impact the delivery timelines. This was catalysed further by the United Nations in 2016 when internet access was recognised as a basic human right [21]. With potential future European laws aiming to harmonise standards surrounding the regulation of insurance and banking, the DC infrastructure that supports those business sectors are more likely to evolve to include standardised designs [2].

Modular Data Centres

Throughout the SLR, design for data centre scalability is identified as important to their future performance, influencing both the construction and operational phases of cloud services [12,38]. While traditional data centres are more difficult to expand, modularised architecture creates more mobility and flexibility in the manufacturing stage as well as for future expansion of the facilities infrastructure [4,15,17,38]. The advent of “smart cities” and “edge computing”, where data centres are required in close proximity to the source of data usage, small and scalable DC facilities can be installed instead of built. This is accelerating the trend toward modular solutions and the idea that modular DCs can be deployed in building blocks that conform to container-like architecture. As DC modules are typically scaled to conform to standard road and shipping constraints, they are more easily transported. Careful planning, combined with the ability to allocate modular solutions to match particular business needs in a particular location could take place with careful capacity planning, resulting in a more appropriate sizing and form factor for modules [17].

Since modular construction techniques can satisfy increasing demands on established KPIs such as safety, quality, cost and schedule, this delivery method may become more popularised [42]. It can be theorised that new and innovative methods for the delivery of this critical infrastructure can fulfil the potential for betterment in the area of data centre construction. It is possible to foresee MC as a potential solution in this regard and a specialism worthy of investment by data centre constructors and end users due to the advantages and improvements that modular construction can bring over traditional construction techniques [9]. However, despite acknowledgement that a modular design and construction philosophy can be used for the betterment of DC delivery and performance throughout the entire lifecycle of the facility, traditional brick-and-mortar-style procurement techniques remain more common in this sector [15].

Across construction sectors, modular data centres have attracted increasing attention due to their excellent stability, scalability, and a sustained economic feasibility profile [12]. Contrastingly, increasing demand for global connectivity means that DC infrastructure has also attracted attention due to concerns regarding its energy consumption. Data centres account for between 1.5% and 2% of total global energy consumption, with total DC energy consumption expected increase globally by 15-20% annually [13,20,37,42]. As a result, DCs are viewed internationally as high-energy facilities that do not fit with the sustainability goals set by governments to reduce carbon emissions [5,36].

As the data centre industry focuses on initiatives to reduce its energy consumption and minimise its environmental footprint, it is suggested that modular DCs can provide considerable operational flexibility through standardisation, creating the potential to limit adverse environmental impact [15]. This is further supported by the theory that a broader blueprint to support good governance in the area of DC design is underpinned by standardisation and modularity [9,12,26]. Additionally, modular DC delivery approach is an emerging trend that may be used to enhance capacity of an existing site, or to deploy new capability in more remote, inhospitable regions such as those that exist in regions of India and Africa, where conventional construction methods present heightened construction risks and are more difficult to execute [8-9,15].

Although the literature exploring the suitability of fully modular construction methodologies, specifically for the data centre sector is limited, there are a number of quantitative academic studies exploring how modularisation of specific component systems within data centre facilities may be beneficial. For example, it is demonstrated that facility performance enhancements can be achieved with the introduction of T-shaped underfloor air ducts, creating airflow uniformity and optimisation when delivered in a modular format [42]. It is proven in multiple cases that modularisation of components such as flooring systems that optimise airflow uniformity and Hot Aisle Containment systems that control airflow within the data hall space can be modularised to benefit the overall facility performance [18]. It is suggested that a more standardised layout and design is more efficient in terms of energy usage. Therefore, it can be suggested that tenets of modular design, such as standardisation and uniformity, are beneficial to the overall performance of the building and, therefore, modular assemblies offer a more optimised solution.

Within the context of critical equipment such as servers, it is demonstrated that a grouping of proprietary server components can be modularised into a universal kit, or "plug and play" solutions. Benefits of modularising specific internal equipment include standardisation, creating further opportunity for efficiency in the area of maintenance, or repair and replacement of parts [22,26]. An experimental quantitative study published within the Energies journal in 2018 carried out research into the modularisation of DC components. The study explored how modular equipment connected to the BMS (Building Management Software) can be used to track root-cause issues and failures in critical equipment parts in real time, citing modularity of the equipment as an up-front investment in design with potential payoff due to resulting resilience [22]. Although this creates a higher standard of front-end design which requires added investment in the design stages of a DC project, the initial outlay of cost and resource to achieve the long-term benefits outweighs the cost of developing a methodology for the replacement of parts during the operational phase of the facilities lifecycle [22,26].

Indeed, the benefits discussed at a components level are also reflected at a macro-scale, where fully modular DC design solutions offer benefits across multiple project KPIs. MDCs offer advanced flexibility in the areas of easy expansion, replacement, maintenance, resolving typical project challenges associated with latency, scalability, and total cost, generating considerable interest from the industry [4,12]. It has been observed that because MDCs utilise a standardized architecture, this results in fewer variations in the IT equipment characteristics and space usage.

Consequently, more precise cooling load estimation can be applied to modular data centres than to conventional data centres [12]. This is particularly beneficial considering that DC cooling accounts for roughly 30% of DC operating energy consumption [13].

Collaboration

Improvements in productivity are less likely in a traditional project delivery approach, as communication between supply chain partners is more limited and fractured than within a modular design team [32,36]. Due to a centralised design approach and the desire for standardisation, modular construction agglomerates an otherwise segregated group of experts and skilled practitioners with task-specific technical competence [15]. The intersection of expertise required to form a coordinated design in a pre-construction environment creates a collaborative platform for standardisation and shared knowledge that would be impossible in a traditional project delivery setting where private enterprises are less communicative, less inter-connected and possibly unwilling to share knowledge. Therefore, innovative breakthroughs are more likely in a modular design approach to construction as coordination and cooperation is encouraged and is mutually beneficial for all stakeholders. The established collective benefits and efficiencies gained are also advantageous to end users in this case. End-users are more likely to benefit from eliminating the siloed approach to project delivery, as more clarity is gained on important project KPIs (Key Performance Indicators) including safety, cost, schedule, and quality [36].

Productization and Servitization

The productization and servitization of data centre construction offerings can result in investment in innovative modularised solutions for supply-based organisations. This can be beneficial for developing and exploiting competitive core competencies, as well as improving and expanding an organisations value proposition for the market it serves [32]. Coupled with the need for a more responsive approach to data centre construction, this can be presented as evidence for suppliers of construction service providers to invest in modular construction as an innovative route to market and a part of their value proposition with growth potential. Additionally, modularisation can extend from the focal firm to its supply networks increasing the likelihood that integration of modular activities will spread beyond organisational boundaries [32]. Therefore, it can be suggested that a modular design philosophy can be beneficial to all tiers of the supply chain, as well as end users.

4. DISCUSSION AND BARRIERS

Although the studies identified present manifold empirical data identifying obstacles to the adoption of Modular Integrated Construction (MiC), a holistic review and presentation of a conceptual framework for barriers to adoption of modular data centres does not appear to be clearly defined [41]. The following section collates the common themes explored throughout the SLR in response to the research question, presenting the outcome as five distinct barriers to the adoption of innovative modular construction methods for the international Hyper-Scale Data Centre sector.

Barrier 1: Existing Conventional Construction Culture

Obstacles preventing the adoption of innovative modular construction methods for the DC construction sector include typical traditional construction cultures which are adverse to innovation and remain difficult to change [14]. Literature suggests that conventional project delivery methods utilise non-standard, more unique project specific designs when compared to typical modular construction concepts [1,22]. Synergies across the academic literature explored as part of the SLR suggest multiple benefits for almost all major KPI's from front-end design through to facility performance.

However, in the majority of cases the benefits are underpinned by a more collaborative, less transparent front-end design philosophy required for standardisation and modularity (REFS). It is well documented that DC facilities are highly complex buildings requiring specialist engineering and design input. Therefore, one of the barriers to choosing modularity over traditional construction may be financial. When faced with the decision to commission a less established, more expensive, and possibly longer modular design process for the procurement of a mission critical DC infrastructure, stakeholders who are risk-adverse may be more tempted to remain loyal to the established construction norms. Equally, transitioning to a lesser-known design philosophy presents a major change in procurement strategy. Therefore, implementing a change strategy across multiple policy makers in large cloud-based organisations and gaining stakeholder buy-in is likely to be more difficult, and more likely to meet resistance. This may also be influenced by a lack of trust, where decision makers do not have established working relationship with new modular supply chain partners.

Barrier 2: Confidentiality

Therefore, following Barrier 1 it is possible that unique solutions driven by a non-modular formatting are supported by a lack of data sharing amongst competitive solutions providers and clients [5,17]. Given the need for standardisation for efficient modularisation of building components, a direct link can be drawn between confidentiality, limiting shared knowledge, and standardisation that could facilitate design evolution from unique projects to standard solutions and modular building products. This potential to move from unique projects to standard modular products presents one potential opportunity for improvement in productivity in the data centre construction sector.

The numerical data relating to finances and performance of data centre facilities is highly sensitive due to the competitive nature of the industry, resulting in a lack of collaboration and a barrier to shared information that may assist stakeholders in making decisions that might improve delivery methodologies [17]. This prevents shared learnings, and therefore limits the progress of the industry and its supply chain partners, again limiting the collaborative culture required for innovative advancement.

Barrier 3: Lack of Shared Data

Awareness of risks, but lack of understanding around what they are is one of the barriers to adopting modular project delivery techniques for the DC sector. Evidence exists to suggest that there is an awareness of risk, but lack of understanding around what they are is one of the barriers to adopting modular project delivery techniques for the DC sector. Risk analysis interviews with experienced industry experts suggest that no one holistic Risk Management (RM) process is currently being applied to the entire project life cycle for delivery of a DC facility, as discussed by [2]. This suggestion of a knowledge gap in the areas of risk assessment is further supported by evidence that there is no extensive review of BIM-based risk management research within the AEC industry, which is identified as an essential component of modular integrated construction RM [6].

This suggests that gaps exist in the information that may support modular project delivery methodologies as a way to reduce risk when compared to more conventional design and construction for DCs. Therefore, application of a robust RM structure could generate opportunity to further analyse risks and mitigating strategies for the purpose of understanding the value of innovative modular solutions over traditional construction techniques [6].

Barrier 4: Financial Cost

Therefore, following Barrier 1 it is possible that unique solutions driven by a non-modular formatting are supported by a lack of data sharing amongst competitive solutions providers and clients [5,17]. Complex data centre design and construction processes involve input from a vast network of stakeholders. This situation limits the abilities of some practitioners to influence the decision-making process. For example, where modular product solutions may demonstrate evidence of benefits in performance in lieu of conventional project delivery methods, the final custodian of those benefits may not be willing to adopt the front-loaded design process that requires a high capital investment [1,11].

Barrier 5: Standardisation

One of the core tenets of modular design and construction is the ability to standardise. Typically, this is achieved within the boundaries of logistical constraints for the movement of modules on roads or via shipping. The ability and desire of the industry to make a major shift in culture and philosophy toward more standardised, agnostic design solutions requires a fundamental change in the way practitioners think about data centre design. Similar to the key points outlined in Barrier 1, a cultural change would be required to dissolve this barrier and limit the degree to which DC projects are designed and built as unique facilities for each client.

5. LIMITATIONS

Some challenges were presented when searching and identifying articles for different modular construction. When describing the varying industry terms relating to modularity and off-site construction, it has been demonstrated that multiple meanings and definitions can be drawn from the term Modular Construction. There are also multiple other terms that can be used to describe the same topic, such as 'off-site', and 'pre-manufactured'. In recognition of this potential limitation, attempts to reduce the risk of this included using Boolean search options, as described. The SLR process utilised to find and assess academic literature is extensive and resulted in the screening of many journal articles. However, it is also possible that valuable studies relating to the research question could have been unintentionally overlooked due to differing terminologies and may not have been explored during the article search process.

Although there are many studies on MC across the construction industry, there have been fewer studies on the design process, as it relates to the topic of modular data centres [12]. Following a review of the academic evidence made available via the initial search (S1), it became clear that although multiple studies exist on the topic, very few addressed the theme of 3D volumetric modular construction for data centres. Despite many of the articles offering valuable insight into modularity, suggesting that it was suitable and beneficial, the analysis in most cases was constrained to empirical expert opinion as opposed to a higher quality of practice-based research data. This increases the risk of potential bias in the findings that support modularity for the DC sector and potentially limits the validity of the information extracted during the data extraction and synthesis stages of the SLR. Further research using a higher quality of quantitative and qualitative methods, such a review of multiple new case studies, would be required to increase the reliability of the identified findings.

The academic journals were also orientated more toward individual building components, such as electrical equipment, or server racking systems for which established, more standardised design solutions may already exist. Whereas the aims of this SLR was to establish the barriers to a fully modular procurement methodology for data centre construction. Therefore, combined with the limited number of studies specific to the data centre construction sector, it is evident that there exists a potential gap in the research in this area. This also suggests that further research into the area of modularity for the data centre construction sector is warranted.

For the academic literature utilised in the report, the quality of the data in some cases was limited by broad reference to the topic of modular construction and generally the articles lacked research data specific to the area of modular data centre construction. For example, as identified as part of the data extraction process shown in Table 3, limitations include small sample sizes for test data, and limited quantitative data relating to building performance when comparing modular to conventional construction methods. This apparent gap in test data and in the academic literature limits the reliability of the response to the research question. Further qualitative and quantitative research into the specific area of modularisation for the hyper-scale data centre construction sector may be useful to offer a more definitive answer to the research question.

6. CONCLUSIONS

Advancements in productivity within the construction industry have been relatively modest [30]. Additionally, research suggests that productivity in the construction industry has gradually declined in recent decades [1]. In terms of sustainability, it has been proven that construction activities contribute negatively to the environment [30]. Comparatively, off-site manufacturing, prefabrication, and modular construction techniques have demonstrated leaner production [10]. The decision to select one procurement method over another is complex and may be based on numerous factors including geography, site conditions, labour supply, budget, schedule, transport, sustainability, and design criteria. More recent developments in the areas of off-site construction, advanced manufacturing, digitalisation, and modular construction methodologies have created an opportunity for betterment [1].

In recent years hyper-scale data centre construction has developed into a buoyant business sector leveraging increased global investment intensity in digital infrastructure [21]. However, the traditional means of construction do not match the ambition or the demand of the DC industry. Adoption of new and innovative construction methodologies offers one possible solution to satisfy this global need [1,21]. The potential rise in modular construction techniques has developed in parallel to advancements in technology and increasing demand mission-critical data centre facilities, increasing the desire for more rapid methods of deployment [17]. Some of the benefits associated with this form of delivery include reduced reliance on a broad network of supply chain partners, reduced waste and sustainability, quality control, reduced on-site labour, cost, safety control, speed of delivery, and design flexibility [1,14].

Limitations of more traditional construction include supply chain reach, scalability, in-situ labour restrictions, legal requirements, logistics, and costs [8-9,15]. Complete, three-dimensional volumetric modular data centre solutions have been identified as a potential innovative strategy for betterment of delivery and facility performance throughout the entire life cycle. However, despite the many apparent benefits of modular construction, the apparent limited research into the area of modularity specifically for the DC market indicates that adoption is slow. This research work aims to help close that gap by presenting the results of a systematic literature review conducted to answer the following research question: *What are the barriers to introducing innovative modular construction methodologies for the international Hyper-Scale Data Centre sector?*

The below subsections summarize the main findings and recommendations we derived from the performed analysis, as well as the methodology used for the systematic literature review (SLR).

Methodology and findings

Where standardisation of design and repeat solutions have been established over time, efficiencies and improvements are evident in a large range of project delivery processes.

However, despite data centre facility designs containing many of the core formatting principles that demonstrate suitability for modularisation, little study has been carried out to determine the potential suitability of modularity for the hyper-scale data centre sector. Equally important to the application of modularity is understanding the potential barriers to its implementation and success. Again, no complete theoretical framework establishing the barriers to innovative modular DC construction methodologies appears to be established within the academic research available within the research explored as part of this SLR.

Gaps identified in the conducted literature review demonstrate a need for further research into the topic of modularisation for the DC construction industry. Alignment with design criteria and characteristics for optimising off-site modular construction is essential to establishing suitability for modular construction. Some of the common characteristics of data centre facility design include repeatability, use of standard materials, interlinking zones of similar scale, standardised architectural layouts, and scalability. However, despite established benefits of modular construction and the apparent suitability of data centre design and construction, limited conclusive studies exists on large scale data centre projects delivered through a fully modular off-site methodology.

This study utilised a mixed-methods SLR to inform research as it relates to modular construction in response to the research question. In assessing the quantitative and qualitative data referenced, the research provides analysis on the hyper-scale data centre construction sector, modular data centre construction, the strengths, and weaknesses of innovative modern methods of construction and the barriers that may prevent stakeholders from adopting modular construction methods over conventional procurement options. The research presents a theoretical framework for designers, fabricators, architectural and engineering consultants as well as end-users, examining the barriers to the use of innovative modular construction techniques. It is hoped that the findings will assist stakeholders in making informed decisions regarding the implementation of innovative modular construction for their future projects and will provide a framework for challenging the barriers to implementing change within this specialism.

The SLR results in the collation of the common themes explored throughout the SLR in response to the research question, presenting the outcome as five distinct barriers to the adoption of innovative modular construction methods for the international Hyper-Scale Data Centre sector. These five main adoption barriers (discussed in Section 4) are: (1) *Existing Conventional Construction Culture; (2) Confidentiality; (3) Lack of Shared Data; (4) Financial Cost; and (5) Standardisation*.

Recommendations

The risks of not adopting a modular solution-based approach in order to serve the needs of clients are numerous. It is possible that off-site construction strategies have the potential to relieve the physical barriers associated with conventional construction that limit international growth and access to developing markets based on geography [15]. Recommendations for specialist suppliers may include acquiring stakeholder feedback to ensure that the market is sufficiently buoyant, and clients are open to modular construction for this sector. This should be completed before implementing strategic action and resource toward a change effort that could present substantial investment in funding and resources. Research and development strategies should be considered as part of the sense making portion of any strategic development plan. Specialist knowledge should also be considered and sought from organisations and suppliers with expert knowledge of modularisation for other construction sectors.

Moreover, where large capital investment may seem justifiable, internal resourcing and hiring of construction, architectural design, engineering specialists should be considered as a way to limit barriers to success. Given the complexity and specialist nature of the delivery method, lack of industry experience and potential high-risk profile, limiting the initial delivery to one smaller scale facility should be considered as a way to reduce risk and build stakeholder confidence. In the event that approval for the development of a modular hyper-scale data centre product is established along with a client, the process and results of the venture should be documented as a case study and analysed for future reference, optimisation, and learnings that could impact future opportunities. This case study, in turn could form the basis of valuable research data required to offer a more definitive answer to the research question explored in this SLR.

CONFLICT OF INTEREST STATEMENT

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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