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Implementation of a novel data-driven approach to optimise UK offsite housing delivery

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Abstract. Several countries have started to more purposefully apply advanced offsite delivery approaches to meet specific housing shortages. The United Kingdom (UK) is no exception. Whilst the concepts and benefits of Modern Methods of Construction are 'typically' well understood, it is generally accepted that there is a paucity of knowledge on the actual understanding of optimization per se, ergo, the interrelationships between processes, and the wider understanding of 'pooling' [resource management] to promote and maximize synergy - especially to target areas of lag or bottlenecks. In this respect, the research methodological approach adopted in this paper used a single case study to critically evaluate an offsite steel-frame solution for the offsite market to deliver social housing. This approach also evaluated the potential of Generative Design, Discrete Event Simulation, and Digital Twins. Findings of this ongoing research include new opportunities and strategies for these technology-driven solutions, culminating in the development of a new conceptual offsite hub-and-spoke model. These are presented for discussion. This model allows decision-makers to interact with data in order to optimise solutions in line with demand and resource requirements.

1. Introduction

Architecture, Engineering, and Construction (AEC) has continued to evidence sustained growth in the offsite market [1,2]. This inertia has in part been supported by several evidential success stories, underpinned by numerous government reports and industry offerings. In short, offsite construction (OSC) has been proffered as a paradigm for delivering new [offsite] solutions – thereby, transitioning away from many of the problems typically associated with 'traditional' construction [cf. quality, cost, waste, energy, etc.]. Increased population with higher demand for affordable housing boost emphasis on applying the modern method of construction (MMC) and OSM on a wider scale. For triggering this goal, it is important to merge different aspects of technology and its subfields into OSM. From a terminology perspective, it is important to note from the outset that several definitions of OSC have been proffered in literature. These cover different contexts and backgrounds [3].

Notwithstanding these, OSC has been espoused as being able to address recurrent challenges such as environmental/sustainability, carbon, and waste [4,5]; through quality, process, and performance [6–8]. However, AEC has also been recognised for lagging behind other industries [9,10], particularly regarding the adoption of emerging technologies [11,12]. Arguably, some might say that things have started to change of late, particularly through increased awareness of OSC techniques, capabilities, platforms, and products. Acknowledging these issues, this paper provides readers with additional insight into some of the challenges facing OSC uptake through the lens of AEC, and in particular, through emerging technological developments. It evaluates OSC purely from a single context [UK], using one OSC solution [steel frame], which engages one manufacturing company [based in the UK]. The treatise of this paper is therefore to present a different way of thinking, one which embraces the potential of technology and postulates the principles of the "Hub-and-Spoke" approach to align with OSC processes.

2. Underpinning research

Globally, several countries are now facing housing challenges of one form or another. The UK is no exception here, with unprecedented levels of demand outstripping supply [13,14]. One might say, the challenge, therefore, is simply to increase capacity. Whilst this statement is arguably altruistic, the real issue concern rests with 'affordability' and wider concomitant social provision. This balance and provision are well recognised [15], where during the last 30 years, around three million fewer properties have been built, yet the population (and demand) has continued to increase [16]. The underpinning challenge is therefore to seek new ways of servicing this demand. One of the approaches presented in the literature has been to investigate how OSC can be used to not only increase capacity *per se* but to provide new social 'affordable' homes to meet demand.

This sector of the market is highly competitive. Whilst government "new starter" schemes have helped many homeowners enter the property market for the first time, contrarily, there are still a high number of people left in the rental market with little hope of securing property ownership. Notwithstanding this, the UK government's target of building 300,000 new homes each year to meet demand, along with making housing more affordable has met with numerous challenges [17,18]. Moreover, whilst OSC is considered a viable approach for achieving high-quality social housing, it is also argued that equally, there is a need to more purposefully align OSC benefits to showcase these opportunities [19]. There are a number of factors that can be promoted to exemplify these benefits, not least through the application of Generative design (GD) and Digital Twin (DT) approaches [20].

2.1 Offsite construction - People, process, and technology

The fundamental principles of OSC rely on the integration of; People, Processes and Technology. Where for example, Goulding and Arif, (2013), highlighted a series of interconnected issues covering nine core areas [People, Process, and Technology x Design, Manufacturing, and Construction] – the work of which highlighted the need to create clear business models with evidential process chains to deliver OSC solutions (Figure.1). These solutions resonate with the need to align with Industry 4.0, especially through integrative measures throughout the production process [21,22], and the ability to offer client flexibility and transparency across supply chains [23]. One of the fundamental ideas of Industry 4.0 is the paradigm shift needed in thinking to maximise integration. In the context of offsite, this means moving away from centralised control to de-centralised control in order to achieve highly flexible production of customisable products and services.

The Hub-and-Spoke model is a good example of this, especially with complex adaptive supply chain networks associated with OSC [24]. However, one of the main challenges facing the offsite sector as a whole is the need to fully understand the interconnections between People, Processes and Technology. This is important, as this forms the basis of "collective understanding", and the need to apply common processes associated with Design for Manufacture and Assembly (DfMA). Moreover, this forms the wider understanding of "design-manufacturing-construction" throughout the whole process [25–27]. More recently, however, literature has evidenced an increased awareness of pooling together a number of technology-driven solutions, ranging from Building Information Modelling (BIM), Generative Design (GD), Discrete Event Simulations and more recently Digital Twins (DT) to deliver evidence-based solutions for OSC [28].

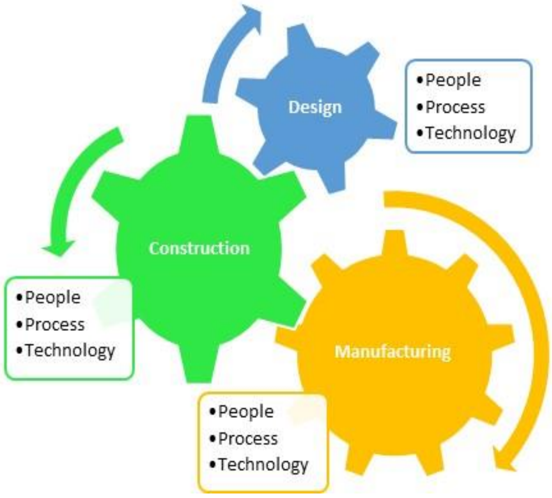

Figure 1. People, Process and Technology CIB Roadmap (Goulding and Arif, 2013)

2.2 Generative Design
AEC has now moved towards the greater utilisation of BIM and the wider use of data-rich 3D geometric models; where Generative design (GD) adds a further dimension to the design process by allowing designers to develop and explore a wider range of parametrically constrained solutions [29]. As a subset of Computational Design, GD brings together algorithmic and parametric modelling to explore design possibilities, placing humans as co-designers in the process to generate many design alternatives [30–32]. This includes new approaches for sequentially and logically generating, analysing, and ranking new integrative approaches [33]. Where GD allows designers to produce an extensive range of spatially novel, yet efficient designs [34]. This computational approach also has the ability to support the move towards Industry 4.0; wherein offsite construction has the potential to transform traditional design-manufacturing construction into a more integrative system-based approach.

2.3 Discrete Event Simulation
Following the production of a successful design, offsite construction processes can still be considered a complex system with the need to analyse multi-tasking behaviours, resource allocation, utilisation, and queuing [35]. However, the introduction of Discrete Event Simulation (DES) is acknowledged as being an effective technique for undertaking quantitative analysis of complex construction operations [36]; as this can also provide a methodology for decision making and logistic planning - especially for dealing with complex multi-faceted systems [37]. A key success factor of DES within the OSC domain is its ability to implement techniques to mirror and simulate distinct real-world operations and systems; by decomposing these concatenated systems into constituent logical units (or events) [38]. This approach is particularly well suited to offsite approaches as it provides an ability to simulate the manufacturing system, including, production planning, maintenance, and inventory management [39]; where the results can lead to analysis and optimisation of process time, resource utilisation and safety. Whilst the benefits of DES within the offsite domain are well documented, there is still some reticence amongst small and medium enterprises (SMEs) to exploit this technology often due to financial constraints and/or skills requirements [40].

2.4 Digital Twins
The first use of the term "digital twin" terminology appeared in Hernández and Hernández's work [41]. It was first introduced as a "digital equivalent to a physical product" by Michael Grieves at the University of Michigan in 2003 [42]. Similar explanations and concepts on DT can be seen through the works of Kritzinger et al., (2018) and Liu et al., (2021); where the underlying principle of the DT links physical objects and digital objects together - thereby, creating a replica. In this respect, it can also,

therefore, be seen as a digital entity that reflects a physical entity's standing and behaviour across its lifecycle, whilst also being able to inherit or absorb characteristics. DT is fast becoming a focus of attention within the AEC sector, especially for its ability to reflect the status of a physical built asset at any given moment [45]. In this respect, its use ranges from supporting asset management, through to the work undertaken by Sacks et al. (2020) on the use of DT's to support evaluation and control of the construction process [46]. This in itself presents a potential step-change in the use of continual real-time data for all aspects of the construction lifecycle. It also provides a range of telemetry to generate feedback loops at all stages of a project. From an OSC perspective, several studies have identified the potential of DT, including that of Rausch et al. (2021) who integrated 3D scanning with a geometric Digital Twin (DT) during manufacture to identify potential problems. Similarly, the potential of obtaining real-time data to mitigate risks in logistics during manufacture and installation [47]; including improved decision-making based on live data throughout the offsite process [48].

3. Research methodology

Drawing from the 'research onion' postulated by Saunders et al. (2012), this research engages both objective and subjective epistemology to meaningfully integrate and contextualise data [49]. Given this, it engages both inductive and deductive reasoning and employs a mixed-method design [50,51] to data collection and analysis - not only to contextualise findings but also to improve data veracity and concomitant validity. Thus, this research engages a series of specific procedures to capture, appreciate and understand OSC manufacturing practices.

Building on the above, the study presented in this paper brings together prevailing technologies and processes through the lens of one offsite provider based in the UK. This single case study approach was centred on a single offsite steel-frame solution – the predication of which was to identify opportunities for the deployment of integrated GD, DES and DT solutions within the context of the UK offsite sector, with the underlying rationale of specifically incorporating People, Process and Technology [52] from the outset. In doing so, it draws integrative theories and complex adaptive supply chain networks [53]. This single case study focuses on one proprietary OSC steel frame system in isolation. This is considered the primary context delimiter. The area of study centres on data capture – from design to simulation, evaluation and prediction (Figure.2). This was adopted in order to uncover 'best practice' with corresponding DES data to uncover new OSC opportunities and key intervention points.

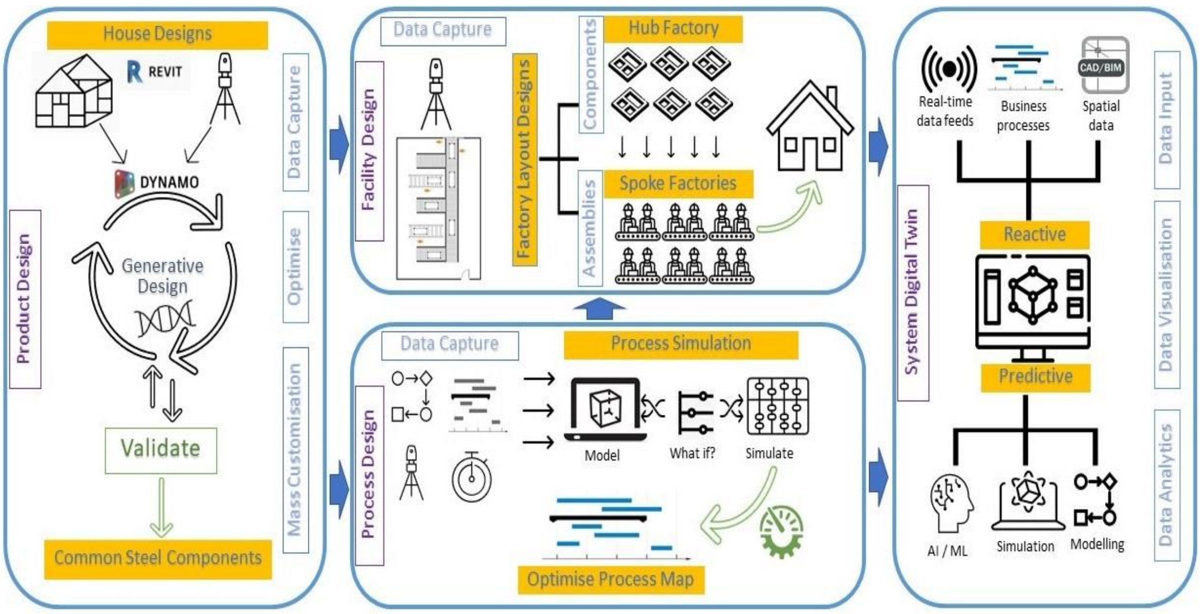

Figure 2. Integrative research methodological approach (People, Process and Technology)

The initial phase of this case study incorporated an evaluation of working documentation, schedules, component structures, data files and models. This also involved consultation with key OSC stakeholders to understand design and manufacturing workflows. In addition, observations and document reviews were employed to explore and capture the ‘reality’ of OSC manufacturing practice. This included evaluation of the manufacturing process (covering the factory layout), module development processes, and productivity of various activities needed to complete each module. Key intervention points were identified to evaluate the potential of exploiting the technologies presented above. This included the application of GD to optimise the design of housing modules, along with best-fit factory layouts. In this respect, DES was seen as a tool for optimising the factory layout. This included the identification of bottlenecks, resource clashes, and/or timing issues. A holistic view of the DT paradigm was then assessed in order to see whether this could be exploited to obtain and utilise data from design, through to manufacture and assembly. More specifically, whether a DT framework could be used throughout the offsite lifecycle process.

4. Case Study Findings

4.1 Generative Design

In terms of GD, two specific areas were identified to explore the potential of this for the offsite market. This included: i) GD for the factory layout - to understand its ability to improve/optimise the layout of workstations within the factory boundary; and ii) GD for the design of individual housing units - to appreciate if this could be used to optimise the spatial layout of the building.

4.1.1 GD for Factory Layout

In order to implement GD to explore the optimisation of the factory layout, Autodesk Dynamo was employed. This implemented an NSGA-II optimisation algorithm, a well-known, fast sorting and elitist multi-objective genetic algorithm. Using data obtained from factory observations a ‘path’ was generated between all module workstations, where the path length was used as one of the GD constraints. In order to provide additional constraints, the first and last module ‘stations’ were fixed to the location of the entrance and exit of the factory. The position of all other modules was mapped to slider inputs within the graph so that the algorithm could manipulate their position during runs of the GD study. In addition to these constraints and inputs, ‘outputs’ were created for the overall length of the path – thereby linking the modules together. These outputs were used by the algorithm as “fitness functions”, which were explicitly set to favour the smallest numbers in order to minimise these outputs. Thus, without any further constraints or requirements, this version simply tried to create the shortest path to satisfy the constraints identified. Following this, in order to add further dimensional control to the overall layout, geometry was added to the factory floor to ensure the modules did not clash with these in any solution created.

Further values included a “fitness function” for the algorithm to ‘minimise’ the number of times the path crossed itself; which in turn, immediately changed the outputs [for the better], as the path joining the modules together naturally tried to arrange themselves into a more linear pattern (Figure.3). From this, iterations were then created to analyse the angular difference between each path segment in order to generate useful outputs to support factory layouts. Where a “fitness function” was created to collect the ‘dot product’ [created by comparing the normal vectors of adjacent line segments]. This led to results favouring straight lines within the overall layout, which minimised the number of diagonal/crossing lines. Moreover, the sum of all the vectors obtained in the previous iteration was divided by 0.25, where the remainder (modulo) was then available as an output for minimisation. Recommendations from this process included the need to incorporate data and relationships with a much finer level of granularity, particularly important for mapping constraints considered ‘high impact’.

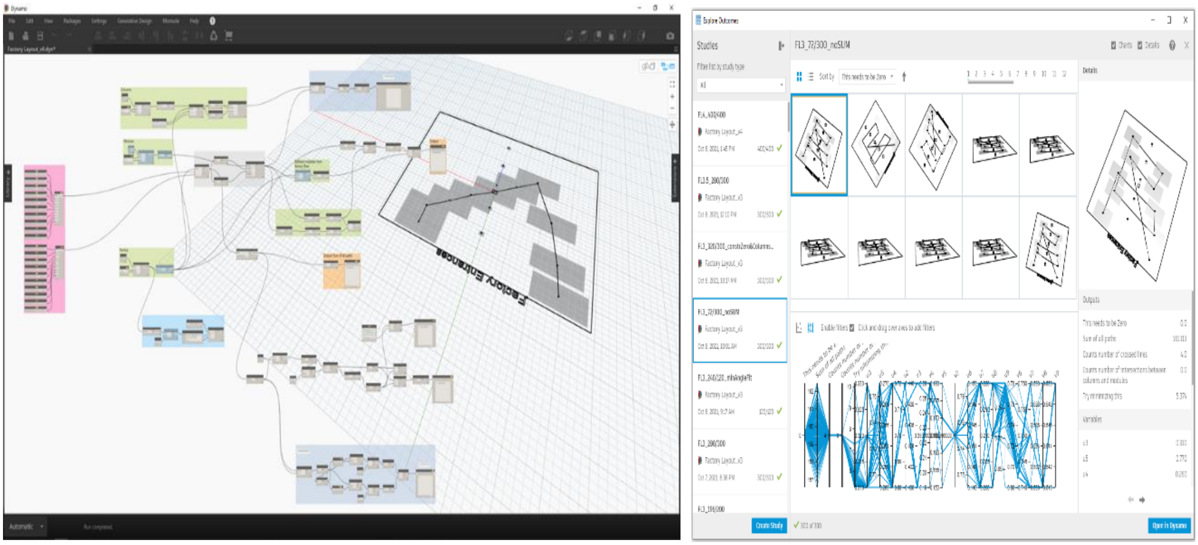

Figure 3. Factory layout model in Dynamo / GD approach

4.1.2 GD Housing Unit spatial design

This application of GD was used to explore design options and processes for the individual housing units. Specifically, to optimise the spatial layout of the building with a specific remit of analysing requirements and dependencies associated with the manufacturer. In this respect, a number of issues were examined, from user requirements capture, to the evaluation of designs against rules, regulations, and pre-defined offsite-related constraints. This involved data and criteria collected from a number of sources, including standards, client information and data extracted from drawings. This information and analysis highlighted the need to map requirements and dependencies in order to evaluate relationships, including the level of compatibility between criteria and design.

The principles of GD were then modelled. This included coding all gathered parameters into the software to develop a much deeper (richer) understanding of these relationships in order to identify new solutions. The specific software used for the process was ‘Dynaspace/Dynashape’[54], the choice of which was made on its ability to apply specific, and structured, constraint data (*cf.* offsite) in order to generate different scenarios for the early design stage (Figure.4). This computational design approach has been successfully used in many prominent designs and buildings elsewhere. Notwithstanding this, for the purposes of this paper, the rationale here was to investigate the potential of deploying this approach to smaller buildings with limited functional areas.

This work used Autodesk Dynamo (a visual programming language) along with Autodesk Revit (a proprietary BIM software solution for design, visualisation and analysis) to develop and evaluate solutions. In doing so, a general script was also developed using Python (a powerful coding language) to generate GD solutions. Where, in addition to providing the size of the functional zones (width, area, and height), the Dynaspace algorithm enables designers to enter additional conditions, such as constraints and preferences (e.g., which type of space should be adjacent to which, or links to functional spaces etc.). Acknowledging this, regulations were applied to the GD algorithm within Dynaspace to generate a number of design alternatives (iterations). This was particularly useful, as Dynaspace provided significant new insight into standardisation and dependencies.

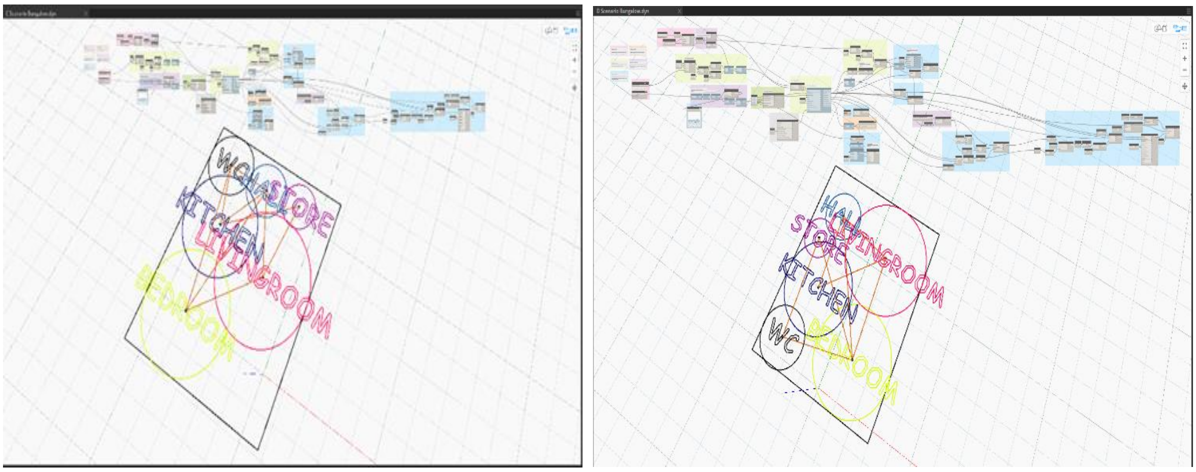

Figure 4. Factory layout model in Dynamo / GD approach

4.2 Discrete Event Simulation

DES modelling was applied based on the seven steps approach highlighted by Montevechi et al., (2015) using the ARENA Simulation tool. The rationale for this was to focus exclusively on simulating factory workflows in order to determine major bottlenecks, process clashes and resource utilisation issues. With optimisation in mind, different scenarios were iteratively modelled. DES was used to explore the performance efficiency of OSC manufacturing processes within the factory layout. From this analysis, results revealed that the factory was operating at 60% efficiency. Consequently, GD was employed to develop design alternatives for the factory layout and module development process. Three designs (A, B and C) were developed and analysed using DES to explore performance efficiency for each design alternative. Following this analysis, new design solutions were generated which highlighted the potential of achieving 96% efficiency. Stage Three involved the development and validation of Design A through a real-life case. This work is ongoing. This further work will undertake DES from different perspectives (and levels of detail) to support the Hub-and-Spoke approach. From a findings perspective, the DES undertaken thus far has focused on the logical units (events) replicating the individual workstations within the factory. Within the Hub-and-Spoke framework, a more abstract level of detail will be applied, such that each logical unit represents either a hub or a spoke system, where collectively, the whole system can be simulated.

4.3 Digital Twin

The concept behind linking DT with OSC was to provide a clear sight for investors, manufacturers and end-users to observe a replica [twin] of the physical entity using real-time data in all phases of the project. This DT would therefore provide stakeholders with a novel platform for anticipating challenges before production and assembly commence. This not only helps achieve operational and process efficiencies but can also help optimise all integrative processes in line with DfMA methodologies. In pursuance of this, data will need to be collected through monitoring systems, BIM models, and through Quick Response (QR) codes on components and sensors installed in the factory. This data would then be processed using GD modelling and DES to assess efficiency gains. Based on these results, alternative solutions for optimisation can then be pursued. This ongoing work will be used to develop a holistic DT approach to support the lifecycle monitoring of project data. This will include pre-construction, manufacturing, transportation, installation and subsequent operation of each individual house. Moreover, telemetry data will be captured from each workstation (following the Kanban approach), in order to integrate with the Hub & Spoke framework. In this respect, the DT will operate at a wider level - collating data from each of the factory units to allow a system-based view of the project.

5. Conclusion

This paper presented the recurrent challenges facing global housing demand. In doing so, it highlighted the UK's housing shortage, and the need to address this problem ergo social housing in particular. The precursor of this examined new OSC solutions to help guide and support housing developers and supply chain, partners. This work also presented a data-driven approach to highlight new tools and approaches for OSC delivery at the point of housing need. Efficiency gains were showcased, along with future developments planned for the Hub-and-Spoke concept. It was proffered that this could be used to centralise and optimise complex design, where frame manufacturing and certification could be orchestrated within a central 'hub'; and 'spoke' factories could be used to engage expertise through the SME-driven supply chain. In doing so, it was proffered that this additional synergy could harness housing throughput with maximum efficiency, but also generate value-laden benefits across the whole product lifecycle. However, it is equally important to note at this juncture the importance of context. This work was predicated on a single case study and context [steel frame], but there were limitations in applying different AI methods in this context. The constrained nature and application of rules and regulations that exist around the housing of this typology provide more stringent restrictions as inputs into the GD algorithms and so this is an area to be reviewed in future work. From a generalisability and repeatability perspective, readers are counselled to engage a wider remit of manufacturers and systems [proprietary or otherwise] to further enhance the applicability and veracity of these findings.

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