Digital Twins and Service Innovation in Designing the Hospital of the Future

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Executive Summary

Digital twin (DT) technology is burgeoning into a core area associated with the Industry 4.0 wave. The global digital twin market is expected to reach USD $35.8bn by 2025, with Gartner estimating that nearly half of all large companies will have implemented some form of a digital twin by the end of 2021. In tandem with this rapid progress, research in DTs have also proliferated. Given the emergent yet complex nature of this technology, much of DT research is focused on the technical aspects of DT development – particularly in engineering, manufacturing and computer science.

Less attention, however, has been given to how these technological developments would impact and benefit the needs of service users. Such an approach would consequently allow organisations to form a better understanding of, and to begin planning for how DT technology will impact their digital transformation and service transition journeys. To this end, this paper takes a service-oriented perspective and explores DT technology's potential to address the specific needs and pain points of users, and the subsequent implications for new models of service delivery. Drawing from our ongoing research, this paper focuses on the healthcare industry – specifically ophthalmology –, and uses **Moorfields Eye Hospital** as a case study. It shows that designing the built environment around a new hospital hub needs to start with understanding the service transition and their user-centric needs, and also showcases DTs' potential to enhance service provision and inclusion in healthcare. Finally, some of the oncoming challenges that will be faced by healthcare organisations looking to implement digital technology in the future are discussed.

This research forms part of Centre for Digital Built Britain's work within the Construction Innovation Hub. The funding was provided through the Government's modern industrial strategy by Innovate UK, part of UK Research and Innovation.

1. Digital twins – Overview and key features

What are digital twins?

The Digital Twin (hereafter DT) is an integral concept associated with the Industry 4.0 wave (Negri et al., 2017). Initially conceptualised in the aerospace field, one of the first definitions of a DT was produced by NASA, as "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin" (Shafto et al., 2010: 7). By integrating sensor data from their interdependent vehicle's on-board systems with maintenance history and historical/fleet data obtained via data mining, NASA suggested that a DT would be able to mitigate damage or degradation by recommending changes in mission profile, and ultimately increase both the life span and the probability of mission success.

Since then, research on DTs have burgeoned beyond the aerospace context. In particular, the DT concept has made notable impact on areas such as (smart) manufacturing and Industry 4.0 (Negri et al., 2017), and has been named as one of the five strategic technology trends to watch in 2021 by Accenture (Accenture, 2021). Here, digital twins are most commonly understood as a realistic digital representation of physical assets, processes, or systems in the built or natural environment (The Gemini Principles, 2018). The connection to the physical twin, in particular, is what distinguishes a digital twin from any other digital model.

A high quality and accurate digital twin depends on three components (The Gemini Principles, 2018):

(i) Data – the quality and quantity of data used for the model
(ii) Model – the fidelity of the algorithms that constitute the model, and the validity of the assumptions/ competence of the model
(iii) Visualisation – the quality of final output's presentation

How can digital twins contribute to society?

While this area of work is still nascent, experts both in industry and academia have recognised the potential opportunities that digital twins can bring to society (Gartner, 2019, 2020). At its core, a digital twin unlocks value mainly through its access to dynamic data from a physical asset/system, which allows it to support improved decision making and provide positive feedback back into the physical twin (Mott MacDonald, 2021). The dynamic nature of this data separates digital twin models from static data models, and offers more tools and information for designers and urban planners, policymakers, resource managers and asset owners to work with (Minsky, 2020).

For instance, DTs of built environments can be used to monitor the conditions of different physical assets – e.g. buildings, bridges, energy grids and more –, alert decision makers when (and/or before) these assets need to be repaired or replaced, and even to predict these assets' performance in the future (Lamb, 2021). Industries such as construction, engineering, manufacturing, and automotive are beginning to use such technologies for

1. Digital twins – Overview and key features

the real-time monitoring, remote control of systems, as well as scenario-testing and strategic planning (Minsky, 2020).

In the natural environment, digital twins can be used to monitor ecosystems and processes, which can then for example help forecast and eliminate waste, create a more circular economy and more reuse of materials, and enable disaster planning (White, 2018; IET, 2019; Lamb, 2021).

Much attention has also been paid to how digital twins can potentially support and improve smart places and cities. From improving security (e.g. managing security operations, informing emergency response, advancing remote operations etc.), collaboration (e.g. coordinating maintenance of underground facilities, re-directing traffic flow, helping emergency responders), to advancing urban design (retrofitting and integrating with existing infrastructure), digital twin technology is seen as an integral component of the smart cities vision (IET, 2019). In November 2021, UK's National Digital Twin programme launched a Climate Resilience Demonstrator (CReDo) – a pioneering climate change adaptation digital twin demonstrator project that showcases how connected-data and greater access to the right information can improve climate adaptation and resilience across infrastructure (with particular focus across energy, water and telecoms networks) (Digital Twin Hub, 2021). Eventually, AI algorithms would also be given a degree of control over such systems to further increase efficiency.

Fig. 1. Air pollution model illustrating the discovery of static and highly polluted urban canyons in Monument, London UK.

Sources: Damoulas, 2020; The Alan Turing Institute,2021a

Case: Digital twin model for air pollution in London

Researchers associated with the Alan Turing Institute have been looking for ways to extract more accurate and dynamic air quality data, using London as a case study – where significant areas still exceed NO^2 EU Limit Values. Poor air quality is detrimental to health, and has been associated with the early death of 9,000+ Londoners every year. Using the London Monument area as a pilot site, the researchers utilised a mixture of quality ground sensors, ground measuring stations, and a space satellite to gain live data of air pollution. Integrating the data with an accurate mapping of the built environment, the researchers developed machine learning algorithms and data science platforms to create a live digital twin model for air pollution around the area. This digital twin model was able to:

- Illustrate air flow at different times of the day in specific areas and streets
- Identify areas with poor air quality (along with the discovery that urban canyons are static areas with particularly high pollution)
- Create a 48-hour prediction of air quality in Central London, and, for example, prepare a running route for different times of the day to avoid pollution

Findings from these models are expected to further help design and evaluate the government's urban planning policies.

1. Digital twins – Overview and key features

Federated digital twins – towards a national digital twin

As the previous examples have shown, digital twin technology can be deployed and utilised across a wide range of contexts, and at different scales – from modelling and tracking individual physical assets, to individual buildings, large areas of the natural environment, and even cities. These different digital twins are all integral to the broader vision of a UK national digital twin – which would combine and integrate all of these models. A national digital twin (hereafter NDT), however, is not a large, singular digital twin of an entire country's built environment. Rather, it is envisioned as an ecosystem – or 'federation' – of a country's digital twins, connected together via securely shared data (The Gemini Principles, 2018; Mott MacDonald, 2021).

The ability of a NDT to integrate data across sectors and locations would allow deeper and broader insights to be gained, beyond what organisation-level or sector-based digital twins could provide. For instance, an NDT would enable better use, operation, maintenance, planning, and delivery of national and local assets, systems, and services at multiple levels – from society and the environment, to businesses and the economy. However, to make this vision a reality, an NDT as an ecosystem of federated digital twins rely on interoperability between asset systems to function. With this scale of complexity, an important focus of DT research revolves around the technical and security components of the algorithms and models.

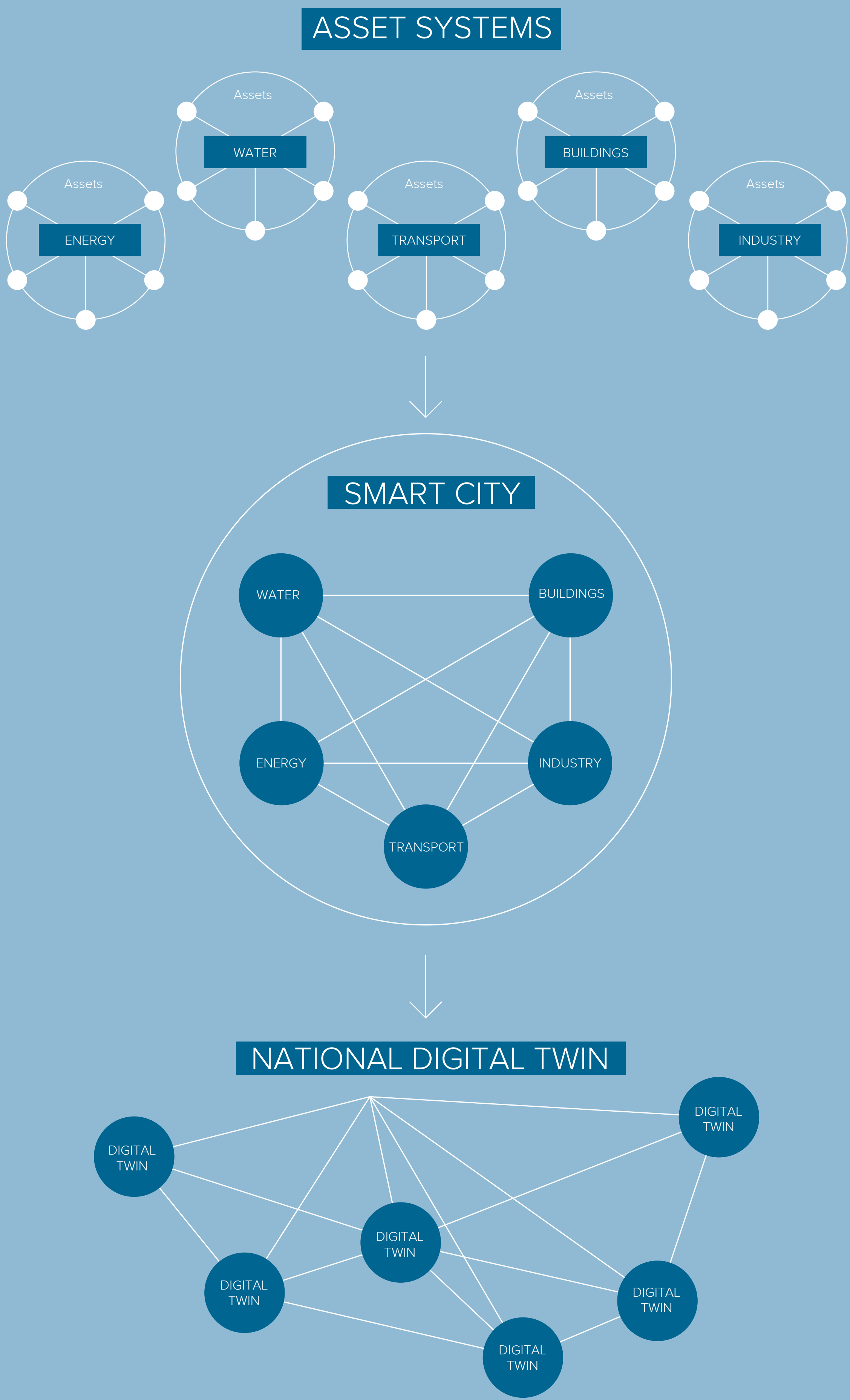

Fig. 2. A visualisation of the multiple layers of systems that make up a national digital twin.

Reproduced from: Mott MacDonald 2021

Managing entire asset systems will bring greater efficiency and oversight.

A smart city brings together its entire asset base as a 'system of systems'.

Interoperability between asset systems will allow better decision making and greater efficiencies.

A national digital twin is an ecosystem of the country's digital twins connected via securely shared data.

2. A service-oriented approach to using digital twins

In this section, we first highlight how digital twins have typically been successfully examined to date, and then explain how our approach complements this by taking a service-oriented approach in using digital twins to innovate for service opportunities.

Much of the existing research on digital twins is situated in the (data) engineering and manufacturing worlds, where a lot of emphasis is put initially on assets and entities. Starting in the physical world, researchers first focus on how assets can be synchronised via the Internet of Things (hereafter IoT). Once that is achieved, data is then able to collected from sensors and devices. This data can be utilised to build models, from which digital twins begin to emerge. Such digital twins can provide a plethora of benefits, for instance, from enabling remote operations (the remote control of a physical process), allowing for post-hoc analysis of events (via rewinding and replaying a series of events), providing the ability to serially track assets, and also enabling digital verification and validation of assets.

Fig. 3. The M3XD bridge being installed.

Sources: Girolami, 2020; MX3D, 2021; The Alan Turing Institute, 2021b

One example of such an approach to digital twins can be seen in the ground-breaking inter-disciplinary work between the Dutch 3D printing company MX3D, and Arup, Imperial College London, Autodesk, University of Twente, Force Technology, and the Alan Turing Institute. Together, they created a digital twin of the world's first 3D-printed steel bridge, to gather data that can be used to push the boundaries of conventional manufacturing structures, and to gather new data about this pioneering material of 3D-printed steel – since not enough is known about the material's properties to guarantee safety standards for wider use and manufacturing.

A 3D-printed steel bridge was created, and was fittted with a state-of-the-art sensor network, such that everyone that crosses over the bridge will generate detailed live data while in operation – including strain, displacement, vibration data and environmental factors such as air quality and temperature. This data is then to be fed continuously into a digital twin of the bridge, which will learn from the live data and then be used to measure, monitor, and analyse the performance of the structure. In the future, the performance and behaviour of the physical bridge will be tested and compared against its digital twin, which will then inform the design and certification of future 3D printed structures. Beyond that, the over-arching vision of this project is also to develop

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the mathematical and software engineering foundations needed for intelligent digital twins, that will lead to a wider variety of engineering applications.

The emergence of digital twin technology represents and provides a wealth of opportunities for radical innovations to take place in the future – the case of the MX3D bridge and 3D-printed steel being a case in point. As such, a considerable proportion of extant research explores how digital twins can provide novel, technical capabilities for existing industries, from engineering and construction to urban planning and policymaking. Simultaneously, given the nascent nature of DT technology that is still being developed, a lot of research focus has also been put into the technical and software engineering foundations of digital twins, so that they can be safely applied in such contexts, at scale, in the future.

These two areas of research outlined are significant, particularly for the development of digital twin technology itself. However, it is equally important in the design and development of a digital twin that a service-oriented approach be taken which centre stages how these technological developments would actually impact and benefit the needs of service users and help them perform the jobs they need to get done. A service-oriented approach to researching emerging technologies is therefore particularly valuable and vital, to prevent a situation of 'a solution searching for a problem', and to ensure that technology developed will be able to relieve end users' pain points and/or enhance their service experience.

Research on service innovation takes inspiration from a service-dominant logic (Vargo and Lusch, 2004, 2008b, 2008a; Lusch and Nambisan, 2015) and reconceptualises service 'as a process of using one's resources (e.g. knowledge) for someone's (self or other) benefit' instead of as a unit of output (Barrett et al., 2015: 138). In this view, all economic exchanges are basically service exchanges, and physical goods (where applicable) are mechanisms for service provision (Barrett et al., 2015). Producing services is distinct from producing products/goods: 'to produce a service...is to organise a solution to a problem (a treatment, an operation) which does not principally involve supplying a good. It is to place a bundle of capabilities and competences (human, technological, organisational) at the disposal of a client and to organise a solution, which may be given to varying degrees of precision'. (Gadrey et al., 1995: 5-6).

In relation to digital twins, taking a service-oriented approach means that the limelight shifts towards the service delivery as a whole. Rather than seeing digital twins as an 'entity' to be further developed, and investigating how particular assets and materials may integrate from the physical world to digital twins, we conceptualise digital twins as an enabling technology to innovate for service delivery. That is, we explore how digital twin technology can be used to address the specific pain points and needs of users, and be used to create new models of service delivery to the end users. Taking such a lens also influences the types of questions that will be asked, for instance on the types of data that will be needed, what the digital twin will be 'of', and who the possible beneficiaries are (rather than owners of the digital twin 'entity').

In the following parts of this paper, we adopt a service-oriented lens to complement and go beyond the typical view of digital twin as a technological tool, and instead relate it to the design and use of the built environment.

Moorfields Oriel Oriel is the joint initiative between Moorfields Eye Hospital NHS Foundation Trust, the UCL Institute of Opthalmology (IoO) and Moorfields Eye Charity that would see services move from Islington to a new, integrated centre on part of the St Pancras Hospital site in Camden.

Source: www.oriel-london.org.uk

3. Moorfields Eye Hospital and its service transition journey

A case study

Sight loss is an increasing problem in the UK. Currently, it is estimated that two million people in the UK are living with sight loss – of which 360,000 are blind or partially slighted – (The Telegraph, 2021), while it's estimated that four million people will be living with sight loss by 2050. AI and digital technologies are pushing the boundaries of how eyecare is currently provided and are offering new possibilities for treatments and cures in the future. To leverage these oncoming opportunities, Moorfields Eye Hospital – the leading provider of specialist eye health services in the UK and a world class centre of excellence for ophthalmic research and education – is designing and constructing a smart hospital of the future. Known as "Oriel" – a joint venture between Moorfields Eye Hospital, UCL and Moorfields Eye Charity –, the new hospital will host state of the art technologies, from telemedicine to machine learning and AI technologies and more. Combined with insights from the data analysis that will be embedded throughout the hospital's service provision, the future Oriel hospital will enhance and transform the ophthalmology service provided to NHS patients.

However, the process of transitioning the current service into the future service is a significant challenge that Moorfields is currently looking to tackle. First, the physical relocation of any hospital is an enormous task, and moving an eye hospital where the visually impaired patient community have a more complex relationship to the built environment and digital technologies presents additional challenges. Second, the current services provided to patients by Moorfields will also need to be integrated with and transitioned onto the future service model and ecosystem – which will be an even bigger challenge. In particular, ecosystem stakeholders such as clinicians and caregivers will also have to work in new ways and take on new roles. The ensuing sections will elaborate on these two challenges, and will be followed by a consideration of digital twin technology's potential to offer solutions.

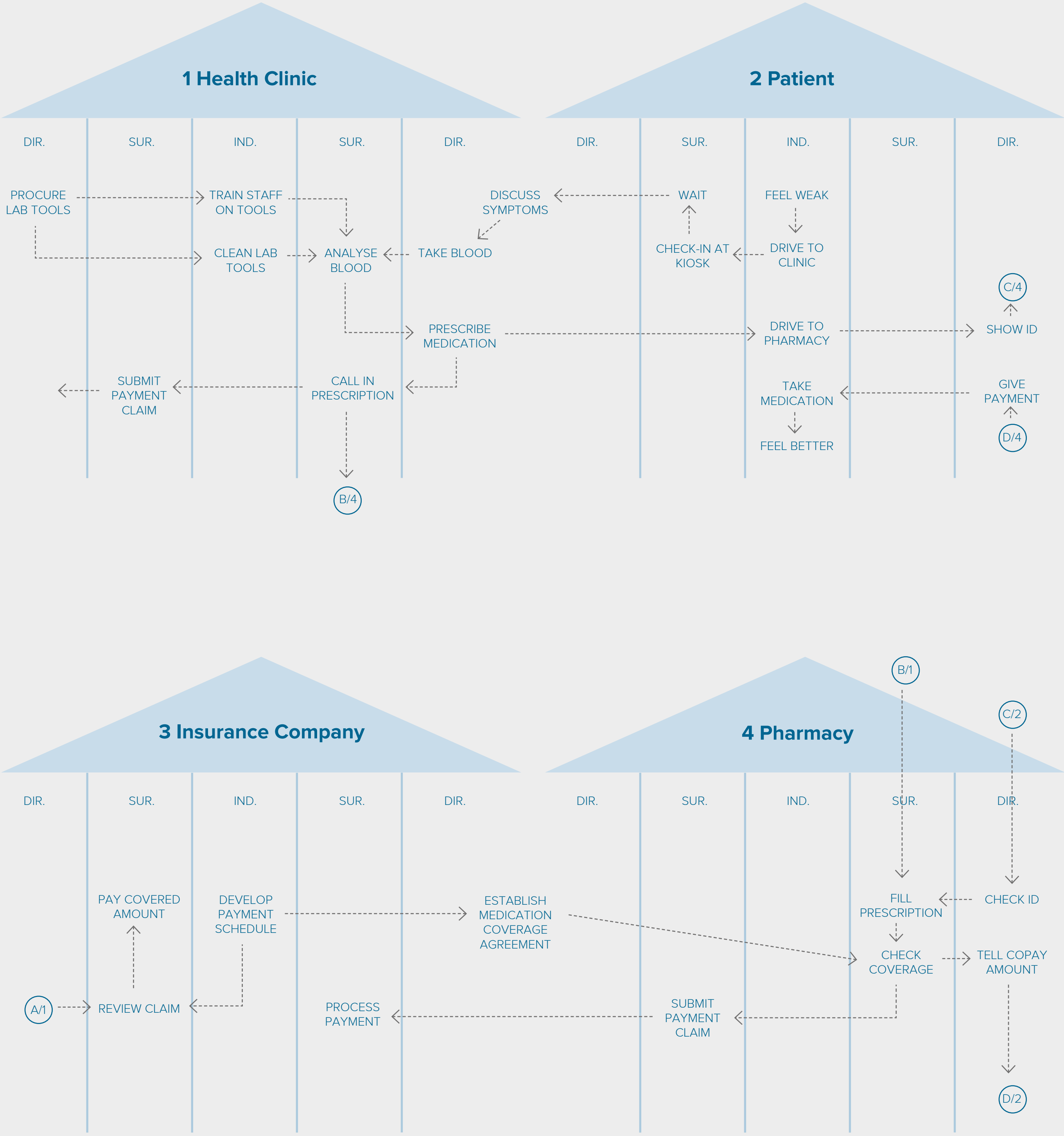

Fig. 4. Diagram showing the process dependencies for a patient who feels weak and needs a prescription based on a blood test.

Reproduced from: Sampson, 2012

Fig. 5.1
A prospective user journey for future Oriel hospital patients

Patients' user journey	Home to Kings Cross	King's Cross to Oriel – 'The Last Half Mile'	Oriel check-in	Flexibility post check in (toilets, tea)
Patient action	Navigate from home to tube station, & navigate complex tube changes	Navigate through London's biggest interchange, crowds, and train passengers to hospital 15 minutes away	Find receptionist to check in	Find the way to a toilet and cafe after a long journey
Environment	Street level, underground	Underground, big crowds, street level	Hospital	Hospital
Pain points and patient emotions	Any obstacles on the streets? How will I find the right interchanges to get to King's Cross	So many exits and such a busy interchange – how can I safely get to the street-level? Crowded streets to Oriel	Will I remember to ask the receptionist everything I need to know navigationally? What if I need navigational help later?	Tired after a long trip. Can I comfortably go to the toilet and get water/tea without fear of getting lost or missing appointment?
Risk to patient	Tripping hazards on street level, getting lost in the tube system	Getting bumped into, getting lost	Not noting down instructions may have consequences	Missing appointment or getting lost inside the hospital

Fig. 5.2
A prospective user journey for future Oriel hospital patients

Patients' user journey	Navigate to doctor (or asking for help)	Pharmacy + leave building	Oriel back to King's Cross	King's Cross to home
Patient action	Navigate through hospital to doctor's room and the correct waiting area	Navigate from doctor to pharmacy, and back to the right exit	Navigate through London's biggest interchange, crowds, and train passengers	Navigate through complex tube system back home
Environment	Hospital	Hospital	Underground, big crowds, street level	Street level, underground
Pain points and patient emotions	Am I waiting in the right place? What if I am not and I have unknowingly missed my appointment?	Have I remembered the receptionist's directions to the pharmacy correctly? How do I find the right exit after?	Can I remember how to get back to King's Cross? Is it peak hour now?	Any obstacles on the way back home? Where do I have to change tubes again?
Risk to patient	Getting lost and/or missing appointment	Leaving from wrong exit could be disorienting for subsequent journey	Getting bumped into, getting lost	Tripping hazards on street level, getting lost in the tube system

3. Moorfields Eye Hospital and its service transition journey

Navigating the 'Last half mile'

As part of Moorfields' transformation process, the century-old Moorfields Eye Hospital will have to relocate from its current home in London's Old Street to a two-acre site at St Pancras Hospital, in the Kings' Cross area. However, the nature of visual impairments that Moorfields treat create additional challenges for the hospital to consider.

The first challenge lies in navigation to the hospital. The ophthalmology healthcare service has traditionally been, and is still, very much dependent on physical examinations though more recently there has been rapid advancements in virtual consultations that have been accelerated as a response to the COVID-19 pandemic (Li, Thomas, et al., 2021). An in-person consultation, where the clinician and patient are co-located, is the standardised service provision for eyecare. This is to allow for physical eye examinations and scans to take place, so that an accurate diagnosis of the patients' eye conditions and an appropriate treatment plan can be produced. These physical consultations are deemed critical, particularly in urgent and unscheduled Accident & Emergency (A&E) cases – for which Moorfields is currently the major provider in London. While it is vital for patients to be physically present at the hospital, it can also be a challenge to navigate to the hospital in the first place, given their eye conditions. As such, Moorfields face a rather unique, and perhaps amplified, navigational challenge in their relocation and transformation process.

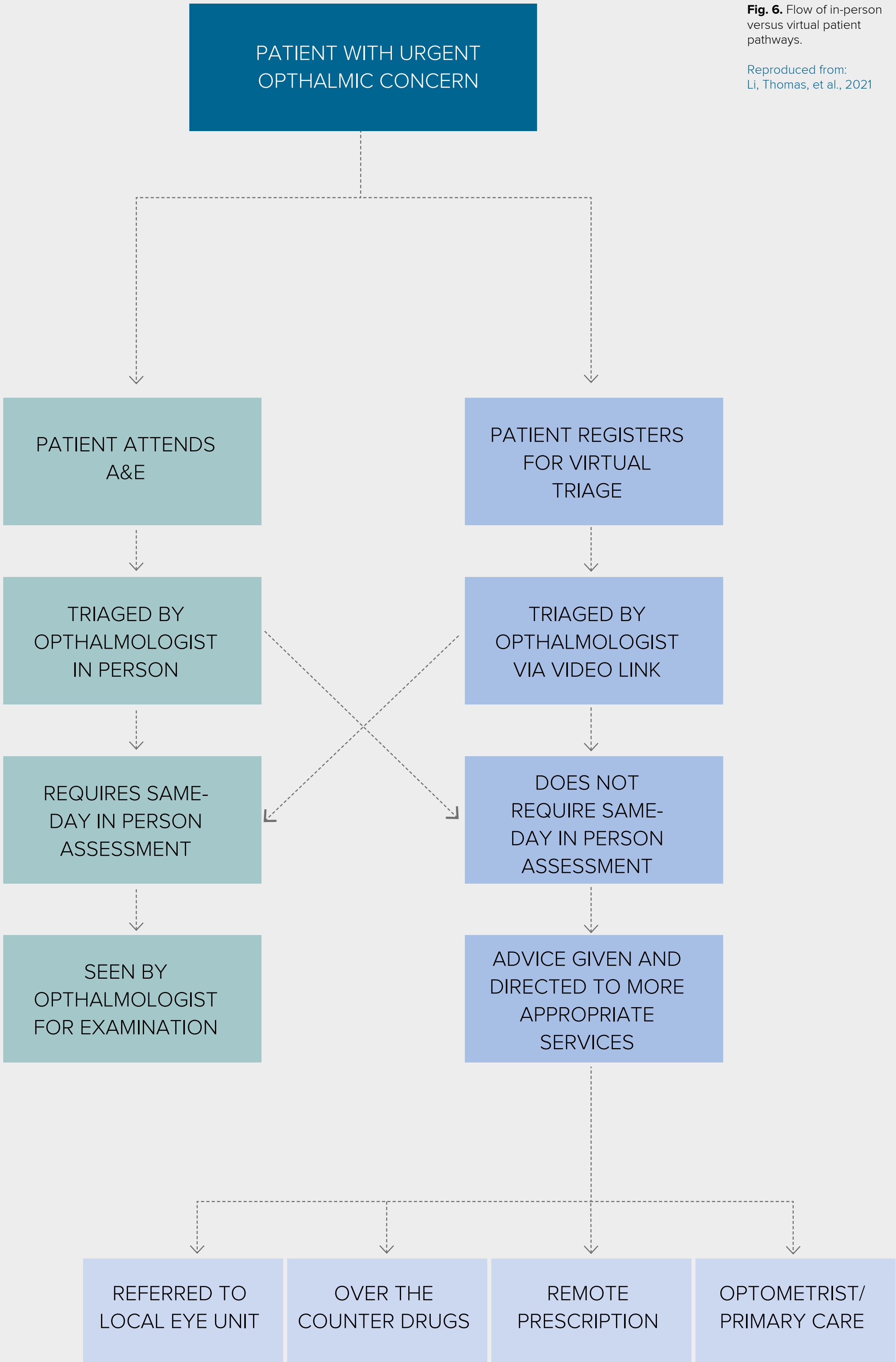

Fig. 6. Flow of in-person versus virtual patient pathways.

Reproduced from: Li, Thomas, et al., 2021

3. Moorfields Eye Hospital and its service transition journey

Moorfields' navigational challenge

Currently, Moorfields is relatively easy to access via public transport. It is located 3-5 minutes from Old Street Underground station – on the Northern Line – via foot. Most notably, Moorfields has a 'Green Line' route in place to help their patients navigate to the hospital. That is, a weather-resistant green line has been painted on the floor, that runs from the exit of the Old Street Underground station to Moorfields' front doors. As such, as long as patients 'follow the green painted line' when they get off the train, they would be able to navigate to Moorfields with relative ease (Moorfields, 2021). In addition, there are also bus stops located right outside the hospital as well as opposite it, on one main road (City Road).

Fig. 7. Green line leading patients from Old Street Underground station to Moorfields Eye Hospital.

3. Moorfields Eye Hospital and its service transition journey

Moorfields' navigational challenge

Navigating to the future Oriel site in the St. Pancras and King's Cross area, however, will be a lot more complex for Moorfields patients in the future. As visualised in the figure opposite, the future Oriel hospital is in fact situated between six Underground stations (Kings Cross/ St Pancras, Euston, Mornington Crescent and Camden Town and Camden Road Overground station) and is 800m and a 13-minute walk away from King's Cross National Rail station. While the access points may have increased, it in fact creates complexities and challenges for visually impaired navigation. In particular, King's Cross/St Pancras International station is one of largest travel hubs in Central London and the UK. The Underground station is the biggest interchange on the London Underground, and is served by six lines in total (Northern, Piccadilly, Victoria, Metropolitan, Circle and Hammersmith & City) (Attwooll, 2018). In addition, there are 11 entry/exit points for the station. As such, just getting out of King's Cross station and onto the street level safely would already be a challenge for the visually impaired, before even considering further navigation to one of the entrances to the hospital site 800m away.

Apart from being one of the largest interchanges, King's Cross & St Pancras stations are also exceptionally busy. Statistics from the Office of Rail and Road show that these two stations are the 9th and 10th busiest stations in the whole of Great Britain (Office of Rail and Road, 2020). In 2019-2020 there were 68,572,484 entries and exits from these two stations, and 7,188,797 interchanges made (ibid.). In addition to the Underground, the King's Cross St Pancras transport hub is also home to two National Mainline rail stations, international high speed rail, connections to London's five international airports, 14 bus routes, and over 400 public bike spaces (King's Cross, 2021). This level of foot traffic makes navigation to the hospital very challenging for the visually impaired, with increased chances for disorientation and accidents to happen.

Fig 8. Map of the future Oriel hospital in proximity to nearby stations.

Reproduced from: Oriel, 2021

3. Moorfields Eye Hospital and its service transition journey

Moorfields has recognised the above navigational concerns as important issues that need to be tackled. Accumulating feedback from previous public consultations, engagements, and a survey conducted in February 2021, the Moorfields team found that patients actively raised concerns for this last part of their journey, from public transport hubs to the new Hospital – now labelled 'The Last Half Mile' (Oriel, 2021). Patients, particularly those with sight loss and mobility issues, were most concerned with the safety of road crossings, the current lack of nearby bus stops and the walking distance from the main transport hubs (ibid.). To tackle this issue, Moorfields has started working with Buro Happold since the summer of 2020, who undertook audits of pedestrian routes and found that routes from some stations were too complex and far for those with sight conditions to navigate and walk. Some initial ideas include implementing a 'green line' – similar to the one between Old Street and Moorfields – from the King's Cross area to the future Oriel hospital, discussions with TfL to change bus stops and bus routes, and the possibility for a charged shuttle service between King's Cross and Oriel.

However, while 'low-tech' solutions such as the green line is deemed 'robust' by those consulted by Moorfields, several issues remain. For instance, the green line will require further trials and consultation as there is currently no nationally recognised format that is suitable for such a long route and purpose. Moreover, the green line and potential shuttle bus would only begin at specific points on the street level, which does not solve the issue of navigating from the complex and busy Underground hub to the street level, or from patients' homes to the King's Cross area. The green line, being an analogue and 'low-tech' solution, is also not capable of dealing with any unexpected and sudden adjustments to the route, for instance from road closures to station and exit closures. Finally, despite being a 'weather-resistant' material, the green line in fact does fade and deteriorate over time – a problem that the current line is facing. As such, Moorfields is continuing to explore how new and evolving wayfinding technologies can help with orientation and navigation (Oriel, 2021).

Innovating technological solutions to tackle visually impaired navigation for service inclusion in transitioning to the new hospital hub

Drawing on a service-oriented approach, the above section has emphasised Moorfields' user needs in detail. The pain points for visually impaired navigation through a large and busy transport hub, and limitations of existing potential solutions have also been made clear. Given this, how can emerging technologies, such as digital twins, be used to provide potential solutions?

Researchers and entrepreneurs have been increasingly trying to tackle visually impaired navigation with new technology (Li, Liu, et al., 2021). For instance, specialist eyesight researchers at the Mass General Brigham non-profit hospital in Boston (USA) have recently developed a smart camera prototype to help visually-impaired individuals avoid collisions (The Telegraph, 2021). The camera captures nearby surroundings, which is then analysed by a connected processing unit to determine risk levels. Two wristbands are connected to the device, and both bands vibrate when a direct collision is imminent, while only one wristband vibrates to warn of a collision on one side. In one of the first randomised-controlled trials to look at the potential benefit of

3. Moorfields Eye Hospital and its service transition journey

these devices at home and outside of a controlled lab environment, the researchers found that the camera could reduce collisions by approximately 37% (Pundlik et al., 2021).

Other technological advancements are also being made, which have the potential to facilitate visually impaired navigation. Instead of creating a new piece of technology, which may ultimately be more costly and less accessible to users, some companies have explored how existing smart phone capabilities could be employed. For instance, Waymap has created an integrated wayfinding system via a smartphone app, which provides navigation, information, emergency assistance and smart services to every day travellers including people with visual impairments or other disabilities.
Waymap's technology utilises dead reckoning – a combination of multi-sensor data – to determine where a user is located as he/she travels. The data used for this calculation is derived from:

- Sensors built into smartphones – including accelerometer, gyroscope, magnetometer, and barometer
- Native location services built into phone operating systems e.g. GPS, Cell network, Compass, 5G
- Integration with transmissions from the surrounding built environment e.g. Bluetooth beacons and Wi-Fi heatmaps

Apart from the use of live data, Waymap also has a map included in the app, which can be downloaded onto the phone. Subsequently, the app would still work without live data, and would be able to use the other functions of the phone listed above to provide navigational assistance to users. Additionally, the app is also able adapt to users over time, and learns their gats, strides, navigation techniques and mobility.

This technology has already gained the attention of several cities' metro systems. Most recently in 2019, the LA Metro commissioned a live trial of the technology within Los Angeles Union Station to explore how this technology could be used for navigation in public transit by the visually impaired (Wesler, 2019). Two test routes were designed for participants to test the usability and accuracy of the technology in real-world scenarios. 95% of the trials' participants expressed that if this technology was widely available, they would feel more confident to travel on their own, and would also be more likely to use public transit (Wayfindr, 2019).

In comparison to the camera and wristband devices, Waymap's technological solution may be more accessible and socially inclusive, in that it does not require a separate piece of specialist and expensive equipment to function. In addition, battery life (which would directly correlate with the distance that can be covered/travelled on one charge) would also likely be less of a concern for Waymap's technology, given that it does not require a video feed to be constantly taken and immediately analysed. However, despite these advantages, there are several distinct areas in which Waymap still face challenges in, and coincidentally also areas where digital twin technology may be able to provide an enhanced solution.

3. Moorfields Eye Hospital and its service transition journey

Fig 9. Passengers leaving Kings Cross St Pancras Underground station

Digital twin technology's potential to tackle visually impaired navigation to/from a hospital

As described above, Waymap's technology creates valuable, new possibilities for visually impaired navigation. However, there are nevertheless several limitations that currently prevents Waymap from being a comprehensive solution to Moorfields' navigational challenge.

First, Waymap's access to transmissions from external objects and places of interest in the built environment is limited. Currently, Bluetooth beacons and Wi-Fi heatmaps are Waymap's main sources of data from the built environment. However, the number of nearby sensors and Wi-Fi points can be rather limited, depending on where the user is. This is especially pertinent when considering the entire user journey from door to door. Transport hubs such as large Underground stations (or the Union Metro station in Los Angeles, where the previous Waymap pilots took place) would possess a higher number of Bluetooth beacons and Wi-Fi points, especially when such stations are designed with accessibility in mind. Despite this, a visually impaired person would need to travel to a station, and away from a station to their final destinations too, and in less populated cities and streets these data points diminish drastically. In fact, in the Los Angeles trial report, one initial finding was that in spaces where there was no continuous beacon coverage, the changing of the phone's orientation on a participant caused incorrect estimates of the person's position in several instances (Wayfindr, 2019: 21).

Having a connection between an app like Waymap and an established national digital twin, would reduce this issue dramatically. In such a scenario, the number of assets that could be used as data points for Waymap's navigational system would be increased by an incredible amount, as even the smallest of assets – such as pipes or light bulbs in a building – along the visually impaired person's route could potentially be used to provide more accurate estimates of the person's live location. Moreover, the costs of implementation/integration would be minimal, if the assets are already fitted with smart sensors for the digital twin model (instead of separate Bluetooth beacons needing to be installed purely for accessibility reasons).

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Having a vastly increased data source would also benefit visually impaired navigation in providing more dynamic and flexible routing options. For instance, if a particularly busy train or bus arrives at King's Cross, which would cause a visually impaired person to suddenly have to navigate through a sea of people, having a connection to a digital twin of the King's Cross area could allow Waymap to be made aware of this clash and provide an alternative route for the user (or give them a choice to reroute). In another example, if items fitted with smart sensors are trip hazards – such as a bin, or even one that has fallen over –, a live connection to the digital twin can again result in a safe and quick change of navigational instructions. A final example can be easily illustrated – current map-based location services (such as Google Maps or Waze, that Waymap is based off) is by and large not able to provide information about where individual or specific cars are located (from having stopped in unusual places due to accidents, to speeding/running lights and causing safety concerns), but a digital twin would.

Second, the establishment of a digital twin would also allow for more efficient negotiation, integration and scaling up of services like the one Waymap offers. In fact, Waymap is currently facing barriers in its negotiation with TfL for access and permission to map the whole Underground system. Such agreements and deals are complex in nature, with multiple sets of stakeholders involved, and a lot of security concerns. To put this into perspective, even the low-tech, physical green lines from Old Street station were not able to be implemented within the King's Cross Underground platforms, and could only start from the ground level; an agreement to digitally map the entire Underground system would be far more complex. Even if such concerns were resolved, not having an existing integrated digital twin/mapping of the Underground for example would drive costs up for each individual company that may end up needing to do their own mapping separately.

Having an existing digital twin would provide notable advantages for more efficient negotiation and scaling up of services like Waymap. The security and mapping concerns would have already been tackled by the efforts involved to create the digital twin in the first instance, such that other companies could potentially be able to easily gain the relevant data and information from the twin via an API. This would open up possibilities for many other innovations beyond visually impaired navigation too.

Digital twin technology's potential to tackle visually impaired navigation within a hospital

Having considered the potential benefits that a DT can bring to a visually impaired person's navigation to the future Oriel hospital in King's Cross, there are also certain additional advantages that a DT could bring to navigation within the hospital itself. This is particularly so if a digital twin of the future Oriel hospital built environment itself is developed (in contrast to a London or UK national digital twin that is considered above).

First, visually impaired patients at Moorfields currently have very limited freedom of movement within the hospital. They still must rely on visual signage to get around the hospital (aside from any verbal instructions given at the registration desk), which can make it very difficult for patients to navigate depending on their specific eye conditions. This uncertainty adds stress to

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the appointment, as patients may not dare to wander too far away from their designated appointment room, even for toilet breaks or to get food/water. One recent advancement by Moorfields in 2018 to address this was through the implementation of an electronic pager system, which alerts patients via a buzzer when they are due to be called, and in so doing allows patients to leave their seats for a drink or comfort break (Moorfields, 2018). However, this relatively low-tech solution does not tackle other outstanding navigational issues that patients face inside Moorfields. Taking into consideration the user journey again, Moorfields patients face uncertainty not only over when they are due to be called, but also over how to navigate to various places: from the registration desk to their waiting area, to the toilets, coffee shops, the pharmacy, and the exit again. Furthermore, if they do get lost within the hospital, there is currently no easy way for patients to ask for help.

Some of these challenges can be resolved if an app-based navigational system like Waymap can be integrated with an established digital twin of the future Oriel hospital. As the digital twin would have all the rooms and places of interest mapped, linking this with an app like Waymap would allow for personalised navigational instructions to be given to patients, wherever they need to navigate to within the hospital. Notifications to alert patients that they are due to be called can also be integrated into the integrated app, which would then also allow patients to be re-directed from wherever they are located within the hospital to the appointment area – something that the current physical buzzer system is unable to do. This can also be done to notify patients of any changes or delays to their appointments (to reassure patients that they are not waiting in the wrong place, or have not missed their appointments). Moreover, if patients do get lost within the hospital, an integrated app would allow patients to ask for help and also allow staff members to locate them. There are also benefits for such a solution, beyond the patient experience. For instance, it is more sustainable to integrate the navigational solution into smart phones that patients already own, rather than having to buy/manufacture separate buzzers that are designed only to tackle one problem. This would additionally also contribute to cost-savings for the hospital too.

Digital twin technology’s potential to enhance Moorfields’ future service provision

Apart from the navigational advantages that an app integrated with an Oriel digital twin could provide, this system could also potentially improve the hospital’s future service provision. For instance, Moorfields are currently heading towards a vision of implementing more automated scans, where patients may ultimately walk into a room of scanners, conduct a scan on each, and will be able to leave quickly. Having an app integrated with a digital twin could potentially streamline such a process, where patients are notified when the next machine is free and that they can move onto it, and can be given audio instructions via the app. This could increase the efficiency of the scanning processes, and diminish the need for individual technicians/clinicians to cater to every single patient’s scans, which would allow the hospital to better allocate expertise to more serious cases. The machines would be linked to the DT, which would also be able to alert the hospital before (and after) any machine malfunctions, and as a result would also lead to increased efficiency and decreased costs.

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Additionally, Moorfields has also been making huge advancements and innovations on telemedicine. As a response to the COVID-19 pandemic, Moorfields created and implemented an unprecedented video consultations system to alleviate the need for physical consultations and the risks they may bring. With the hospital reaching the milestone of 100,000 virtual consultations within three months, this virtual consultation platform has been deemed a hugely successful and necessary operation, and Moorfields is now beginning to explore how it may be integrated as a permanent fixture of Oriel's future service provision. Through recent experiences, Moorfields clinicians have come across occurrences where the queue for the physical A&E consultations were too long, such that they offered patients the choice of jumping into the virtual queue for virtual consultations instead. This offer was taken up happily by some patients, who preferred not to have to wait for a long period of time to speak with a clinician. This scenario provides another potential user case for an integrated app connected to Oriel's future digital twin. Instead of clinicians having to make impromptu decisions on the day over whether the physical queue is overfilled in comparison to available clinicians, this decision could be optimised with algorithms; the combination of a digital twin and an integrated app would be able to provide live data of the number of available clinicians on site and the number of patients in both the physical and virtual queues. Furthermore, instead of Oriel staff having to physically and individually ask patients whether they would prefer to jump into a virtual queue, the app could provide this function, further improving efficiency. Exactly how virtual consultations will be integrated into Moorfields' future service provision is something that is currently being explored – with safety, efficiency, and reattendance rates being considered.

The current vision consists of an integrated 'Oriel' app for the future smart hospital, which would incorporate wide-ranging, DT- and digitally-enabled possibilities into a single solution. Such an app would have the potential to improve and transform patient navigation, waiting times, eye-scanning, health records (with electronic health records and future patient digital twins on the horizon), and possibly also enable home vision monitoring (where patients can monitor their own vision at home and submit information to clinicians digitally). These solutions would not only improve service provision and inclusion – they would also create more effective patient flows, reduce crowding, and enhance future pandemic preparedness planning.

The above two sections have outlined how digital twin technology could bring huge opportunities to Oriel's future services and resolve some of its challenges. First, digital twin technology could improve visually-impaired patients' navigational issues faced when travelling to/from the hospital – by providing live and accurate data. sources that can be used to create dynamic and precise navigational instructions. Second, digital twin technology can also provide much-needed navigational guidance for patients within the hospital, in so doing reassuring patients, easing uncertainty, and providing flexibility for patients during the visit. Third, digital twin technology can also further improve Moorfields' future service provision, providing new capabilities for their machine learning-based and telemedicine ventures. Despite all these opportunities that digital twins can bring to Moorfields, however, there are nevertheless some pertinent challenges to this future vision. The following section outlines some of the complexity and challenges that will have to be faced to make this vision a reality.

4. Future challenges for digital twins in smart hospital of the future

Despite the various benefits and opportunities for innovation that digital twin technology can bring into the future of healthcare, there are also distinct challenges that organisations must face in the process. This section highlights some of these future challenges.

Social inclusion and equality of access

First, there is the issue of equality of access. In the past few decades, scholars and public policy makers have given increasing attention to the themes of social inclusion and equality of access, which have also been described as important foundational elements of public policy (Sawyer and Green, 2013). This theme is similarly important in healthcare, and particularly so in relation to Moorfields' navigational challenge which is primarily centred around patients' accessibility. Given this, it is pertinent to consider how current technological solutions, especially if coupled with digital twins, will raise issues for social inclusion.

On the one hand, smartphone-enabled digital solutions have proven to increase social inclusion for Moorfields patients through the pandemic. Patients who may otherwise have been excluded from physical care were able to attend virtual consultations during the COVID-19 lockdowns; for instance, Moorfields clinicians remotely treated immobile patients in nursing homes for serious conditions, rather than them needing ambulance transfers to hospital. This further frees up ambulance access for others in need – a particularly relevant topic while the NHS attempts to solve the ongoing ambulance crisis (October 2021 in particular saw the highest ever figures for both life threatening ambulance call-outs and ambulance response times) (ITV, 2021; NHS Confederation, 2021). In terms of social inclusion/accessibility for visually impaired patients who do need physical consultations, the Waymap solution would be considerably more inclusive and accessible than other solutions such as the camera-mounted solution being developed in Boston – as it eliminates the need for acquiring a specialist piece of camera equipment, which would also be vastly more limited in supply.

On the other hand, however, an app-based solution would still require a smartphone to function – one with enough capabilities and the battery life to handle the potential connections between the app and a digital twin. Naturally, not all patients would be able to have access to such a smart phone, or one that is powerful enough. Further, even for those that do, not all of them would be able to use this technology competently; an integrated app solution may also require an initial learning curve and training. What are then the alternatives for those without a smart phone or those unable to use one?

Security and privacy concerns

A theme that has consistently been at the core of the machine learning and artificial intelligence discourse is security and privacy. To realise the opportunities outlined above and achieve the potential solutions, a high amount of integration is needed between a user and his/her surrounding digital twin environment. For instance, to be able to navigate with that level of accuracy and ease to a hospital would require a person's exact location to be known throughout the journey and the hospital visit. This can create potential hazards for the user.

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A well-known navigation app – Google's 'Waze' – that is both used by drivers internationally, as well as by Waymap themselves for their street mapping functions, has faced such problems (Montalbano, 2020). Waze is known for its innovativeness in integrating crowd-sourced information into its platform for users' benefit. It utilises user data to monitor and relay traffic information onto its maps internationally, allowing users also to actively report on and share live events with each other (such as road blocks, traffic accidents and jams, hazards, map issues and more) (Muller, 2018). In principle, it is somewhat similar to the Waymap and digital twin solution, although at a smaller scale and with different sources of information. However, recently, a security development operations engineer discovered an API flaw in Waze's navigation software, that allowed him to track the specific movements/locations of nearby drivers in real time, and even reveal their exact identities (Gasper, 2020) – a flaw that could have been exploited by hackers. Furthermore, University of Santa Barbara researchers had previously also discovered another flaw with Waze, where they could echo the GPS location of a person and virtually follow them around by creating a 'ghost rider' (Montalbano, 2020).

Such issues, especially in a healthcare context, will have to be taken into very careful consideration. The integrated solutions outlined in this paper may require certain medical profiles and sensitive information to be stored in-app, and as such successful hacking attempts would be particularly detrimental. Future and ongoing developments in 5G technology will be an interesting and relevant space to watch in relation to this. On the one hand, 5G has the potential to offer more anti-tracking and spoofing specs and enhanced security features – such as improved authentication, authorisation, and integrity protection mechanisms (Sajjad, 2021). On the other hand, 5G technology is simultaneously under the limelight for security concerns, focused around decentralised security and strained security monitoring (from a higher volume of traffic points-of-contact), low-end IoT devices that lack security measures, and hackers which can target such a lack of encryption early in the connection process (Kaspersky, 2021; Gupta, 2021).

Technological complexities

The vision and potential solutions outlined above may offer new breakthroughs for the future of visually impaired navigation; however, the technological complexities behind such a vision is vast and challenging.

First, multiple federated digital twins are in fact involved in the proposed ideas. To provide patients with accurate navigational guidance and real-time assistance within the future Oriel building, the patient-facing platform (potentially an app) will have to be connected to a hospital digital twin of Oriel's built environment. To realise the other more advanced digitally-enabled features outlined above (such as automated scanning and home vision monitoring), integration with patients' electronic health records will be necessary, and perhaps even with patient digital twins further on. To help patients navigate through the vastly complex and busy transport hub of Kings Cross & St Pancras so that they can reach the future Oriel building, a London digital twin – or one that focuses on transport and navigation in London – will have to be involved (preferably, as some patients may choose one of the neighbouring six Underground stations too). Furthermore, to provide patients navigational assistance from their front doors to one of the London transport

4. Future challenges for digital twins in smart hospital of the future

hubs – as many currently travel from all over the UK to get Moorfields' premier treatment –, a national UK digital twin may be required. With these different types of federated digital twin models involved, they do not only need to be interoperable in the backend – the integrated patient-facing app/platform would also need to be able to seamlessly connect between these different models, while maintaining data security. As such a scale of digital twin has still not yet been developed, the technological complexity behind it is a considerable challenge that needs to be traversed.

Second, the patient-facing platform also needs to be considered. Would it be an app like Waymap that ultimately provides all the above features? If so, Waymap has not been designed to provide the extra features outlined such as pushing notifications for (delayed) appointments, helping patients ask hospital staff for help, potential options to choose between virtual/physical queues and more, so Waymap would have to develop a customised app for the future Oriel hospital if such is the case. If not, Moorfields may have to develop a future Oriel app for the in-hospital features that have been highlighted in this paper, which would then bring other challenges in such as the transition between apps for patients. Either way, there are also currently no public, user-facing navigational apps that have been developed with a connection to an existing digital twin, and so the technological challenges amplify still.

This paper provides an overview of digital twins and highlights their vast potential to contribute to many aspects of society. Simultaneously, it emphasises the importance of a service and user-oriented approach to using and developing digital twins in the near future, and how such a perspective can also help organisations plan for their digital transformation and service transition journeys. Using the healthcare industry, and Moorfields' service transition challenge as a case study, the paper showcases how this service-oriented perspective can reveal specific and pertinent user cases, that will help guide the future development of digital twin technology. Finally, the challenges and considerations that lie ahead for healthcare organisations looking to adopt digital twin technology are discussed.

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2022