HEALTHCARE PROCESS AND VARIABLE MAPPING FOR IDENTIFYING DIGITALISATION OPPORTUNITIES AND BUILDING A HOSPITAL DIGITAL TWIN

Anandarup Mukherjee[1], Nicola Moretti[1,2], Yin-Chi Chan[1], Gokcen Yilmaz[1], Manu Sasidharan[1], Jorge Merino[1], Zahrah Rosun[3], Colin Carr[3], Duncan McFarlane[1], Ajith Kumar Parlikad[1]

[1]Institute for Manufacturing, University of Cambridge, Cambridge, UK
[2]Bartlett School of Sustainable Construction, University College London, London, UK
[3]Department of Histopathology, Addenbrooke's Hospital, Cambridge, UK

Abstract

Hospital facilities are critical social infrastructures where the assets and process performance are closely related to the patient-centric services, i.e., ensuring/improving their health on time. The positive effects of digital technologies on products, processes, service design and management have a high impact potential for hospital management. This work identifies the key variables that inform opportunities for hospital digitalisation, providing a baseline for Digital Twin ideation. Using technology forecasts in the literature, through evidence-based research, and focusing on holistic digital transformation aspects, we categorise hospital-specific challenges and features that a Digital Twin can address. Further, we identify a set of eight parameters across the healthcare processes/product/service chain underpinning transformative insights and relevant Key Performance Indicators for a hospital Digital Twin. The case study on a histopathology department provides insights into the areas where digital transformation can inform operational decision-making. Finally, the challenges in developing a Hospital Digital Twin are identified.

Introduction

Modern-day hospital facilities are critical social infrastructures where the capability of the assets (e.g., the number of samples processed by medical and lab equipment, the filtration capacity of the Heating, Ventilation, and Air Conditioning - HVAC system) has a major impact on the service provided to patients, i.e., ensuring/improving their health. In addition, process control plays a fundamental role in the patient treatment capacity (Brown, 2004). This issue has become particularly critical given the high number of patients waiting for treatment generated by the COVID-19 pandemic (Nehme et al., 2022).

The Digital Twin (DT) concept is gaining traction in many industries and is closely related to the rapid digitalisation of assets, processes, and services (Negri et al., 2017). Many conceptualisations of DT can be found in the literature. In broad terms, a DT is characterised by a set of digital models of an asset or a process that dynamically exchanges information with its physical counterparts. This interconnection enables optimisation of the asset or process performance (Kapteyn et al., 2021) and extracting deeper knowledge than can be inferred from the individual models.

In this paper, we aim to identify the key variables that inform opportunities for hospital digitalisation and provide a baseline for DT ideation as opposed to defining the characteristics of a hospital DT adopting a top-down approach. From a process and service-oriented perspective, these variables are controlled to meet the turnaround times in different departments, reduce backlogs, and ensure high-quality healthcare provision. Digitalisation can improve the management of healthcare operations in the following ways:

- Automated workflows: digitalisation can automate many repetitive tasks performed in a hospital, such as appointment scheduling and medication administration. This can help to reduce errors and increase efficiency.
- Remote monitoring: digitalisation can enable remote monitoring of patients, allowing healthcare providers to track vital signs and other health data remotely. This can improve patient outcomes and reduce the need for hospital visits.
- Improved communication: digitalisation can improve communication between healthcare providers, allowing for real-time collaboration and faster decision-making.
- Data analytics: digitalisation allows for collecting and analysing large amounts of data, which can be used to identify trends and improve patient care.
- Cost reduction: by automating many of the tasks and reducing the need for paper records, digitalisation can help reduce costs and improve the hospital's overall efficiency.

Related Works

Karakra et al. (2019) propose a futuristic hospital framework that creates a DT using core elements of the Internet of Things (IoT), Body Sensor Networks (BSN), data modelling, simulation, and Artificial Intelligence (AI). This framework aims to improve patient care quality by monitoring their states, behaviour, and pathways. Elayan et al. (2021) propose and implement a DT framework for context-aware healthcare systems. Their work primarily focuses on the automated classification of human biometrics, specifically, the electrocardiogram signals, intending to monitor and detect abnormalities automatically. Similarly, Ali et al. (2023) propose an architecture using the new metaverse concept to provide a faster, more secure, and more realistic experience in the digital space. They propose to store heterogeneous data such as images, text, audio, clinical data, and others on the blockchain. Further, they propose using explainable AI (XAI) tools to interpret information better and enhance its explainability.

Clinically, but non-diagnostically, DTs have been reported to be used by the US Food and Drug Administration (FDA) to anatomically compare the digital reconstructions of patients' digital breast tomosynthesis, and digital mammography (Huxley, 2023). Similarly, there are efforts around using DTs of humans to streamline orthopaedic device regulations through the "Musculoskeletal Atlas" project in New Zealand (Huxley, 2023).

In contrast to DTs focusing on clinical aspects of healthcare, Peng et al. (2020) report their successful integration of multi-domain management systems with a DT framework and AI tools. Their system, which has been running for over a year in a large hospital in Shanghai, China, reports the benefits of reduced energy consumption, reduced facility faults, and improved routine maintenance tasks. Similarly, Madubuike and Anumba (2023) propose DTs for real-time hospital equipment and system monitoring for enhancing Healthcare Facility Management (HFM). They also study the shortcomings of current HFM systems. Shetty et al. (2023) explore the possibilities of using the metaverse in healthcare, primarily focusing on the technological aspects of telepresence, DT, and blockchains. They also suggest using recent technological paradigms, such as the metaverse, to augment digital twinning efforts for the pharmaceutical industry.

Synthesis: A majority of the works on hospital and healthcare digital twins look into twinning clinical parameters or are more patient-centric. Some works address a healthcare establishment's management aspects but take a narrow approach to enhancing HFM. In contrast, our work approaches the hospital twin holistically by considering the core and auxiliary operations. On a larger scale and as part of our long-term goal, as shown in Fig. 1, we group the hospital operations under the categories of – *Fabric*, *Process*, *Resources*, and *Supply chain*. This approach allows us to consider various KPIs (qualitative and quantitative) that may influence the processes being twinned and plug in all challenges and opportunities that may arise in developing a holistic hospital DT. Considering these advantages and many more, we focus on the Histopathology department of Addenbrooke's Hospital, a part of the Cambridge University Hospitals NHS Foundation Trust in the U.K., which allows us to scope the problem better and define the following research questions:

RQ1. What are the key challenges towards the ideation of a Hospital DT that:

(a) can capture (identify and define) assets and process data,

(b) use the data to generate and update the DTs, and

(c) enable efficient asset-data and human-data interaction?

RQ2. What are the common parameters for a chosen hospital department that can be used as a template to cluster processes within and across hospital departments for building a Hospital DT?

Identifying Common Functional Parameters in Healthcare

Organisations such as Forbes (Gaskell, 2022) and McKinsey (McKinsey and Co., 2021) forecast transformative trends in healthcare for the near future, specifically focusing on information availability, and user connectivity in the healthcare ecosystem. There is an upcoming surge forecasted in healthcare, predicting the digital transformation of healthcare establishments through digital strategies focusing on business, management, and the clinical aspects of such organisations (Reddy, 2022). Digitalisation is also expected to influence the healthcare sector with improved connectivity through 5G technologies, the ubiquitousness of IoT, deeper functional and behavioural insights through big data, and better assistance through Augmented Reality (AR) and Virtual Reality (VR) in enhancing their current operations. A thorough digital transformation exercise needs to focus on the goals of organisation-wide digital acceptance, including cultural and business adoptions, training resources, operational efficiencies, profitability, new product/service introductions, asset upgrades and modifications to comply with the needs for digital connectivity, and others (Harvard Business Review, 2022).

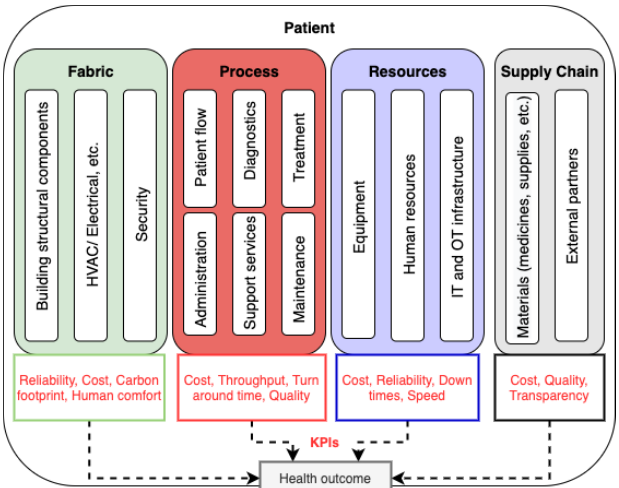

Figure 1: A categorization of hospital-specific challenge areas (patient-centric) and some of their expected KPIs for a Digital Twin

Due to the vast operational and functional diversity within and between healthcare organisations, a hospital DT needs to leverage functional commonalities, which can be reused in several applications. These functionalities (e.g., process modelling and simulation, inter-operable data modelling, and real-time data analysis) must capture the variables and constants in the hospital processes and be broad enough to be standard across departments.

Methodology

The methodology for this work follows a mixed-methods approach. It was initially inspired by literature for identifying the hospital-specific challenge areas and then further informed by interviews with hospital managers, clinical staff, third-party consultants working with the chosen department, and other relevant documents such as standard operating procedures for the laboratories, building plans, and staff rota. This was also accentuated with multiple site visits to identify assets and their locations and observe their usage. Combining insights from the literature with first-hand experiences from hospital staff and other relevant documentation, the methodology effectively identifies the variables most critical to addressing hospital challenges.

Fig. 1 represents hospital-specific challenge areas that can be addressed through the DT approach. The goal is to connect the KPIs, traditionally used to measure the performance of the four areas (Fabric, Process, Resources, and Supply chain) with the patient's health. In addition, data within the four areas can be combined and used to achieve deeper insights, which can inform advanced interdisciplinary decision-making strategies. In this paper, we select and access the various parameters and variables in a case study from the "Process" vertical of the hospital DT.

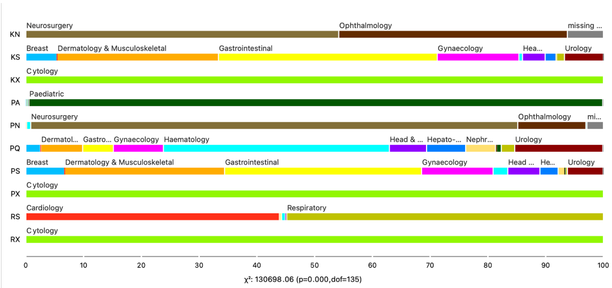

Figure 2: A representation of the different samples received at the specimen reception based on originating locations and relevant departments

Focusing on holistic digital transformation aspects of a healthcare establishment – which can be a hospital, a laboratory, or even a pharmaceutical company – we identify eight sets of variables for generating transformative insights and generate relevant KPIs that are reusable across any healthcare process or product/service chain. These eight identified variable sets are:

- **Input**: these variables can be biological samples, materials, identifiers and instructions, or anything considered fundamental to the current process's objective, particularly the items "worked on" by that process.
- **Output**: these variables are processed, edited or transformed versions of the input to the process, that can be the final result of the process or act as an input to another stage of the process.
- **Constraints**: these variables primarily limit the capabilities of a process, which may be in terms of time, cost, space, security, and others.
- **Information**: these variables are primarily composed of identifiers, status, and history, which can be attached to patients, products, services, machines, and others.
- **Equipment**: these variables identify the pieces of equipment attached to a process.
- **Supplies**: these variables identify the various materials and items not covered under the equipment parameter that support the primary operation of the process.
- **Human efforts**: these variables identify all the human efforts/actions required to complete the primary operation of the process.
- **Disposal**: these variables identify all items that have to be disposed of/recycled or that can generate the requirement for disposal during the functioning of a process.

Note that these eight variable sets are not mutually exclusive but interact with each other within a process and, at times, with other variables in other processes. We chose a case study to validate how well these identified parameters work under different operational settings.

Case Study: CUH Histopathology department

For this case study, we chose the histopathology department at Addenbrooke's Hospital, a large regional hospital in the East of England region. This hospital is the centre of excellence for specialised medical services such as organ transplantation, neuroscience, paediatrics, and genetics. They are also heavily involved in local emergency, surgical, and medical care. The hospital is a critical centre of care and medical research in the region; their dependence on the timely availability of reports on biological samples for testing and diagnosis is of utmost urgency. Post-Covid, this department is under significant stress to adhere to the stringent Turnaround Time (TATs) standards for the growing number of tissue samples received daily for testing. In addition to external factors such as global supply chain lags, internal challenges also contribute to the need for studying possible ways to optimise the ongoing processes and look for future opportunities to handle such issues. These include the unavailability of a trained workforce for specialised services, sub-optimal resource utilisation (both equipment and personnel), and an increasing workload.

According to records collected over a six-month period, this department saw tissue samples arriving from ten different locations, targeting any of the 16 specialities available at the department. (see Fig. 2). The inclusion of stringent TAT standards, the variable availability of specialist

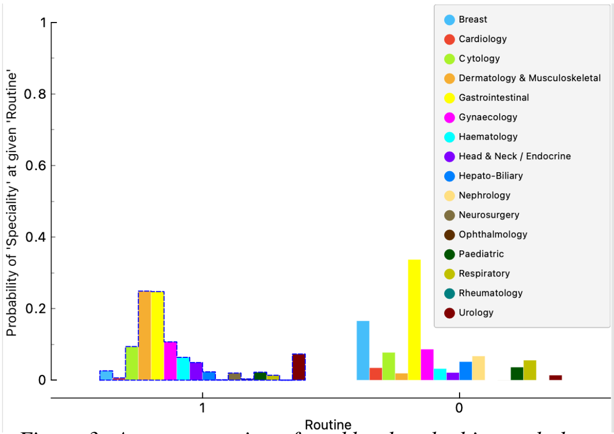

Figure 3: A representation of workload at the histopathology department divided by speciality, for routine (1) and priority (0) tissue samples, over a six-month period.

consultants, the sorting of samples by priority (for example, cancer-pathway samples take precedence over routine tissue samples), differences in processing time for different tissue types, and other factors all complicate the decision-making process and the overall management of the department. Fig. 3 shows a snapshot of the load on the various specialities of the histopathology department from routine and priority tissue samples for an approximate duration of 6 months. It is seen that a majority of *priority* samples involve gastrointestinal and breast tissues, whereas dermatological and gastrointestinal tissues comprise the majority of samples submitted under the *routine* pathway. Prior availability and fundamental analysis of the above information from past records can ease the department managers' planning and resource allocation issues. There are numerous advantages of utilising digital technologies and adopting a "digital strategy" through a DT platform for hospital operations across clinical and management roles.

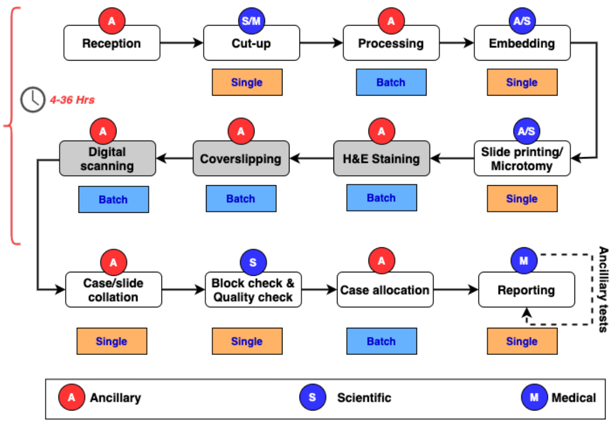

Figure 4: Routine histopathology process identification

Process Identification

A typical hospital department is functionally made up of multiple processes, a majority of which interact with each other in some manner (Mills, 2022). However, for our chosen case, the often complex dependencies among the various processes can be linearly mapped in a stage-wise manner (Brown, 2004). Fig. 4 represents all the identified stages (which we consider as individual processes) that a tissue sample arriving for testing has to go through the histopathology department (routine histopathology) in our chosen case study. Typically, a specimen travelling down the process chain from the reception to case/slide collation can take between 4-36 hours (refer Fig. 4). These durations vary depending on if the specimen follows a priority, cancer, or routine pathway. Sometimes, the type of samples and the availability of specialists for specimen cut-up also govern the time taken to process the specimen. Note that some stages handle the sample as a single unit, whereas the transformed samples are collectively processed as a batch in other stages. The stages marked with **S/M** in Fig. 4 indicate that a medical/biomedical specialist is required for that stage, whereas stages marked with **A** may be completed by ancillary staff. Table 1 summarises each stage/process's functionalities and identifies the category to which its primary operation belongs (i.e., management, information, and clinical), and the staff/workforce involved in that stage (ancillary, scientific, medical).

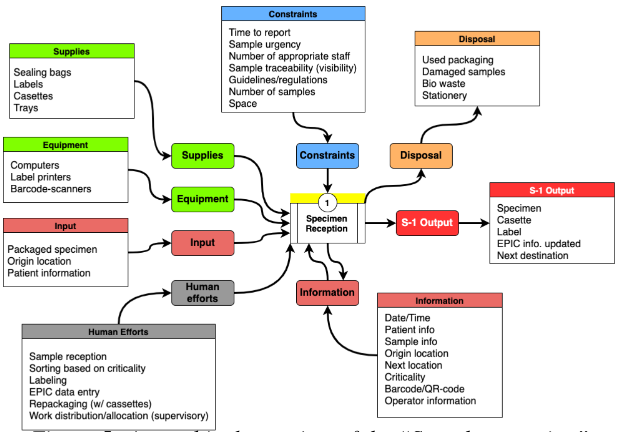

Figure 5: A graphical overview of the "Sample reception" process, its parameters, and constituent variables for each of these parameters.

Digitalisation Opportunities

Each of the identified processes consists of multiple variables and constraints. For each of the eight identified sets of common functional parameters in the previous section, we identify the variables and constraints in each histopathology process (Fig. 5). These variables and constraints help identify current and future bottlenecks and narrow down the scope and type of technology required to manage these bottlenecks. These can be considered as digitalisation opportunities or technology identifiers for the hospital DT, contributing towards the greater goal of digital transformation in healthcare. Table 2 expands on the information listed in Fig. 5 and shows a brief outline of the parameters and their respective variables for specimen reception, which is the first process in the histopathology department. This table also identifies if the parameter is core to the process, the existing digital technologies used to ac-

Table 1: Identified processes and their dependencies within the routine histopathology process.

No.	Process	Sample Processing	Category	Workforce involved	Overview
1	Specimen reception	-	Information/ Management	Ancillary	Tissue samples are received from local and regional areas. The samples are logged in the Electronic Patient Record (EPR) and processed according to the sample site, type and clinical urgency.
2	Specimen cut-up	Single	Clinical	Scientific/ Medical	The received tissues are cut up by specialists according to the specimen type and clinical details and focusing on areas of interest, so that they can be easily processed as wax blocks. Descriptions of the cut-up tissue samples are recorded as audio files.
3	Specimen processing	Batch	Clinical/ Information	Ancillary	The samples taken at cut-up are then processed using an automated tissues processor. The blocks undergo a series of steps including further fixation, dehydration, clearing and paraffin wax infiltration via different reagents.
4	Embedding	Single	Clinical	Ancillary/ Scientific	The processed tissues are embedded in paraffin wax, to allow them to be sectioned at microtomy.
5	Microtomy/ Slide printing	Single	Clinical	Ancillary/ Scientific	The wax-embedded specimen blocks are sectioned into very thin sections (2-4 μm) using a semi-automated microtome. These sections are then mounted onto pre-labelled glass slides.
6	H&E staining	Batch	Clinical	Ancillary	The samples on glass slides are stained using an automated H&E (Haematoxylin & Eosin) stainer. These dyes help highlight the cell structures within the tissue samples for easy inspection using a microscope.
7	Slide coverslipping	Batch	Clinical	Ancillary	The glass slides with the stained samples are protected by a thin glass coverslip that secures the sample between the slide and the coverslip. This also ensures that the slide is preserved for a longer time.
8	Digital scanning	Batch	Information	Ancillary	An operator loads a digital scanner with the racks of stained slides, which are then scanned in batches. The core operation is automated.
9	Case/slide collation	Single	Clinical/ Information	Ancillary	The slides are batched together with their request forms to be sent for the next stage of Block and quality check.
10	Block check and quality checks	Single	Clinical/ Information/ Management	Scientific	The slides are block-checked and quality-checked as per laboratory process and staining criteria.
11	Case allocation	Batch	Clinical/ Information	Ancillary	The stained and quality-checked slides are distributed to the histopathologist for reporting
12	Reporting	Single	Clinical/ Information	Medical	A pathologist analyses the slides under a microscope of a digital image and prepares a diagnostic report.

complish the various operations, and suggests new digital solutions. Although not an exhaustive list of variables, the identified ones are fundamental to the specimen reception process. There are common variables under each of the eight parameters, which appear multiple times for a process, whereas others are unique to each process. These could help decide incremental features of the planned hospital DT and forecast possible bottlenecks.

Insights derived from the data processed through DTs and digital tools will help managers to make decisions across four levels:

- **Level 0** – Processes and their relationship identification: This level includes understanding high-level processes and their relationships, which creates a basis for decision-making across Levels 1-3.
- **Level 1** – Process level: These decisions are based on the process dependency analysis, and need to be made daily or weekly.
- **Level 2** – Constraint level: These decisions are made based on constraints such as time and cost, including bottleneck analysis, and need to be made weekly.
- **Level 3** – Simulation level: These decisions are made based on simulations of the whole process, including their interdependencies and constraints, and need to be made monthly, though can to be monitor constantly through a bi-directional information flow between the digital and the physical counterparts.

Challenges

The following are some of the specific challenges that need to be addressed during the development of the hospital digital twin:

1. **Data security and privacy**: One of the most challenging issues for building a hospital DT will be addressing various issues around patient and data privacy, security, and confidentiality. Anonymising data before embedding it within the DT system is a possible solution. However, it is not an option for most of the clinical and information-based opportunities of digitally twinning processes in a hospital.
2. **Interactive dashboard**: An intuitive and well-designed user interface reduces training time for the users and makes adopting a digital culture in an organisation much faster and easier. Functionalities such as summary status reports and visual alerts are desirable but quite challenging to de-clutter and conceptualise minimally on a dashboard.
3. **Information forecasting**: Another powerful potential feature of a DT is a forecasting tool that can forecast process performance or trends or health based on various input parameters. However, a forecast is only as good as the granularity of the data generated from the process model, which will, in turn, depend on the types and number of input variables and parameters being mapped to each process.
4. **Asset information and history**: A DT can also be a good map of asset locations, along with several critical asset information about them such as location, manufacturer, maintenance history, health, owner, and other similar parameters. However, streamlining how existing and new assets and their information will be mapped to the DT could be challenging.
5. **Interaction with legacy IT and OT systems**: The most crucial aspect of any new technology aimed towards the digitalisation of an already functioning organisation is its ability to interact with legacy Information Technology (IT) and Operational Technology (OT). The decision on what level of interaction and interoperability is expected between the new system (a DT in our case) and legacy IT and OT systems is challenging and may not be uniform across all departments within the same organisation.
6. **Data modelling and interoperability**: Another crucial aspect concerns the ability to bring together data enabling the development of the DT tools supporting interdisciplinary decision-making on the process performance, facility operation and patient's health. Data is organised, stored and accessed through diverse approaches and systems. Effective interoperability and data access will enable to unlock of DT-based multi-dimensional decision-making capabilities.
7. **Sensor data fusion**: The fusion of data from various IoT sensors in a hospital healthcare environment includes integrating data from diverse sensor types, dealing with the variability in sensor accuracy, ensuring data privacy and security, and managing the large volumes of data generated by multiple sensors. This becomes a significant challenge that affects the choice of sensors, scale-up strategies, and technology investment decisions.
8. **Integration with other technologies**: Integrating healthcare digital twin with other technologies like Blockchain, AI, and IoT presents challenges such as ensuring data privacy and security, developing interoperability standards, managing the complexity of the system, handling large volumes of data, and ensuring ethical and legal compliance.

Concluding Remarks

The digitalisation of hospitals can help to address the challenges faced in healthcare and improve operational efficiency. In order to achieve this, it is necessary to understand the key challenges towards the ideation of a Hospital Digital Twin (HDT) that can capture assets and process data, use the data to generate and update the DTs,

Table 2: Digitalisation opportunities with parameters and variables mapped to one of the identified processes.

Process	Parameter	Variables	Category	Type	Digital solutions	Existing?	Comments
Specimen reception	Equipment	Barcode scanners, computers, label printers	Auxiliary	In	Job tracking, equipment utilisation, equipment tracking, etc.	Job tracking	Samples are registered into the hospital EPR system using barcode scanners
	Supplies	Specimen bags, labels, cassettes, trays	Auxiliary	In	Predictive maintenance, inventory tracking, assisted inbound goods validation, etc.	No	Identified digital solutions can help with better management and planning of supplies and spare parts, which will help reduce some of the TATs in the chosen department.
	Human efforts	Sample reception, criticality-based sorting, data entry, repackaging samples	Auxiliary	In	Process monitoring, digitised work instructions, internal lead time monitoring, digitised training, etc.	Internal lead time monitoring	Specific locations within the histopathology laboratory keep track of internal lead times of workforce aspects digitally and so do the managers. However, this can be centrally integrated with other lead times to generate more concise and accurate insights.
	Disposal	Packaging, damaged samples, papers, un-used cassettes	Auxiliary	Out	Waste monitoring, maintenance management	No	As histopathology deals with medical samples and instruments, the waste generated has to be monitored for proper category-wise segregation.
	Input	Packaged specimen, origin location, patient information	Core	In	Job tracking, internal lead time monitoring, digital job cards, task scheduling, etc.	Job tracking, task scheduling	The specimen received has to be recorded on the central EPR, a tracking ID assigned to it, and then sent to the cut-up section for further processing.
	Output	Specimen, cassette, label, EPR information updated	Core	Out	Same as above	Same	Same as above
	Constraints	Time to report, sample priority, staff available, regulations, physical space	Core	In	NA	NA	NA
	Information	Date/time, patient info., sample info., origin location, next location, criticality, barcode/QR-code, operator info.	Core	In/ Out	NA	NA	NA

and enable efficient asset-data and human-data interaction (RQ1). Additionally, it is important to identify the common parameters for a chosen hospital department that can be used as a template to cluster processes within and across hospital departments for building a HDT. According to the proposed approach the critical variable sets are: constraints, information, equipment, supplies, human effort and disposal (RQ2).

The case study on the histopathology department of a major hospital in the UK provides insights into how digitalisation can contribute to improving operational efficiency and the quality of healthcare provided. The streamlined processes within the histopathology department, as presented in Table 1, can be compared to other industries such as manufacturing and logistics, where bottlenecks can significantly impact throughput and other KPIs. By employing digital transformation through DTs and digital solutions, managers can identify and mitigate bottlenecks, making informed decisions across all four levels defined in the "Digitalisation opportunities" subsection of this paper, within the process areas identified in Fig. 1. This would not only help to optimise the processes within the histopathology department but also potentially reduce errors and free up staff to focus on patient care, ultimately leading to improved patient outcomes and cost savings for the hospital.

Therefore, the development of a HDT can contribute to improving and optimising the design and planning, by simulating the flow of patients, staff, and equipment within a facility, as well as providing insights to support decision-making at all levels. These benefits highlight the potential of digitalisation in healthcare, particularly in relation to the development of a HDT.

Acknowledgements

This research is funded by the Cambridge University Hospitals NHS Foundation Trust. We thank the Lifecycle Management Group Ltd team for the fruitful conversations on Histopathology process modelling.

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