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Strategizing towards the future hospital: a systems thinking approach

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Abstract

Background The complex systemic nature of Future Hospital design in the rapidly ageing city-state of Singapore calls for systems thinking. We apply this approach to answer two research questions: (i) What are the variables that drive the present and future dynamics of the Future Hospital system? (ii) How are these driving variables related?

Methods Causal loop diagrams (CLDs) were developed collaboratively by a cross-functional system modelling team through group modelling discussions and reviews, totalling 20 sessions. Network analysis of the resulting CLDs was used to identify dominant variables.

Results Seven interlocking CLDs (national view, cluster view, and study hospital top level, outpatient, emergency department, inpatient and surgeries and procedures views) were created to serve as "boundary objects" for different Future Hospital stakeholders, as well as researchers and planners of other Future Hospital systems. Important feedback loops and 15 interventions for redesign were identified. In all the modelled services (outpatient, emergency, inpatient and surgeries and procedures), capacities are subject to positive feedback loops. Alternative models of care are needed to restrain ever-increasing demand. Need for agility (the need for ability to quickly deploy and pivot capacity in responses to crises) is the variable with the highest betweenness centrality in the combined network of seven CLDs.

Conclusions We address the need for greater openness on Future Hospital initiatives by making our resulting logic maps public. Due to their qualitative nature, the CLDs are insightful for Future Hospital strategic planning exercises globally.

Keywords Strategic planning, Computer simulation, Hospital of the future, Complex systems, Systems thinking, Network analysis

Background

The acute care hospital is an important institution of healthcare, embodying a significant investment in human, information and physical assets. The building of a new care acute hospital presents an opportunity to radically re-align the supply of care with the changing demand for health services, taking a "future-back" approach. On the supply side, advances in the frontiers of capabilities are made through alternative models of care, clinical, process and technological improvements. On the demand side, the known challenges include the

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increasing burden of chronic disease, efforts for healthy longevity and the threat of crises such as pandemics.

The WHO (2023) has called for a rethink of the technical architecture of hospitals, both outside (referring to the integration of the hospital with community and environment) and inside the hospital [1]. A central idea in the thinking on the hospital of the future is that of "hospitals without walls" delivering care in a patient-centric manner [2–5], so that hospital services are better integrated with community and primary care, there are fewer professional silos within the hospital and care is brought to the patient (rather than vice vera).

The vision of the Future Hospital as a "health factory" with a preventive focus dates back to at least 1942 [6]. Yet, Edwards and Harrison highlighted in 1999 [7] that future hospital planning teams faced a "research and policy problem" created by lack of evidence; for example, there was a need to make assumptions about the use of hospital at home and intermediate care facilities in an environment of uncertainty. Leggat (2008) points out that hospital planning need to account for complex and interacting drivers of change and cannot be based on past data [8]. In their vision of the hospital of tomorrow, Vincent and Cretuer (2017) suggest 10 points – for example, hospitals will be smaller, more specialized and more user-friendly [9]. The five dominant themes that emerged from the 2021 Wolfson Economics Prize for hospital design were: a calming environment; systems of care; distribution of services; use of technology; and going green [10]. The WHO (2023) has laid down recommendations for the physical architecture of the Future Hospital [1]. According to Sebire et al. (2025a), the key factors that will drive Future Hospital requirements are changing care needs and shrinking workforces driven by population ageing, changes in financing and technological advances; hospitals will need to evolve in their core design and architecture in response [11]. Sebire et al. (2025b) emphasize the need for the Future Hospital to take a systems approach so that they be flexible and resilient in the face of uncertainty [12]. Whilst the literature emphasizes the complexity inherent in Future Hospital design, published studies focus on the physical architecture, digitalization and overall aims of the Future Hospital. To the best of our knowledge, there is no work applying systems thinking to the problem of Future Hospital design with the aim of visualizing and documenting the present and future dynamics of a hospital system.

In this global context, the design of a new-generation public sector general hospital in Singapore, slated to be operational in 2037, is a project of national importance. Singapore is a city-state that ranked 12th in the world on the Human Development Index in 2021, with life expectancy at birth being 82.8 years [13]. Whilst healthcare costs as a proportion of gross domestic product have historically been contained at a sustainable level, the nation now faces challenges of a rapidly ageing population with a high burden of chronic disease, and has responded with a population health reform program that emphasizes health promotion, primary and community care [14]. Hospital overcrowding is a symptom of a health system under increasing stress and concerns on this front are periodically reflected in media reports [15]. Right-siting is a term used in Singapore to refer to redirecting healthcare provision to appropriate and lower cost settings, for example, by treating stable patients in primary care clinics rather than specialist clinics [16].

The planning of a national healthcare facility for the community must seek to optimize across multiple conflicting objectives in this situation. These objectives include, but are not limited to, the quadruple aim (population health, cost, patient experience and provider satisfaction) [17]. The coronavirus disease 2019 (COVID-19) pandemic has engendered a heightened awareness of the need for rapid response to future crises. Thus, the Future Hospital must be capable of agility in being able to quickly ramp up and redeploy capacity. As the Future Hospital is meant to care for acutely ill patients and to be closely integrated within a larger healthcare network [1], it is also expected to strengthen leadership in quaternary care (that is, advanced care, such as specialized burn care or multiorgan transplantation, that goes beyond routine tertiary care) and preventive care. Finally, as a large public facility, it is expected to meet environmental sustainability targets.

Future Hospital planning must account for population dynamics and healthcare needs that will last for multiple decades. This problem domain has the traits of complex systems: decisions taken in one part have rippling effects on others, with full consequences only becoming visible after long time delays; there is tight coupling between system elements, with feedback and non-linear effects; and the systems are adaptive and evolving [18, 19]. To develop a better understanding and unravel the inherent complexities, we aim to develop a series of visual logic maps to elicit and codify the systemic structure of the present mode of operations of the hospital (within its wider context) and the interventions that will enable transition to the future mode of operations. These visual logic maps are in the form of casual loop diagrams (CLDs), which are proven systems thinking tools [20–22]. A CLD is "a diagram intended to capture how the system variables interrelate and how external variables impact them"[23]. It serves to "visualize and unpack complex health system behaviour" [24]. Our CLDs encapsulate the shared mental models (perceptions of systemic structure

[23]) of those involved in strategizing for the Future Hospital. Further, the CLDs form a network of variables (nodes) connected by hypothesized causal relationships (directed edges). Network analysis of the CLDs helps to extract additional insight on the relationships between variables. The key research questions that we seek to address in this study are:

RQ1 What are the variables that drive the present and future dynamics of the future hospital system to realize long-term goals?

RQ2 How are these driving variables related?

In addressing these research questions, this study will inform a quantitative simulation model that will provide time series estimates for capacity units such as inpatient beds, outpatient consult rooms, emergency medicine treatment units and operating theatres.

Methods

Setting and context

The study site is a major hospital under the largest public healthcare cluster in Singapore. This healthcare cluster consists of 3 comprehensive acute hospitals, 1 speciality hospital, 5 national speciality centres, 2 community hospitals and 10 primary care institutions (polyclinics) [25]. Amongst the acute hospitals, the study hospital (SH) is the oldest and largest in Singapore, with about 1800 beds. Healthcare clusters in Singapore have both regional and national healthcare delivery functions. In the regional role, a cluster is expected to also promote population health in specific geographical regions in Singapore. Planning for the new SH is part of a campus master plan to redevelop Singapore's largest medical campus to meet the future healthcare needs of Singaporeans.

Key domain and opinion leaders from clinical and allied health domains, and support services, such as logistics, human resources, finance, education and research, were involved in the study. They were supported by workgroups focussed on three hospital subsystems (emergency, inpatient including surgeries and procedures and outpatient) and four service domains (care in the community, education, research and innovation and support operations). A notable limitation of this study is that patients were not involved at any stage.

The study team was led by the Future Health System department in the SH and comprised members from the cluster health service research office working closely with the hospital's Organization Planning & Performance and Data Science departments. Members included key data and domain experts with expertise in qualitative research, quantitative modelling and systems thinking. The study team reported through the Future Health System department to an executive committee, with oversight by a steering committee comprising of senior organizational and clinical leaders across the spectrum of community health, primary and tertiary care, acute and emergency services and speciality care.

Study methodology and participants

The CLDs were developed through a series of collaborative discussions in a group modelling process [26]. Workgroups leads from the 3 hospital subsystems and 4 service domains participated in 8 modelling discussions and 12 reviews conducted between September 2023 and February 2024, with about 40 unique participants. The meetings were facilitated by members of the study team. Due to the very large number of stakeholders involved in Future Hospital planning, we decided to focus on groups that have a broad overview of how the hospital works and who have sufficient insight into its dynamics. We emphasized the inclusive and participatory aim of the meetings to participants.

Hospital executives and subject matter experts in hospital planning, strategic management, health system planning and data science were invited to participate in the workshop. Clinicians from the Hospital Planning Committee representing four Future Hospital subsystems – outpatient, inpatient, emergency care and surgeries and procedures (S&P) – also joined the study.

Data collection and thematic analysis

The group modelling process involved 8 modelling meetings and 12 review meetings covering the hospital subsystems (inpatient, outpatient, emergency department and S&P) and the service domains. Supplement 7 summarizes the sequence of meetings. First, the modelling meetings were conducted face-to-face to gather the necessary inputs for CLD development and validation. Roles in group modelling include those of facilitation (leading the sessions), modelling/reflection (developing the model and reflecting insights to participants), process coaching (observing dynamics), recording (note-taking and encapsulation in models) and gatekeeping (interfacing between clients and modellers) [26]. These roles were assigned prior to meetings, and a discussion guide was developed prior to each of the eight modelling meetings.

All modelling and review sessions were audio-recorded and transcribed. The transcriptions were checked and edited manually to ensure accuracy. Two study team members analysed the transcripts to get a better understanding of the transcripts and generate codes individually. A codebook was developed on the basis of their analysis. In parallel, two study team members served an recorders and manually compiled notes. An initial set of CLDs was built on the basis of the codebook and notes. These CLDs were then presented to hospital executives and clinicians through 12 additional review workshops. When participants were first shown a CLD for review, it was explained to them stage-wise, as illustrated in Supplement 3, to help them "digest the pieces one at a time" [20]. Participants were invited to comment, following the categories of legitimate reservation approach [27], on the variables, linkages and potential interventions and leverage points within the system in the reviews or through email correspondence. Inputs given through documents (for example, analyses of SH utilization), emails and annotations on CLDs were also considered source documents and coded. The codebook and CLDs were iteratively updated after each session. After reviews, the refined CLDs were presented to the Future Hospital planning committee and stakeholders for further validation. Data management was performed using NVivo (QSR International, Australia) [28] and CLDs were drawn and revised using Vensim software.

Causal loop diagrams

Though they are limited by their qualitative nature, CLDs help to capture hypotheses about dynamics, elicit and capture mental models of stakeholders, articulate dynamic hypotheses and communicate about important feedback effects [21, 29]. The use of CLDs in a collaborative way, where stakeholders are included in workshops to jointly build a system overview, belongs to a class of approaches termed participatory system mapping [30]. In the health policy domain, Knai et al. (2018) use CLDs to study the influence of unhealthy commodity industries in influencing policy towards noncommunicable diseases (NCDs) [31]. Parmar et al. (2021) identify and map how community health volunteers can help improve management of NCDs amongst refugees on the basis of a CLD analysis [32]. CLDs have also been applied to study the interacting components in a society responding to COVID-19 [33], healthcare coordination for youth experiencing homelessness and the exogenous effect of urban health indicators on built environment policy and decision-making [34]. Recent applications of CLDs in other domains include strategy formulation in complex systems [35], technological disruptions in automative retail [36], soil salinity management [37] and city resilience to natural disasters [38]. Roxas et al. (2019) find that CLDs are useful in situations where outcomes depend on various interacting and adaptive parts and actors [35].

CLDs are expected to follow guidelines and best practices [24, 29, 39, 40]. Supplement S1 contains a reading guide for CLDs. In brief, every variable in scope is represented by a node, and directed edges connect driving variables to their dependent variables. Edges can be positive or negative, depending on whether the relationship is directly or inversely proportional. When a series of edges is connected so that a node "feeds back" to itself, we have a feedback loop. Feedback loops can be either reinforcing, in which case a change in one node will cascade through the loop to amplify the original change, or balancing, when a change in a node will cascade back to dampen the original change.

Sterman (2010) [29] advises against "a large, wall-filling diagram" and recommends that CLDs be built up in a series of stages rather than all at once, keeping in mind that human short-term memory can hold five to nine chunks of information at a time. Overly dense CLDs have been criticized for being difficult to absorb and interpret [41, 42]. With this advice in mind, during the group modelling process, the SH system was decomposed into seven views or sectors enumerated below. The views were organized along functional lines on the basis of discussion with the Hospital Planning Committee. There is a CLD for each of these views, with variables that serve as connectors between the views being highlighted for ease of reading. The CLD views, shown schematically in Fig. 1, are:

- [1.0] National View: Macro-level national and public-sector variables that have a bearing on SH utilization.
- [2.0] Public Healthcare (PH) Cluster: The organizational entity, under the Ministry of Health, which is one of three public healthcare clusters that provide healthcare through a network of hospitals, public sector primary care polyclinics and associated specialist clinics.
- [3.0] SH Top-level View: SH variables that cut across the four hospital subsystems 3.1 through 3.4.
- [3.1] SH Outpatient: The subsystem concerned with patients who are referred from primary care or are returning from previous hospital visits for appointment-based consultations with specialist doctors.
- [3.2] SH Emergency Department (ED): The subsystem tasked with providing urgent and life-saving care to patients with unscheduled care needs. These patients may be brought in by ambulances, or they may be "walk-in" patients.
- [3.3] SH Inpatient: The subsystem of patients admitted for stays greater than 24 h in hospital wards. These patients can only flow into the hospital through the outpatient or ED subsystems.
- [3.4] SH Surgery & Procedures (S&P): The subsystem of patients who need surgeries or procedures to be

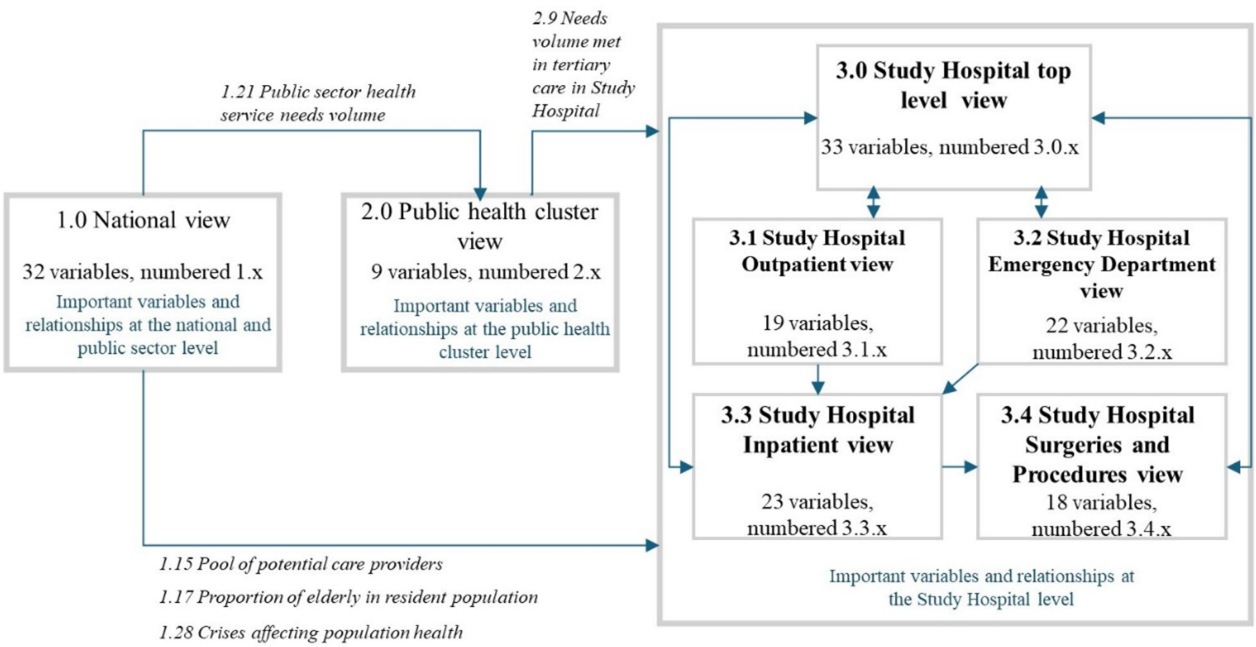

Fig. 1 Schematic diagram of the seven CLD views. Arrows represent links between variables in different views. Selected linking variables are named

performed. There are outpatients in the case of day surgeries and inpatients in all other cases of surgery or procedure.

Network analysis

Given that a CLD is directed graph, or digraph, it is possible to complement our understanding of the dynamics of the system under study with computational insights from network analysis. We applied network analysis to generate additional insights on potential high-leverage points on the basis of the principle of many-model thinking [43]. The network view also enabled the integration of the seven subviews in a combined analysis. A fundamental axiom of network analysis is that structure matters [44]; understanding complex systems requires us to understand the networks behind them [45]. Realizing the potential from the confluence of two network approaches, studies have applied network analysis to CLDs to extract insight on central drivers in subjects including childhood obesity [46], pathways to suicide [47] and innovation systems [48].

Network analysis was performed with the Python NetworkX package [49] and visualized with Gephi [50]. The measure that was evaluated for each variable was its betweenness centrality, which measures the extent to which nodes are located on the shortest paths between other nodes and hence have greater criticality in the network due to their mediating function [21, 46] (see Supplement 5.1 for details). The concept of betweenness centrality is explained further in Supplement S5.1.

Results

This section will first discuss the details of the SH Inpatient View. Due to space constraints, this view was selected as an example from amongst the seven views, noting that inpatient bed capacity is generally used as a proxy for hospital size. (Supplement S8 includes all seven CLD views and Supplement S4 contains tables of feedback loops in each of these views). This is followed by a summary of the key interventions across all the views. Further, we present the results of network analysis for insight into the systemic structure across the seven CLD views.

SH Inpatient View

The SH Inpatient View is shown in

Fig. 2 Supplement S3 contains a staged and detailed explanation that helps to read and interpret it. The view exhibits the traits of a complex system: Tight coupling and interactions between different components ensure that it is not possible to "do just one thing" [18], meaning that actions have intended as well as unintended consequences. Variables are connected in feedback loops, both reinforcing and balancing. The variables shown have dynamic behaviours over time. Nonlinearity arises due to multiple reasons: need for inpatient services is driven

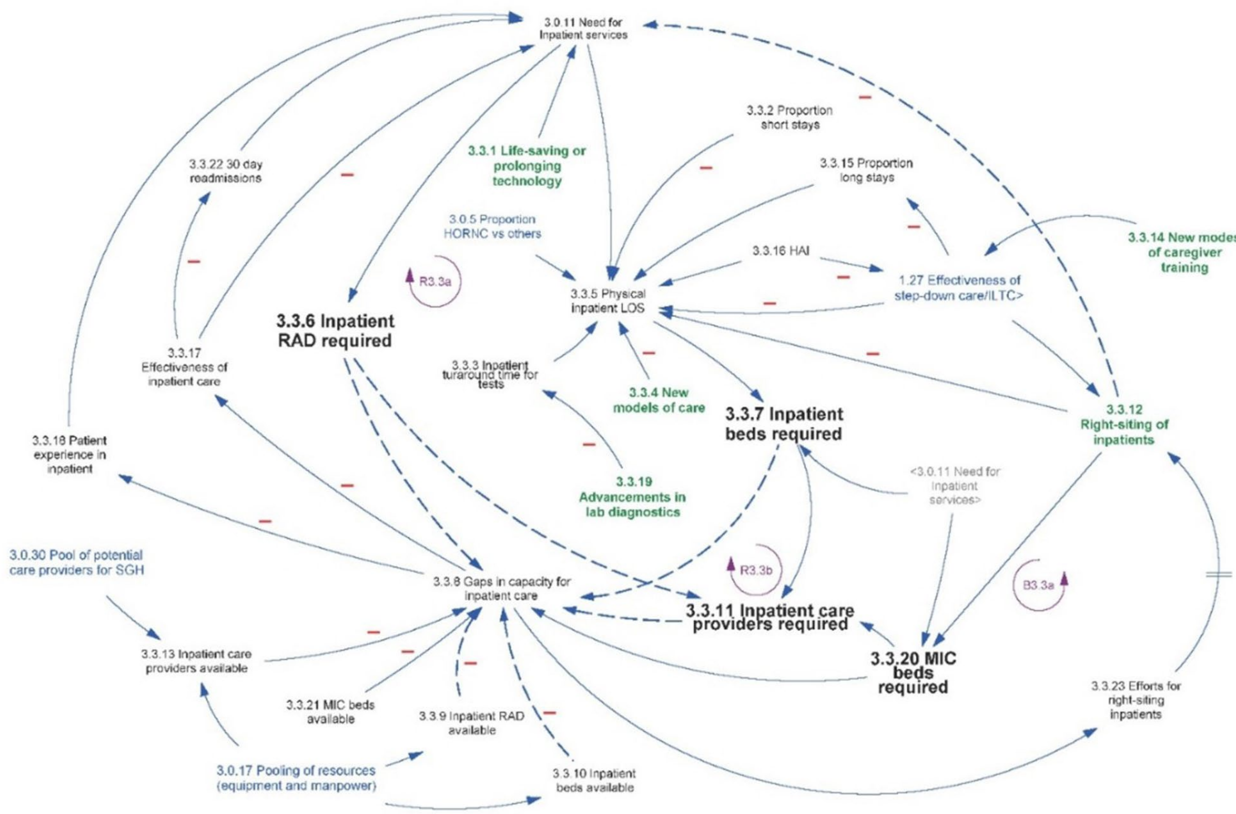

Fig. 2 CLD 3.3 – SH Inpatient View

by underlying (nonlinear) shifts in patient demographics and external shocks (shown in another view, CLD 1.0) as well as by the outcomes (e.g., patient experience) of internal actions taken in response to the level of need, interventions (the variables in green) that follow diffusion curves and delays between actions and results

Three important feedback loops identified during the CLD creation process for SH Inpatient View are listed in Table 1. R3.3a reflects the core problem that building out more beds in the context of an ageing population is a vicious cycle. This phenomenon is known as Roemer's Law: a hospital bed built is a hospital bed filled [51–53]. A similar dynamic applies to hiring more staff to resource the beds. The balancing loop B3.3a, on the contrary, shows the possibility of reining in the runaway demand for beds with Hospital at Home (HaH) initiatives. These initiatives, however, bring their own demands for distributed care, reflected in the number of HaH beds that need to be supported.

Key interventions for the future hospital

Table 2 summarizes selected key interventions identified through the group modelling exercise that enabled CLD creation. On the basis of consensus amongst study participants, interventions are categorized on the basis of whether they reduce the flow of inpatients (typically from a more acute setting to a less acute one) or whether they reduce length of stay and hence increase throughput.

Table 1 Important feedback loops in the SH Inpatient View

Loop	Description	Variables
R3.3a	Need for inpatient services drives need for inpatient beds	3.0.11 → 3.3.5 → 3.3.7 → 3.3.8 → 3.3.17 → 3.0.11
R3.3b	Need for inpatient services drives need for inpatient care providers	3.0.11 → 3.3.5 → 3.3.7 → → 3.3.11 → 3.3.8 → 3.3 .17 → 3.0.11
B3.3a	Increasing needs calls for right-siting	3.3.5 → 3.3.7 → 3.3.11 → 3.3.8 → 3.3.23 → 3.3.12 → 3.3.5

Table 2 Selected interventions for re-imagining the Future Hospital system

Sector/ View	Intervention/ Alternative Model of Care	Reduces inflow of patients	Reduces Length of Stay or increases throughput
3.0 Study Hospital top level	3.0.1 Regionalisation	✓	
3.1 Outpatient	3.1.1 Right-siting to teleconsult	✓	
	3.1.13 Tech advancement in consultation		✓
	3.1.17 Operations efficiency advances to reduce waiting time		✓
	3.0.4 Right-siting from SOC to Primary Care	✓	
3.2 Emergency Department	3.2.4 Right-siting to telehealth nurse	✓	
	3.0.7 Right-siting to primary care	✓	
	3.2.20 Advances in point of care technology		✓
	3.2.23 Preventive care in ED	✓	
3.3 Inpatient	3.3.1 Life-saving or prolonging technology	✓	
	3.3.4 New models of care, e.g. team-based peri-op care		✓
	3.3.19 Advances in lab diagnostics		✓
	3.3.12 Right-siting of patients	✓	
3.4 Surgeries and procedures	3.4.6 Advances in surgeries and procedures	✓	
	3.4.7 Advances in scheduling policies		✓

The table presents the primary effect of the intervention; an intervention that reduces patient inflow may also increase the length of stay of the remaining patients that flow into the subsystem. Importantly, secondary effects need to be considered in modelling interventions.

Network analysis

The variables of the CLDs are shown in the form of a directed graph in Fig. 3. The 157 nodes are colour coded according to the sector they belong to, and nodes sizes are proportional to their weighted betweenness centrality. This picture helps to comprehensibly put the seven views together. All seven views contribute to highly critical nodes, reinforcing the interconnected nature of the SH system. Analysis of network.

Table 3 lists the 20 nodes with the highest betweenness centrality. Need for agility [3.0.15] (the ability to quickly ramp up and redeploy capacity) at the SH level, which is driven by the need to respond to crises and drives measures for flexible assignment of resources, is the node which has the greatest brokerage in the network. The list is dominated by those in the SH Top-Level view, as expected, since these variables carry influence across the four sectors, 3.1 through 3.4.

Discussion

The aim of group modelling is to collaboratively produce "boundary objects" that are used to facilitate knowledge sharing across user and knowledge domains [26]. For example, boundary objects enable clinicians, nurses, allied health professionals, hospital operations planners and architects to discuss the Future Hospital system. Boundary objects must meet three essential requirements: they must (i) be diagrams with few words; (ii) show the key concepts, actions and relationships; and (iii) be accessible and modifiable to all the group modelling participants [26]. In keeping with these requirements, the SH CLDs have demonstrated their value in eliciting SH systemic structure. The group modelling process facilitated the creation of rich CLDs across seven linked sectors (in the interest of tractability, we have explained one in detail, the SH Inpatient CLD). Network analysis helps to combine the seven sectors and take an integrated view of the system on the basis of computation. It highlights the idea that the need for agility is paramount in the Future Hospital plans. Though this insight has been subjected to critique by stakeholders, it remains to be tested in our quantitative modelling phase.

Insights from CLD modelling

In the national view (CLD 1.0), the presence of reinforcing loops reflects the spiralling nature of long-term health system behaviour. Population health initiatives aimed at prevention and upstream interventions may be expected to result in higher workload for a shrinking pool of potential care providers in the short term, but hopefully a reduction in chronic disease burden in the long term. This sets the context for the Future Hospital plans. In the long term, current preferences for public versus private sector may not hold. An important outcome from the stakeholder discussion is that the primary driver of demand for the SH is the resident population (and not just the population residing nearby), since the SH has historically played a national role, and the mental

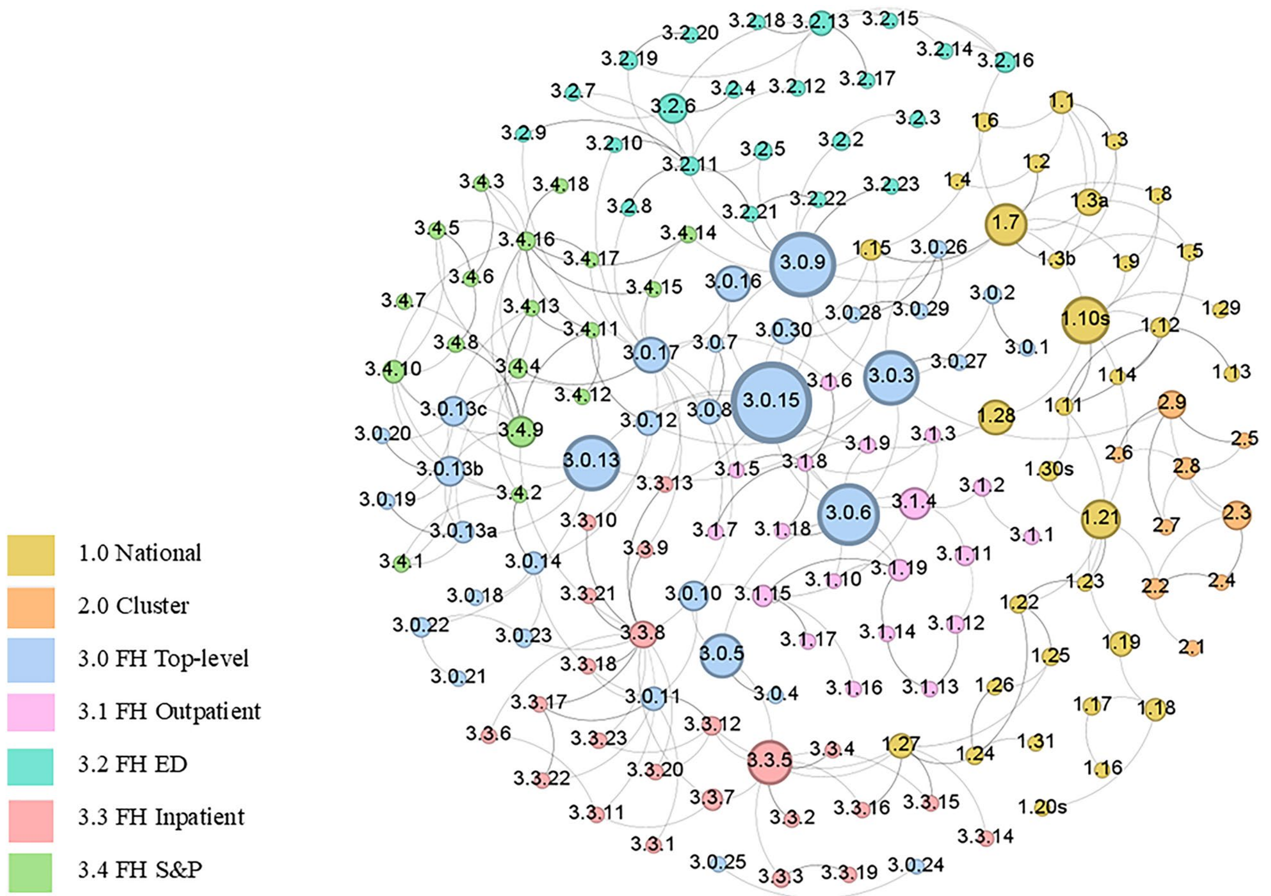

Fig. 3 Combined digraph view of the seven sectors of the CLD. Node size is proportional to weighted betweenness centrality; node colours indicate the view they belong to; density (see Supplement 5.2) shows that the overall network is sparse but the separate views have relatively higher density, indicating greater cohesion along functional lines

model of the stakeholders is that it will continue to do so. This dominantly national role of the SH makes the PH cluster view (CLD 2.0) rather sparse. The SH Top level view (CLD 3.0) is a parent layer that common to the four children CLDs (outpatient, ED, inpatient and S&P). In this CLD, a key construct is that the proportion of haematology, oncology, renal, neurology, and cardiology (HORNC) patients is an important driver of need for SH services. Analysis by SH staff has shown that HORNC patients tend to be more frequent users of SH services and are less likely to switch to newer hospitals. Pooling of resources (whether doctors, nurses or equipment), is a key factor that can affect future efficiencies across SH subsystems.

Traditionally, the roles of different subsystems are specialized and care may be siloed. For example, ingrained patient preferences drive them to specialist outpatient facilities although some of their needs can be managed well at primary care facilities. Gaps in outpatient care, and even more so primary and community care outside the hospital, also drive the proportion of needs met at the emergency department [54, 55]. The CLDs show an integrated systems perspective can help to understand the interdependencies across the various subsystems to derive more effective interventions for demand and capacity management.

The SH Outpatient View (CLD 3.1) identifies technology advances in consultation, operations efficiency advances, right-siting of care, teleconsulting and pooling of resources as the primary interventions for future change. The effectiveness of teleconsultation is dependent on the operational strategy (e.g. dedicated pool of resources versus a percentage of each provider's workload being decanted to teleconsulting). Financial incentives have a distinct role; in the current system, reimbursement mechanisms can incentivize patients to seek specialist rather than primary care [56]. Better scheduling and increasing efficiency for patients can improve patient experience (e.g. with multiple appointments synchronized on the same day). Waiting time for appointments

Table 3 Nodes with the highest betweenness centrality

Rank	Node (v)	Description	CLD View	$c_B(v)$
1	3.0.15	Need for agility	SH top-level	0.377
2	3.0.9	Need for ED services	SH top-level	0.288
3	3.0.6	Need for SOC Services	SH top-level	0.266
4	3.0.13	Need for surgical and other procedure services	SH top-level	0.232
5	3.0.3	Need for SH services	SH top-level	0.229
6	1.10 s	Resident population health service needs volume	National	0.180
7	3.3.5	Physical inpatient LOS	Inpatient	0.166
8	3.0.5	Proportion SOC of total need for SH services	SH top-level	0.165
9	1.7	Proportion of elderly in resident population	National	0.152
10	1.21	Public sector health service needs volume	National	0.135
11	3.0.17	Pooling of resources (equipment and manpower)	SH top-level	0.122
12	3.0.16	Design for flexible assignment of resources (equipment and humanpower)	SH top-level	0.118
13	1.28	Crises affecting health	National	0.114
14	3.1.4	Outpatient consult rooms required	SOC	0.096
15	3.4.9	Waiting time to surgery appointment (WTA)	S&P	0.088
16	3.2.6	ED treatment units required	ED	0.085
17	3.0.10	Proportion HORNC versus others	SH top-level	0.084
18	3.0.13c	Need for emergency surgery	SH top-level	0.081
19	3.0.13b	Need for elective surgery	SH top-level	0.081
20	2.3	PH Cluster gap in met needs	Cluster	0.076

ED emergency department

HORNC haematology, oncology, renal, neurology, cardiology

LOS length of stay

SOC specialist outpatient centre

is a key parameter that drives capacity expansions in this subsystem.

The necessity to keep length of stay (LOS) under control and maintain care effectiveness for EDs traditionally may mean continuously increasing capacities [57]. However, as shown in the SH ED view (CLD 3.2), the relationship between acuity and LOS has nuances. Low acuity patients may have longer wait time and hence high LOS as higher acuity patients are prioritized; this primarily affects patient experience but not health outcomes. Key interventions elicited include the departure from the current mode of operations through regionalization with more EDs, right-siting away from ED with reduction of gaps in other subsystems (e.g. primary and community care, integrated long-term care or ILTC), and preventive care and HaH (rather than admission to inpatient wards) to reduce exit block.

For the SH Inpatient View (CLD 3.3), LOS is a key parameter of the subsystem. Key interventions to depart from business-as-usual are reducing LOS and avoidable bed days through right-siting of inpatients. Right-siting includes appropriate decantation of patients to step-down care and ILTC, HaH and day rehabilitation centres. Long stayers are often symptoms of unmet social needs [58, 59] and stress this subsystem, with effects on other subsystems as well.

In the SH S&P view (CLD 3.4), the key driver of capacity increases is waiting time for appointments. The number of surgeries and procedures that can be done is limited by surgical theatre and procedure room availability relative to the need for surgeries and procedures from inpatients as well as outpatients [60]. The key interventions to depart from business-as-usual are pooling of resources, clinical advances and advancement of scheduling policies. Advancements in surgical techniques allowing more procedures to be converted to day surgeries (so that equivalent care is provided without admission to an inpatient ward) can also reduce the need for inpatient services.

Insights from network analysis

The network analysis results point to a set of diverse variables that have high betweenness centrality. Two issues deserve special attention from Future Hospital planners. Firstly, these variables show that the SH system is predisposed to nonlinearities. They include demand- and supply-side variables, as well as waiting time, which arises from the interactions of demand

and supply. This is a source of nonlinearity, because waiting times in queueing systems are known to increase disproportionately when systems operate closer to full capacity utilization [61]. Another example source of nonlinear behaviour is the interaction between age and per capita use of hospital service [62]. Secondly, the high betweenness centrality variables are not silver bullets for enhanced system performance. For example, the need for agility requires design for flexibility, pooling of resources and adequate availability of care providers (see CLD 3.0). The latter is challenging in an ageing population. More efficient pooling of resources is linked to gaps in care (see CLDs 3.1 through 3.4), which affect the patient experience, and are linked through service needs to the need for agility. Again, this illustrates the tightly coupled nature of the system. The list contains nodes that reflect demand (service needs), supply (capacities), demand–supply interactions (waiting time, LOS), exogenous factors (crises), demographics (proportion of elderly) and strategic choices (design for flexibility, pooling of resources, public sector volumes). The diversity of this group of critical nodes is an illustration of the tightly coupled nature of the health system (alluded to by Sterman 2006 [18]), which is associated with feedback and nonlinear effects.

Contribution and limitations

Our study adds much-needed systems thinking insight, including interconnectedness, feedback loops and interventions, to the literature on Future Hospital planning, which has thus far been dominated by the technical architecture perspective. Taleb et al. [63] highlight issues in the context of systems designed for the public domain, in the absence of evidence, and with incomplete scientific knowledge. They provide examples of unintended consequences in health systems that can result from inadequate consideration of complex interdependencies. In specific cases, ruinous outcomes are those from which there can be no recovery. Consequently, the ideas of cost–benefit analysis are not applicable in these cases. The long-range planning horizon for the Future Hospital (until the year 2100), the changing structure of the population (affecting both demand and supply) and the threat of future crises combine to create a context in which accumulated statistical evidence is inadequate to guide policy. In this situation, the soft systems (qualitative) CLD analysis is effective in the elicitation of mental models, the first documentation of shared understanding and deep domain knowledge. This provides a basis, a live planning document, which can be updated and enhanced with new insight.

Our work has visible limitations. The CLDs reflect the views of a diverse group of stakeholders, but they are specific to this group, which does not include patients. For other Future Hospital planning groups, they provide a set of extensive reference material, which was not available prior to this, to the best of our knowledge. However, the systems thinking leads within these groups do need to ensure that this material complements but does not bias the elicitation of the mental models of their domain experts. Further, the present work needs to developed further with quantitative modelling, which is work-in-progress. The long-term modelling horizon makes simulations results dependent on population scenarios. Agility of the health system, a variable highlighted through our analysis, may be difficult to operationalize in a robust manner. This is an important topic for future research. We acknowledge that the qualitative maps produced through the work need to remain living documents.

Conclusions

The design of a Future Hospital is a rare opportunity to re-imagine the delivery of healthcare without neglecting the present reality. Complex systems approaches are well suited to mapping the logic of Future Hospital design. This study presents accessible, visual Future Hospital design logic maps to support these approaches.

Abbreviations

CLD	Causal loop diagram
DSS	Dynamical system simulation
ED	Emergency department
HaH	Hospital at home
HORNC	Haematology, oncology, renal, neurology and cardiology
ICU	Intensive care unit
ILTC	Integrated long-term care
LOS	Length of stay
PH	Public healthcare
S&P	Surgeries & procedures
SH	Study hospital
SOC	Specialist outpatient centre

Supplementary Information

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Supplementary material 1.

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Author contributions

A.K., S.S.W.L. and C.S.L. designed the study; G.G.K.T. and T.H.K. provided future hospital (FH) domain expertise; A.K., S.S.W.L., C.S.L., G.Y. and X.Y. edited CLDs in

Vensim; A.K. and S.S.W.L. performed network analysis; all authors participated in collaborative modelling and reviewed the CLDs; and A.K. and S.S.W.L. wrote the first draft manuscript. All authors reviewed and approved the manuscript.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Ethics approval not applicable. Participants in group modelling meetings were verbally briefed and meetings were recorded with their consent.

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Competing interests
The authors declare no competing interests.

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