Challenging Space Frontiers in Hospitals

Accelerating capabilities and advancing platforms for modern hospital manufacture

The project *Challenging Space Frontiers in Hospitals* is led by Dr Grant Mills from the Bartlett School of Construction and Project Management, UCL in collaboration with Loughborough University and Cranfield University.

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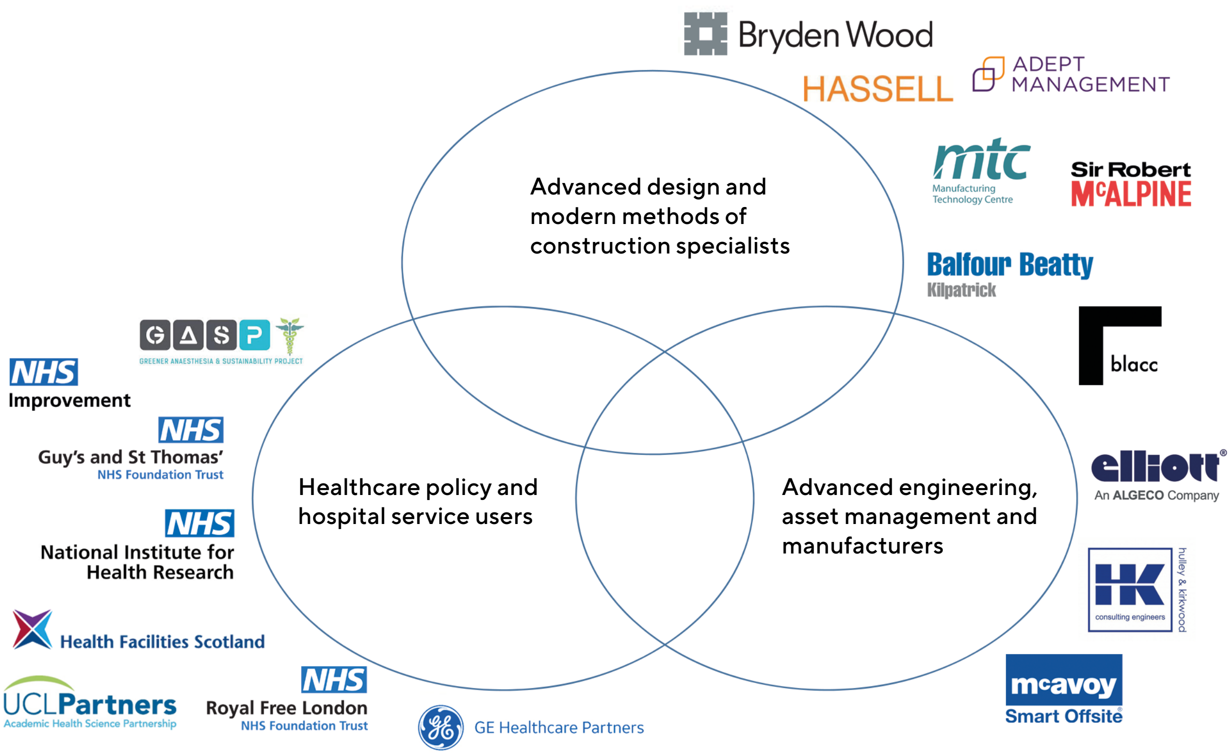


Contents

Foreword to the Research

As the most significant hospital building programmes in a generation commences, we need to challenge how we design and deliver NHS infrastructure. In the Health Infrastructure Plan the Secretary of State for Health and Social Care set out the country's ambition for a rolling programme of investment in the NHS Estate to enable delivery of efficient and personalised health and social care.

Research such as this is critical to advance our planning approaches and to ensure world-class facilities. We cannot sit back. The NHS will continue to demonstrate to the government through the delivery of new hospital infrastructure, that we can innovate year-on-year to strengthen efficiency in the delivery of this programme of investment.

Design and construction of a new hospital exhibits high levels of complexity; some elements of which are comparable to space craft, others have been compared to similar government programmes to deliver school or prison buildings. However, hospitals are driven by fast moving technologies and highly innovative clinical practices. The healthcare sector is unique, and so we plan to develop and apply modern methods in our design and construction approach that are responsive to the NHS' national and local needs.

It has been a pleasure to be involved in this interdisciplinary research that has drawn together NHS clients, clinical specialists, designers, engineers, manufacturers, academics and policy makers to investigate and advance our understanding of modular construction in hospital projects. Using operating theatres (one of the most complex settings) as an example – we have been challenged to think beyond the transactional and short-term project environment to a more transformational environment for learning.

This year, we have witnessed first-hand the agility of the construction sector to respond to supporting the NHS' response to the COVID-19 pandemic. Many are excited to transform this sector and the Health Infrastructure Plan gives us a great opportunity to align incentives, promote advanced capabilities and scale capacity to future challenges.

Martin Rooney
NHSI/E National Estates Delivery Lead

Introduction

1.1 Background to the Report

This executive report describes the final outcomes of *Challenging Space Frontiers in Hospitals*, a collaborative research project involving UCL, Loughborough University and Cranfield University, funded by The Transforming Construction Networking Plus under the UK government's transforming construction challenge (TCC) and Industrial Strategy Challenge Fund (ISCF). It is written for healthcare policy makers, innovative hospital service managers, modular designers, engineers and manufacturers who must work together to innovate advanced operating theatre solutions.

It reports on the advanced capabilities needed to increase the productivity, scalability and speed of delivery of modular operating theatre design for manufacture and assembly, and challenges existing manufactured, volumetric, component and traditional solutions by comparison with spacecraft system manufacturing. The following research objectives were initially defined:

- To research the "presumption for offsite construction" in complex healthcare settings such as operating theatres, and to investigate the basis for their design, manufacture and assembly.
- To explore the capabilities, business models and incentives for accelerated pathways to higher-quality modular operating theatre delivery; and
- To challenge existing frontiers by drawing comparisons with spacecraft system manufacture (e.g. fast-moving technologies, complex interfaces, air tightness and must stay clean throughout operation).

1.2 Need for the Research

It is hoped that this work will inform guidance on the government's Health Infrastructure Plan (HIP) and repeatable hospital design so that the long-term, rolling five-year HIP programme of investment can be delivered more efficiently. Trusts can use one of six commercial models proposed by NHS England and NHS Improvement (NHSI/E) to stimulate solo or collaborative NHS client procurement (Corporate services productivity programme, July 2018). A highly coordinated system of learning and sharing is therefore of paramount importance to enable repeatability and standardisation. This must align commercial interests and build incentives beyond the boundaries of a single project. It should challenge conventions and deliver innovation (as is done in the spacecraft manufacturing sector).

The UK Sector Deal (HM Government, 2018) and the Department for Health and Social Care operate on the "presumption of offsite construction across suitable capital programmes, where it represents best value for money". While cross-government platforms for design for manufacture and assembly (DfMA) are developing (IPA, 2017; Construction Innovation Hub, 2020), universal applicability continues to be assumed (Buildoffsite, 2018), particularly in highly complex spaces such as theatres. This research looks to investigate the capabilities and business models that would drive improvements in modern hospital manufacture (using the test case of an operating theatre).

Healthcare is a key sector in transforming construction. With a capital portfolio of £21bn, it is the second largest area in the UK government's major projects portfolio, for which major deliveries are planned for 2020 and beyond. The NHS is also the biggest adopter of offsite construction in the UK. However, past and existing delivery models, such as NHS Local Improvement Finance Trust (£2.5bn), Procure 21 (£2bn), Procure 21+ (£4bn) and Procure 22 (£4bn), have used relatively traditional design and manufacture platforms. These frameworks favour high-volume repeatability, rather than modularisation of the most complex settings (such as theatres). This research explores potential opportunities and scenarios for delivering modular operating theatres.

1.3 The Research Design

The research had three phases (see Figure 1) to document the contextual influences on the business models, capabilities and evidence informing modular operating theatre DfMA.

Period 1 explored the existing stable environment for theatre manufacture, and established why functional compliance may be stifling innovation in project delivery. This phase involved five interviews, three steering group meetings, and two workshops.

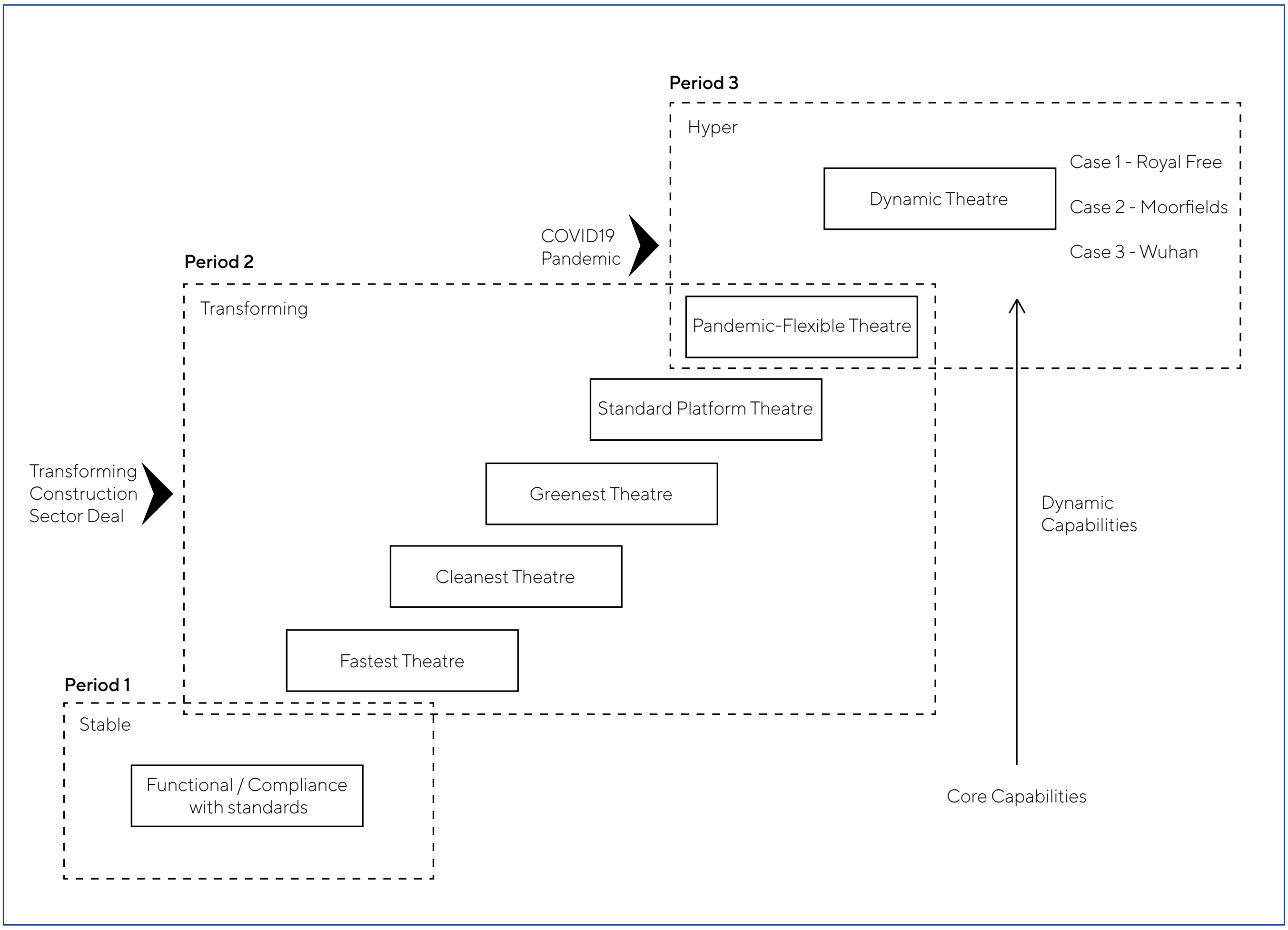
Research in Period 2, which investigated stimulation of the market by the government's TCC through the ISCF, was based on nine interviews, three workshops and one case study.

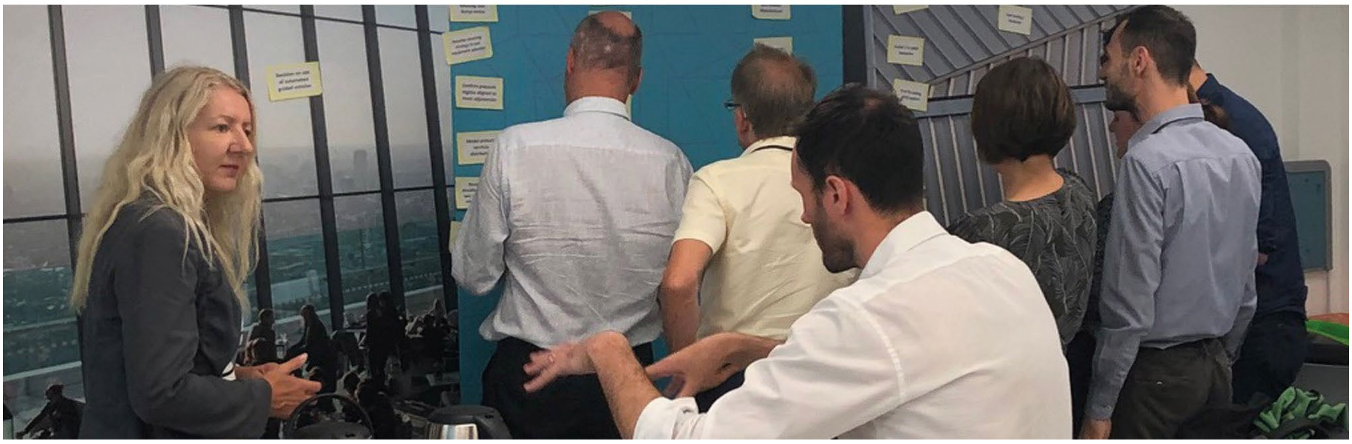
Finally, Period 3, which responded to the COVID-19 pandemic and required rapid and dynamic integration across scientific, engineering, clinical, design, manufacturing and operational expertise. This phase involved three meetings, two case studies and action research.

In the hyper environment of the pandemic, modular manufacturing took on a new significance to deliver flexibility, sustainability and resilience.

The research was undertaken by seven individuals (four practising architects, two engineers and one social scientist). A spacecraft engineer joined the team to challenge advanced systems and modular thinking throughout. The research team was complemented by six practitioners, who facilitated workshops and provided direct inputs into the work (including process engineering, modular system integration, national healthcare facility design policy, infection control, anaesthesia and a national healthcare construction framework leader).

Figure 1. Stable, transforming and hyper periods, demonstrating a need for a functional, fast, clean green, standard platform and flexible, dynamic theatres





Modern Modular Operating Theatre

2.1. Responsive to Clinical Innovation

The research showed that the principle aim of a modular operating theatre is to respond to advances in clinical delivery. Therefore a repeatable solution must be sufficiently flexible to allow changes to be incorporated. For example, we have seen an expansion in theatre sizes to respond to twin arm gas pendants, increased use of specialist and surgical robots, the introduction of ultra-clean theatres, and hybrid imaging and surgical procedures (Figure 2).

A repeatable modular solution cannot be future-proofed against such highly significant changes, but we must develop ways of working with clinical colleges, surgical innovators and technology developers to ensure that we can manage the process of technology succession. As in space engineering, we must investigate areas of high technology risk, future integration issues, adaptions and alternative technology development pathways. We must also work with the supply chain to build expert capabilities and advance approaches to digital systems integration.

2.2. Developing a Mass-Customisable Layered Modular Theatre

To develop economies of scale and scope in layered modular theatre design and manufacture, the level of clinical specialty-specific customisation (Figure 3) must be anticipated. Changes to surgical technology must be facilitated by a flexible and layered modular design that responds to innovation, with system separation between room details, infill services and shell and core. This research has shown the market need for a mass customised solution, but the business models, capabilities and evidence to inform a modular operating theatre DfMA process do not yet exist.

We envisage that different modules of an operating theatre must be co-designed through collaborative planning and specialist supply chain engagement. Coordination must happen through the involvement of a strong and integrated client defining the modular platform and creating systems integration, as is done in spacecraft engineering sector.

Figure 2. Escalation of expectations and requirements for operating theatre standards

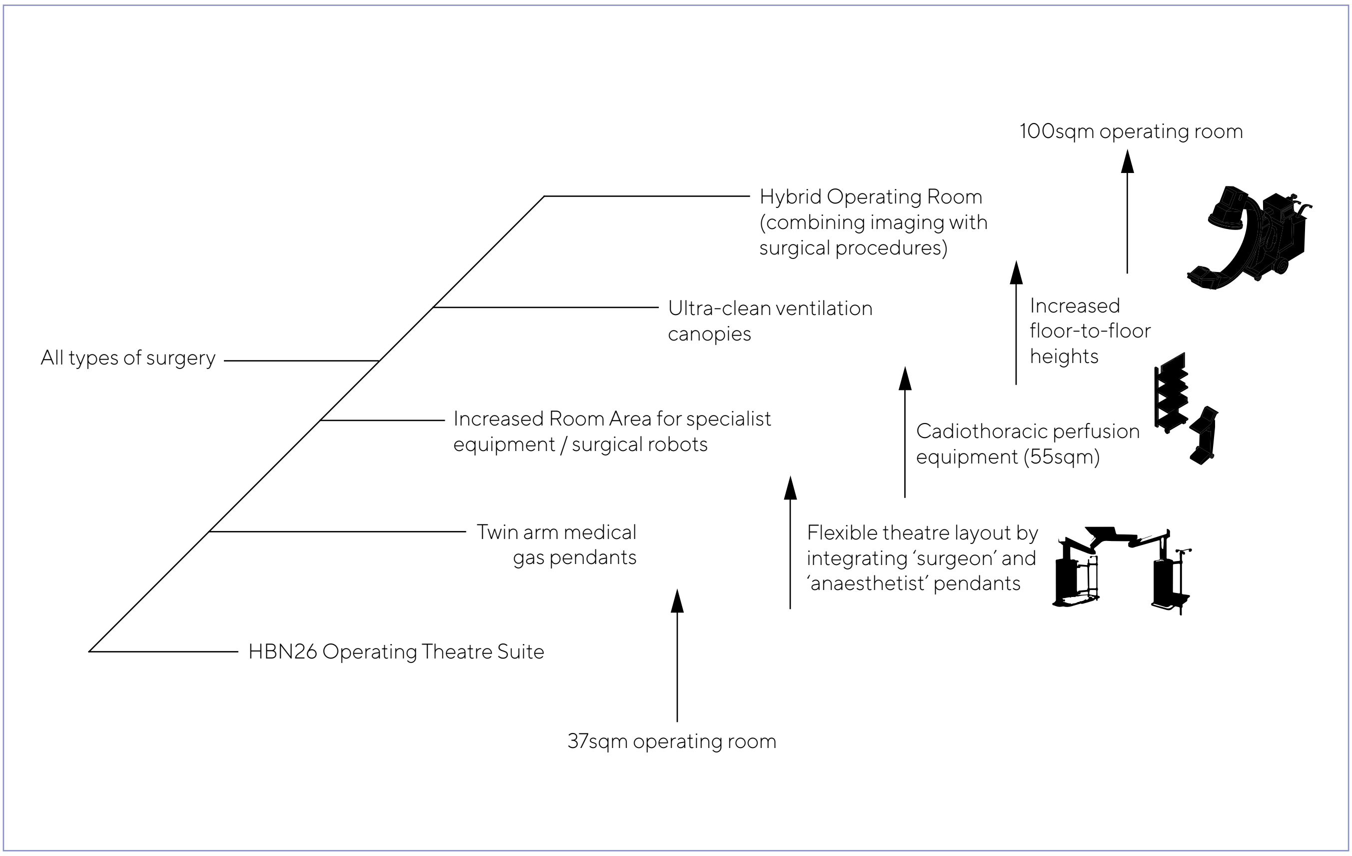
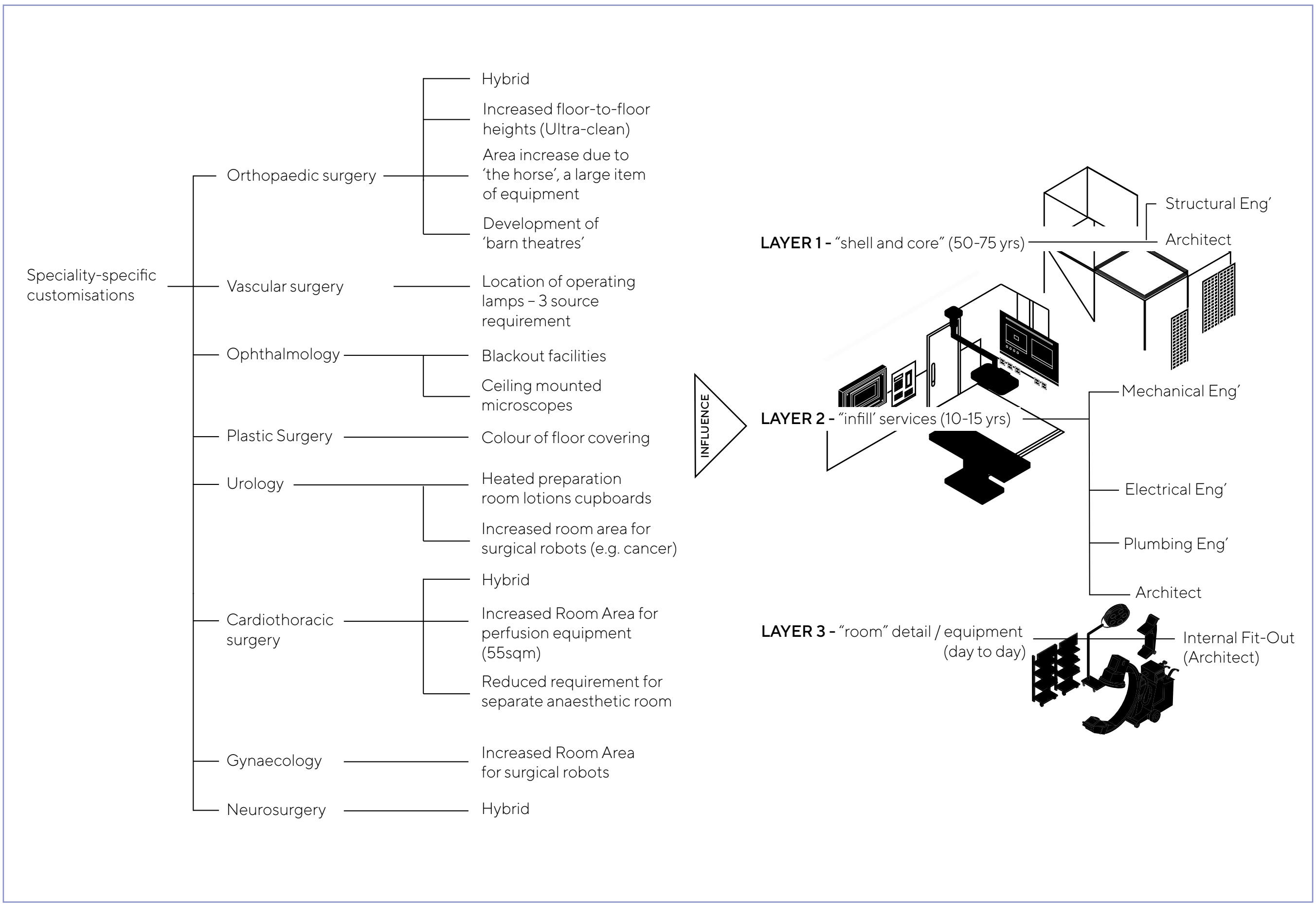


Figure 3. Theatre customisations responding to specific clinical specialties, and the importance of considering these across cluster layers



2.3. Envisioning a "Flat-Pack" Modular Solution

The research showed that a more advanced modular theatres DfMA approach is needed, which would utilise a network of capabilities and become the incubator for a platform to drive forward advances in design engineering. We must research and develop the following components:

- Ceilings (e.g. creating universal connections for medical gas pendants, operating lamps, ultra-clean canopies, lighting and ventilation systems); Ceilings (e.g. creating universal connections for medical gas pendants, operating lamps, ultra-clean canopies, lighting and ventilation systems);
- Floors (e.g. integrating services for robots, imaging equipment and operating tables); and
- Walls (e.g. integrating door and control systems, internal glazing, patient anaesthesia controls, environmental controls, digital displays and fumigation ports).

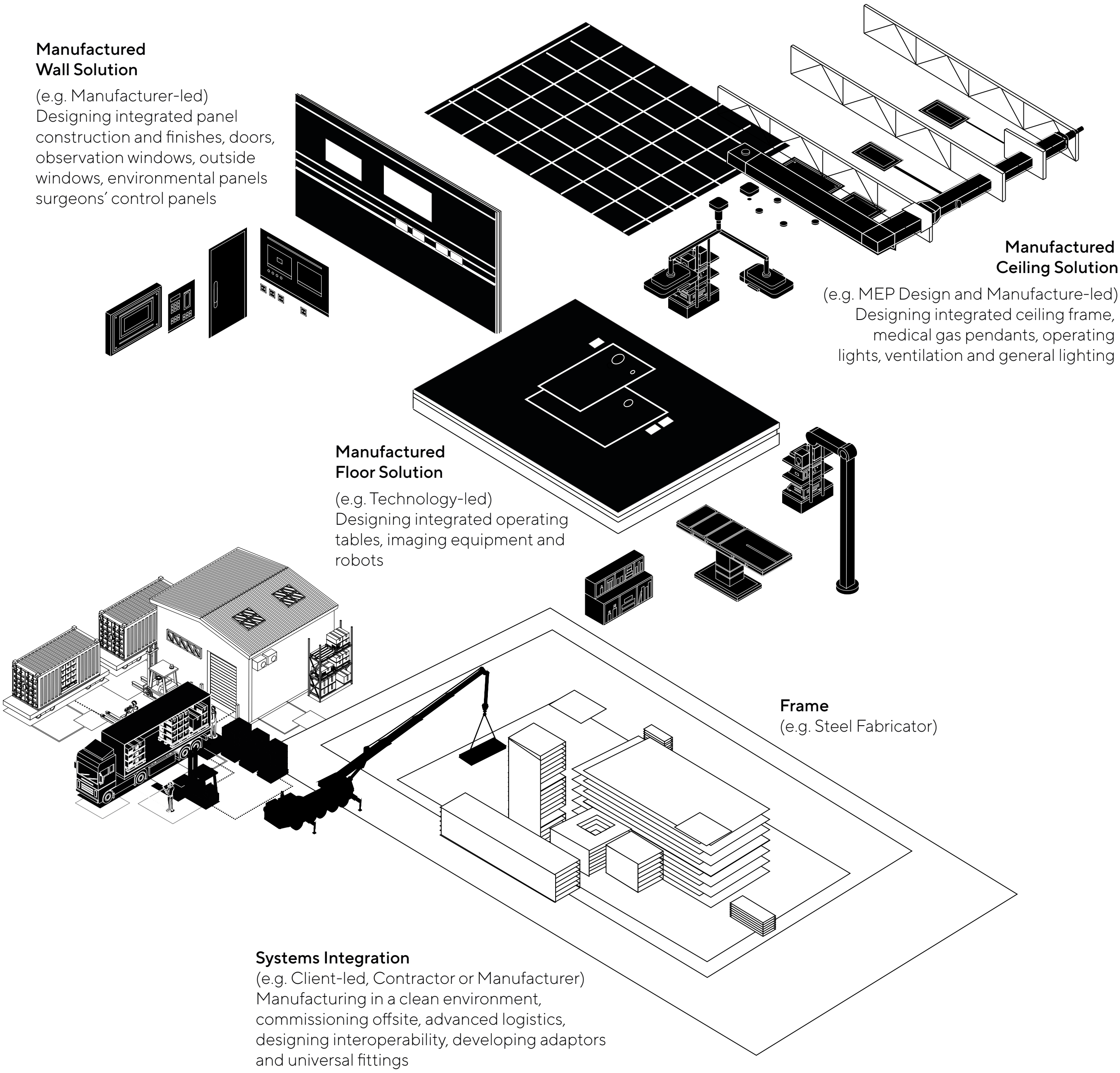
Figure 4 shows an example of how these might be integrated using a flat-pack platform approach.

A "Flat-pack" portable modular theatre would provide a palleted DfMA platform that could be procured at volume. This approach would see the design of a minimum number of portable packages. It would require various users, designers, consultants, contractors and manufacturers to work together to develop a kit-of-parts platform, ideally on a modular framework that invites supply chain joint ventures, or through a wider open ecosystem platform.

Existing integrated solution providers would include contractors or kit-of-parts platform specialists, who would start from scratch or reverse engineer theatre products to optimise manufacturing, logistics and assembly. This would require working across supply chains to leverage their experience, and aligning commercial relationships to achieve volume discounts and programme efficiencies. Simplifying systems into the minimum number of units and parts would require cluster team collaboration. Recognising that some suppliers would be asked to invest in new capabilities and manufacturing technologies and to compete from new positions in the supply chain.

It is critical that the kit of parts is designed to be flexible, to allow choice and to address the largest possible user base and user choice. The approach should be optimised around standard design details and designed for automation wherever possible, with designed components being embedded with metadata, logical rule sets and advanced data flows. Ideally, a digitally enabled web-based configurator would allow selection by the end user and make it easier for architects, engineers, manufacturers and contractors to work collaboratively.

Figure 4. Palleted and repeatable approach to flat-pack theatres using DfMA



A Dynamic Programme of Platform Integration

Throughout the research, we attempted to trigger supply chain innovation by using the spacecraft sector as a comparison and drawing on a wider interdisciplinary capability pool.

Table 1 provides a general comparison of construction and spacecraft platforms at a project, supply chain and wider-industry level. We shared experience of how to change the delivery model, the approach to innovation, access to capability, governance and digital systems integration.

Table 2 illustrates the need to move from a project-based delivery model, which may focus more on core rigidity, closed collaboration, within-firm capabilities, project-only governance and traditional design and construction, toward an open integration model that invests in research and development and overcomes barriers to innovation.

Post-COVID-19, we show the potential for dynamic integration, and what an ecosystem delivery model might look like, with open collaboration and innovation, access to high levels of capability, and dynamic leadership and governance.

Table 1. Comparison between construction and spacecraft platforms

	PROJECT PLATFORM	SUPPLY CHAIN PLATFORM	WIDER-INDUSTRY PLATFORM
DELIVERY MODEL AND GOVERNANCE			
Construction Industry	Many clients procure somewhat unique operating theatre projects from one of many systems integrators. Variability in delivery model, local capabilities and governance.	Limited supply chain involvement in early stage design and programme innovation. Few programme level wider clinical, NHS property or research leaders driving modular innovation.	Competition, contestability and compliance conflicts with innovation across a wider system of collaborative partners. Responsibilities for quality fragmented across policy, design, engineering, manufacture, assembly and operation.
Spacecraft Industry	A small number of procuring clients. Long-term integrated client-systems integrator-manufacturer framework arrangements that drives incremental improvement across projects.	Strong supply chain incentives to design and manufacture an integrated modular solution. Architectural and staged investment in innovation. Modular cluster collaboration and competition. Large systems integrators favour vertical integration of most innovative specialist suppliers/technologies.	United around a single delivery model and standardised governance structures, process/product systems approaches. Strong quality regimes (testing, verification, and validations standards shared industry wide). SME specialist suppliers, systems integrators and clients all investing in R&D. Industry alerts and recalls.
PLANNING AND DESIGN			
Construction Industry	Inconsistent standards and incomplete planning and design (caused by competitive project-based procurement models and clinical consultation processes that delay decision making).	Design and delivery fragmented across design and construction consultants. Limited early engagement of the specialist supply chain in collaborative planning and design.	Few incentives to drive innovation or develop capability. A culture of innovation is hampered by fear of building and system failures. High profile project failures and litigation has meant that contractors, designers, engineers and specialist suppliers comply with outdated standards or transfer risk.
Spacecraft Industry	Standardised and systematic planning and design (applying advanced modular methodologies). International standards for planning, design and project management. Common collaborative digital data environments and consistent approaches to requirements tracking. Rigorous accelerated concurrent engineering requirements.	Integrated planning and design with strong emphasis on continuity roles through business case, design, manufacture, assembly and operation. Early exploration of project options and advanced technologies by a strong client. Clear business/scientific case and adequate budget. Clear decision to invest at an efficient scale for systems integrators and their specialist supply chain.	High levels of standardisation, ongoing challenge for innovation is tempered by a commercial conservatism and the investors and insurers testing regimes that favour heritage, tried and tested technologies, and traceability/reliability. Independent factory visits, quality audits and clients in residence as part of the team and providing continuity and oversight (from planning, through design, manufacture, assembly and operation).
CAPABILITIES, INNOVATION AND DIGITAL SYSTEMS INTEGRATION			
Construction Industry	Discipline specific capabilities development. Capabilities are partially integrated due to the process of supply chain engagement, an inconsistent approach to design and innovation.	Limited contracted supply chain engagement at a programme level to learn between projects and lack of future systems innovation. Lack of shared responsibility and integration across the supply chain.	Institutional and organisational boundaries between disciplines. Reorganisation and structural changes have fragmented common purpose. Need for strong client integrator to drive programme innovation and sector wide capability development.
Spacecraft Industry	Expert systems integrators and advanced client quality teams ensure continuity. Capabilities of the supply chain to deliver projects are regularly assessed. Advanced integrated modelling and common data environments across project planning, design and delivery. High levels of technology readiness and modular flexibility.	Repeated and ongoing supply chain learning and innovation facilitated by client, systems integrator and supply chain R&D. Error-minimisation and strong approach to failure investigation. Consistent planning, design and manufacture standards and clear roles and responsibilities enforced by all.	Singular strong integrated client and highly specialist systems integrator. Co-evolutionary dynamics and modular innovation at a sector level. System, process and product standards, quality testing regimes and roles established and implemented across education-industry boundaries by strong clients.

Table 2. Characteristics that advance innovation, access to capability, governance and digital systems integration

	PROJECT PLATFORM	SUPPLY CHAIN PLATFORM	WIDER-INDUSTRY PLATFORM
DELIVERY MODEL	**Project-based delivery model creates core rigidity:** Procurement route oriented to traditional delivery and existing capabilities with uncertain triggers for innovation. Technical lessons are not learned owing to the project-based nature of the procurement model.	**Existing supply chain delivery model creates core rigidity:** Innovation focus on existing supply chain. Innovations such as standard serviced walls in line with existing delivery model of project-based procurement and volumes. Alignment of future needs and funding with existing delivery models/capabilities, rather than innovation and evidence.	**COVID-19 triggers ecosystem delivery models:** Innovation through appointment of advanced capability pools. Clear target setting, outcome definition and risk allocation to speed development and create dynamic project control. New delivery model that allows direct supplier payment and rapid procurement. Early supply chain involvement and rapid joint working. Aligned vision, incentives and targets, from policy through to the supply chain.
INNOVATION	**Closed collaboration:** Need for approved suppliers, equipment databases, input into design manufacturing and testing. Procurement constraints imposed on manufacturers.	**Somewhat open collaboration:** "Coopetition" (cooperation and competition) dynamics between contractors who protect their supply chains. Full open innovation difficult to achieve as existing frameworks have pre-allocated programme resources and projects are competitive. Innovation from outside the framework is controlled or prevented. Need for innovation and advanced dynamic capability development.	**Open collaboration:** COVID-19 creates uncertainty and reveals need for rapid, open, collaborative and learning platforms. Clinically-led design with technology manufacturers leads to uncertainty, so full service integration is valued. The shell-and-core principle is applied, but not deliberately planned. Innovative interfaces between equipment manufacturers, suppliers and integrators drives more advanced client-led solutions. However, the scale of the market and the uncertain environment are causing business failure.
INNOVATION ACCESSIBLE CAPABILITIES	**Within the firm:** Capability is triggered by project funding, so volatility in demand and fluctuation of funding do not stimulate innovative capabilities beyond core rigidities. Lack of scale prevents capability development within and between firms.	**Within the supply chain:** National funding triggers investigation of opportunities, but there are barriers to co-evolutionary dynamics and a sharing business model. Need for dynamic capability and aligned commercial relationships, and for advanced real-time data to build capabilities and change core rigidities.	**Ecosystem-wide capabilities:** COVID-19 has triggered new co-evolutionary dynamics, funding and a need to move fast. It has highlighted opportunities for a flexible and resilient response, rapid procurement and selection of the most capable teams to integrate design and engineering solutions and build rapid new workflows around army-style logistics.
GOVERNANCE	**Programme and project misalignment gap:** Client leadership at a local level and competition between trusts and suppliers challenge sharing. Major innovation challenges are prevented by project-based procurement.	**Minimal programme governance to stimulate supply chain innovation/ learning and strong contractual relationships:** Limited client-driven innovation targets and procurement barriers. Strong clients are needed to sanction testing of sustainable innovation, and integrate equipment manufacture, control of infection, flexibility and resilience.	**Strong ecosystem through dynamic leadership and governance:** Collaborative working with equipment manufacturers who facilitate customised rent/buy relationships and relocatable and integrated units. Post COVID-19 need for radically redesigned rapid/high-volume clinical care pathways that apply social distancing. Need for a wider system of sharing to integrate new technologies into modular building solutions.
DIGITAL SYSTEMS INTEGRATION	**Traditional design and construction:** Traditional sequencing does not provide effective delivery, suggesting a need for a standard configurator that increases customisation and interdisciplinary integration.	**Repeatable and customised design:** BIM standards for repeatable rooms shared between and beyond framework partners. Need for modular standards that facilitate open sourcing of design to increase volume and contestability.	**Digitally-enabled design integrator:** Advanced planning and logistics across various scales. Need to introduce layers and kit-of-parts approach. Relationship planning by specialist healthcare designers who understand the modular system. Highly integrated cross-professional teamwork facilitated by information technology.

Conclusions

Operating theatre innovation is critical to the development of a modern approach to hospital design and manufacture. This is the most complex setting in a hospital. It requires the integration of 80 to 90% of a hospital's advanced clinical technologies in a single space, thus amplifying the speed of change. Although cross-government platforms for DfMA are being developed (IPA, 2017; CIH platform-design-open-call), there is a need for leadership to drive forward operating theatre innovation.

There is evidence of modular manufacturing in the UK's healthcare construction industry, but the fragmentation and volatility of healthcare programmes may prevent longer-term supplier innovation. History highlights the enduring challenge of producing sustainable healthcare-specific modular solutions. In contrast, spacecraft engineering programmes and projects create co-evolutionary dynamics, advanced modular clusters and develop integrated digital engineering solutions. Diverse teams, who are often not co-located or even in the same country, deal with the complexity of the system through shared common standards and an ecosystem environment that is organised and incentivised to maximise successful outcomes.

The research highlighted a range of areas for development. The need: to advance alliance-based models of procurement; to incentivise short, medium and long term innovation in major items of medical and building services equipment; and to remove technical constraints on innovation. Scaling up the theatre market and continuing the development of an advanced ecosystem platform to build dynamic capabilities would address a number of these challenges.

In order to develop a process to integrate the design of flat-pack walls, ceilings and floors (e.g. panels, controls, ceiling frames, medical gas pendants, ventilation, general and operating lights, operating tables, imaging equipment and robots) more needs to be done to encourage innovation. There are significant opportunities for continued collaborative working to further develop an open platform for innovation, and interdisciplinary contributions to a mass-customised solution.

Recommendations

The following areas of development are required:

1. Establish a new delivery model, smart policy and governance framework

This must establish a long term platform for programme and project level improvements and innovation. It should build strong client systems integration capabilities and encourage the development of supply chain involvement strategies and procurement mechanisms to strengthen the opportunities for technological and modular developments.

2. Create a roadmap toward future modular clusters

This will involve the creation of a network or incubator platform with organisations such as CIH and BuildOffsite, to drive forward advances in design engineering. It will include defining modular clusters, design rules, potential delivery models, innovation stretch targets (e.g. Net Zero), capability development goals, governance frameworks and new digital systems integration tools. It may also involve major medical equipment specialists to align building and technology development.

3. New innovative planning and design process

The research demonstrates that there were inconsistencies in the engagement of clinical champions, infection control nurses, specialist suppliers and academics that would support scientific developments. A new platform, supply chain and project approach is needed that integrates capabilities across levels and triggers new innovative modular designs.

4. Assess the value of the advanced modular platform

Once created, it is important to assess the value of a new modular cluster. We must therefore measure economies of scale and scope, and the IP and benefits of open innovation. This will also involve documenting advanced case studies, for example showing the impacts of reducing the number of parts and variability. This may help to inform future HIP value assessments.

5. Demonstrate a modern modular operating theatre

If possible, we should seek funding to advance the design, manufacture and assembly of a new modular operating theatre. This live implementation would explore technical products, materials and requirements, the production system, parts libraries, and organisational roles and decision-making structures that enable a modular approach. It should also challenge operational aspects such as maintenance.

6. Leveraging HIP insights and learning through research

Learning between key parties is critical, so a programme of sharing must be established (between HIP1 schemes and Trusts, and subject matter experts from NHSE/I, NHSX and external parties). To share NHS Trust learning, researchers must be employed to build evidence and leverage external opinion and best practice, thereby ensuring excellence, minimising costs and making the best use of public funds.

7. Apply innovations from the space industry

Experts from the spacecraft industry have stimulated innovation in our thinking, so further engagement and collaborative research would be highly valuable. Significant opportunities are offered by pressurised docking and cross-docking logistics. For example, temporary docking of an isolation room, or a decontamination or mobile imaging suite might be used for routine expansion, or to react to disaster surges as in a pandemic. The process that is taken by spacecraft engineers to DfMA, standardisation, error-minimisation/validation and testing, systems engineering, modular innovation and process control all warrant further investigation.

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