Healthcare System of Systems Vulnerability

Health

GCA Learning from Practice

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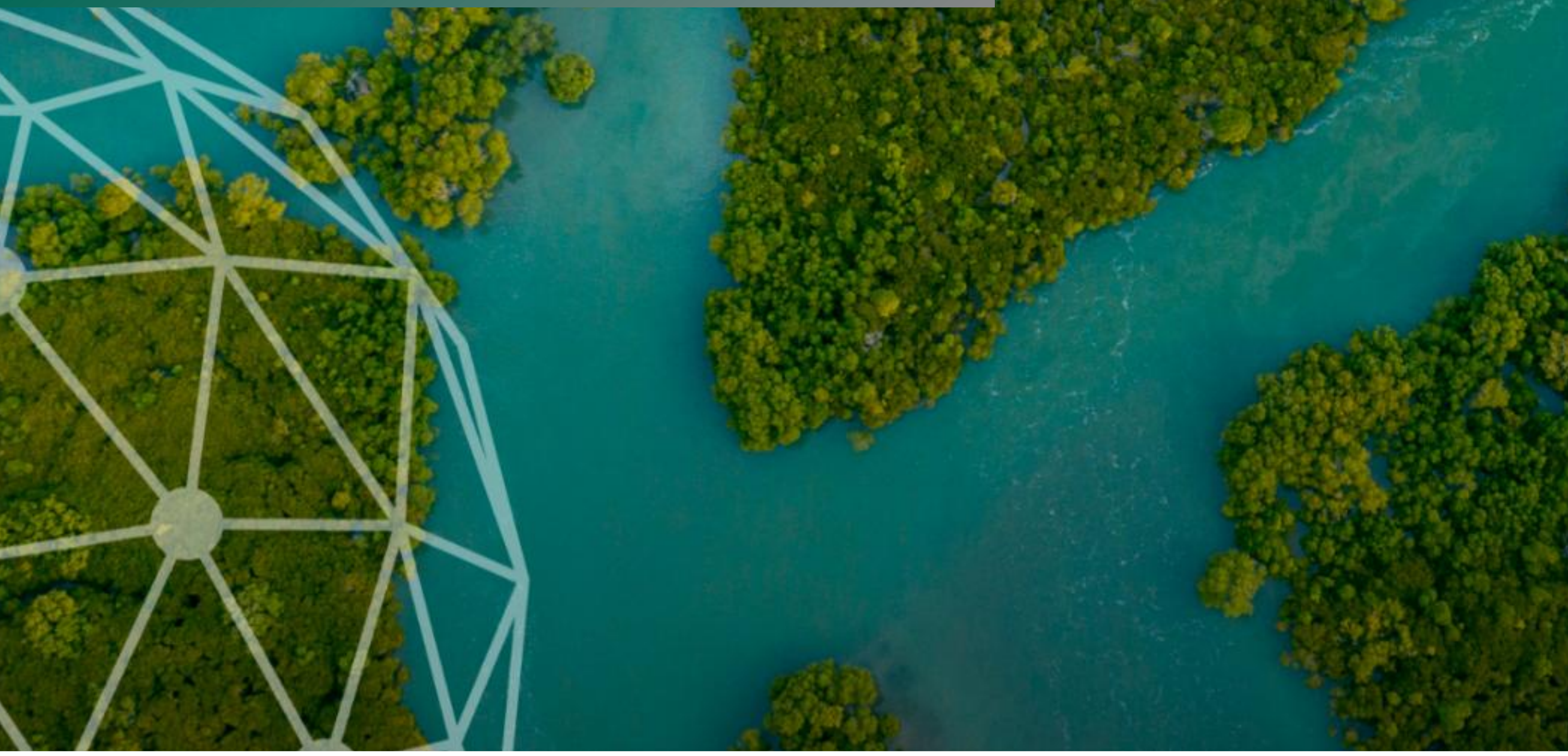

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Oxford Infrastructure Analytics

This series of GCA Learning from Practice notes provides a practical reference to support the design and implementation of climate adaptation analyses. Drawing on the experience and lessons from GCA programs, each note focuses on a specific methodological component, offering guidance on key concepts, minimum standards, and recommended practices to strengthen the quality, consistency, and usability of analytical outputs.

Intended for practitioners, analysts, and decision-makers, the notes aim to balance scientific rigor with operational relevance. By translating experience into clear methodological benchmarks and actionable guidance, the series supports credible analyses and enables more informed planning, investment, and adaptation decisions.

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GLOBAL CENTER ON ADAPTATION

ABOUT THE GLOBAL CENTER ON ADAPTATION

The Global Center on Adaptation (GCA) is an international organization, hosted by the Netherlands, which works as a solutions broker to accelerate action and support for adaptation solutions from the international to the local, in partnership with the public and private sector, to ensure we learn from each other and work together for a climate resilient future.

AFRICA ADAPTATION ACCELERATION PROGRAM

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ABOUT OXFORD INFRASTRUCTURE ANALYTICS

Oxford Infrastructure Analytics (OIA) specializes in systemic climate risk analysis and adaptation planning for infrastructure systems. OIA was founded in 2017 from the award-winning Oxford Programme for Sustainable Infrastructure Systems, University of Oxford.

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ABBREVIATIONS

Acronyms	Definitions
CHW	Community health workers
GCA	Global Center on Adaptation
GP	General practitioner
IFI	International Finance Institution
IPCC AR6	Intergovernmental Panel on Climate Change, Sixth Assessment Report
OIA	Oxford Infrastructure Analytics
PHC	Primary healthcare centre
SDG	Sustainable Development Goal
UDHR	Universal Declaration of Human Rights
WHO	World Health Organisation

1 INTRODUCTION

Healthcare systems provide a variety of services that are fundamental for all modern societies. Health is the subject of one of the seventeen dimensions of development that are represented in the Sustainable Development Goals (SDGs): SDG 3 Good Health and Wellbeing. The importance of healthcare is also reflected in the Universal Declaration of Human Rights (UDHR), where research has discovered that the provision of healthcare services can support 17 of the 30 UDHR articles.[1] This includes UDHR article 3: Right to life; and Article 16: Right to marriage and to establish a family, amongst others.

Healthcare spending is growing rapidly because of increasing demand for healthcare services due to population growth, aging demographics, and the rising burden of chronic diseases.[2] Technological advancements, policy decisions, and investment in infrastructure have made possible the advent of universal health coverage initiatives in countries such as Thailand and Rwanda, telemedicine across Sub-Saharan Africa and South Asia, and investment in healthcare facilities and associated infrastructure construction in countries such as China and the United Arab Emirates.[3] Alongside the growth in service provision, we also observe an increase in dependency of external infrastructure services such as water, energy, transportation, waste management and digital infrastructure systems.[4] Electrification and digitalisation are also creating new healthcare services that are expanding in scope as well as complexity. Climate hazards pose a serious threat to these systems, and climate change is increasing this threat. A recent modelling study estimated that anthropogenic climate change (between 1990 and 2020) had the potential to increase the risk of damage to hospitals by 41%.[5] Such risks are observed globally, with risks concentrated in areas that face high levels of exposure to climate hazards. The United Nations Population Fund estimates that close to 1,500 hospitals in Latin America and the Caribbean are in low-elevation zones vulnerable to extreme weather events, with over 80% of hospitals lying in these regions for certain countries.[6] In 2022, Pakistan suffered from months of extreme flooding, limiting the function of 10% of the country's healthcare facilities, totalling to 1,460.[7] In 2023, a combination of floods and landslides in Thailand caused 12 healthcare facilities to close across five provinces.[8]

In 2005, Hurricane Katrina caused the failure of multiple levees and flood walls that had protected New Orleans from flood waters. This caused widespread damages to assets, including New Orleans's Charity Hospital due to inundation of the first floor of key buildings[6]. Further disruptions then occurred due to failures within supporting infrastructure, including energy, digital communications and water systems – impacting building cooling, dehumidification, amongst other key services – worsening health conditions. Beyond impacting healthcare service delivery, these cascading failures also resulted in impacts to access to communications about live reporting of the storm damage resulting in misinformed emergency decision making.

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[1] Thacker, S., et al. (2025). Building fairer futures: Aligning infrastructure development with human rights principles. In preparation to be submitted to Nature.

[2] Schäferhoff, M., et al. 2019. Trends in global health financing. BMJ 2019; 365: l2185.

[3] Katoue, M.G., Cerda, A.A., García, L.Y. and Jakovljevic, M. (2022). Healthcare system development in the Middle East and North Africa region: Challenges, endeavors and prospective opportunities. Frontiers in Public Health, 10(1).

[4] Thacker, S., Adshead, D., Fay, M. et al. 2019. Infrastructure for sustainable development. Nature Sustainability 2: 324–331.

[5] Cross Dependency Initiative (2023). 2023 XDI Global Hospital Infrastructure Physical Climate Risk Report.

[6] UNFPA (2024). Climate emergency threatens 41 million people, their livelihoods and health care in low-elevation coastal areas in Latin America and Caribbean. United Nations Population Fund. Press release. United Nations Populations Fund.

[7] OCHA. (2022, September 9). Pakistan: 2022 Monsoon Floods—Situation Report No. 5 (As of 9 September 2022). UN Office for the Coordination of Humanitarian Affairs.

[8] The Star Online (2023). Flooding in five southern provinces affects 10 Thai hospitals. The Star.

Climate change adaptation provides a means to address climate risk and in doing so enhance the resilience of the healthcare system. This can be achieved through adaptation that is targeted directly at the healthcare systems themselves, for example building protective walls to mitigate the impacts of flood waters. They can also enhance the resilience of infrastructure that the healthcare system is dependent upon, for example through the provision of back-up electricity generators or water storage tanks – providing redundancy in the event of a hazard.

With large volumes of investment expected in healthcare systems in the coming decades it is essential that they are designed with resilience in mind. Adaptation of healthcare systems provides a means to safeguard service provision that is essential for our socio-economic development and fundamental human rights. Failing to do so can entrench systemic vulnerabilities for decades to come – creating impacts that are often felt by those most marginalised within societies. Addressing this issue will require targeting and coordinated action from a variety of stakeholders, as well as a holistic approach to healthcare systems and the ever-evolving risks that they face.

Decision makers in this area are supported through a range of practical assessment frameworks and indices. This includes the World Health Organization's (WHO) hospital safety index guide, which provides a framework for administrative staff to evaluate a hospital's treatment and operating capacity. For example, the quantity of beds per service (surgery, intensive care, etc.), medical, surgical, and nonclinical staff capacity, and operating departments.[9] This index and related tools such as the safe hospitals checklist and baseline assessment tool divide the assessment into the hazards affecting the structural and non-structural safety of the hospital, and the management protocol in the event of emergencies and disasters.[10] This asset-centric view is also reflected in the evaluation of physical climate risks, which are typically evaluated at the scale of individual assets, such as a hospital. Whilst providing important insights, such studies often under-represent the systemic characteristics of healthcare and its dependencies – in doing so, under-representing the range vulnerabilities and magnitude of risks, and the benefits associated with adaptation interventions.

The **overall aim of the project is to address this limitation in current theory and practice: Developing a theoretical understanding of healthcare as a system-of-systems and characterising potential systemic vulnerabilities**. In doing so, providing the Global Center on Adaptation (GCA) with important and novel information that, when coupled with physical climate risk and adaptation methodologies, can support their aim of catalysing high-quality adaptation with International Finance Institutions (IFIs) and other stakeholders.

Three objectives have been developed to help address this aim:

- **Objective 1: How can healthcare be conceptualised as a system of interconnected assets and services?**
- **Objective 2: How can the healthcare system, through its dependence on infrastructure systems, be considered a system-of-systems?**
- **Objective 3: How can the potential systemic vulnerabilities of the healthcare system-of-systems be conceptualised?**

For the purposes of this study, we define a system-of-systems as a collection of multiple independent systems that form part of a larger, more complex system. Where an individual system can be defined as a group of interconnected components that form a complex and unified whole. Grounding this

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[9]WHO & Pan American Health Organization. (2019). Hospital safety index: Guide for evaluators (2nd ed.). World Health Organization. Switzerland. .

[10] WHO and Pan American Health Organization (2019). Hospital Safety Index Guide for Evaluators. Second Edition. Washington D.C., USA.

definition, the healthcare system-of-systems can be considered to contain the healthcare system, as well as the energy, transport, water, waste management and digital communications systems on which the healthcare system depends.

This report addresses these aim and objectives through the development of theory to support our understanding of *Healthcare System-of-Systems Vulnerabilities. The report is part of a larger project on climate-resilient health systems for sustained value chains, healthcare access and services.*[11]

The study builds upon over a decade of research and development undertaken by Oxford Infrastructure Analytics (OIA), in collaboration with the University of Oxford, into infrastructure systems risk and adaptation analysis that is recognised globally. Central to these developments are the characterisation of infrastructure as a 'system-of-systems' that represents not only the physical but functional interconnectivity and interdependence between assets and systems.[12] It builds on applications that OIA experts have undertaken in over 40 countries in a variety of contexts around the world, from the UK,[13] to Palestine.[14]

Following this introduction, Section 2 addresses the first objective – conceptualising healthcare as a system. Building on this description, Section 3 describes how the healthcare system is supported by a variety of infrastructure systems – to become a system-of-systems (objective 2). Objective 3 is then addressed in Section 4 by identifying potential systemic vulnerabilities that threaten healthcare services. Finally, section 5 provides a conclusion for the project, including its contributions to theory, its limitations, and areas of future work.

IMPORTANT:

Building on academic and grey literature (citations provided throughout this report), we provide a generalized characterisation of the healthcare system-of-systems and its systemic vulnerabilities. It is important to understand that the composition, interconnectivity and interdependence of these systems vary greatly by country and context. As such, the proposed characterizations should act as a guide to the reader – highlighting a conceptual framework through which to understand these systems – rather than being an absolute description that is appropriate for supporting decisions a given context.

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[11] Leppert, G., Mercer, E., Thacker, S., Ridde, V., De Allegri, M., Massie-Vereker, V., Adshead, D., Solnon, A.-L., Hossain, A. T., & Ramadan, F. (2026). *Climate-resilient health systems for sustained value chains, healthcare access and services*. Global Center on Adaptation (GCA); Oxford Infrastructure Analytics (OIA); Centre Population & Développement (CEPED, Université Paris Cité, Université Sorbonne, Inserm, IRD); Heidelberg Institute of Global Health (HIGH, Heidelberg University).

[12] Hall, J.W., Tran, M., Hickford, A.J. and Nicholls, R.J. (eds.) The future of national infrastructure: a system-of-systems approach. Cambridge University Press, Cambridge, UK:241-267.

[13] Thacker, S., Pant, R., Hall, J.W. (2017) System-of-Systems Formulation and Disruption Analysis for Multi-Scale Critical National Infrastructures. Reliability Engineering and System Safety, 167: 30-41.

[14] Pant, R., Thacker, S. and Hall, J. (2017) System-of-systems Framework for Global Infrastructure Vulnerability Assessments. GGKP Annual Conference, November 27-28, Washington D.C., USA.

2 HEALTHCARE SYSTEMS

2.1 Healthcare service provision

Healthcare systems provide a wide variety of services to support the needs of individuals within modern societies. Table 1 provides a generalized and non-exhaustive representation of healthcare services and the typical nature of service provision. This includes for i) urgent (emergency) treatment; ii) non-urgent treatment; iii) long-term care; and iv) access to materials. In each case, the services may be delivered at the location of the patient (transient) or at a specific location (fixed – where the patient will make a journey to receive the service). Healthcare assets are typically organised in space based on economies of scale – were practically, this means that larger facilities that provide more specialised services are located close to large population centres or distributed regionally to support remote populations.

	Nature of service provision access points	
Healthcare service	**Transient**	**Fixed**
Urgent (emergency) treatment	• Emergency vehicles	• Hospital (emergency departments) • Clinics (emergency departments)
Non-urgent treatment	• Mobile clinics • Community health workers (CHW)	• Hospital • Clinics; Primary health care centres (PHCs) • Training facilities • General practitioners (GPs); Nurses
Long-term care	• Home care	• Residential care homes
Healthcare material provision	• Material delivery	• Pharmacies; Drug dispensaries

Table 1: Generalized representation of healthcare services and the nature of the service provision.

The system of referrals facilitates a patient experience that connects different service access points. For example, a patient diagnosis at a mobile clinic may result in a referral to received non-urgent treatment at a hospital, which may then result in a referral to receive medicines from a pharmacy (through medical prescription). The time taken to receive services and advance through referrals is context and case specific – being determined by the determined level of urgency of healthcare needs, as well as the capacity of the healthcare system to respond to that need (which may be capacity constrained due to waiting lists, insufficient supply of medicines etc.).

The following sub-sections provide a high-level description of a selection of the services that might typically be delivered at given healthcare service access points.[15]

[15] The high-level description below does not take into further consideration decentralized local healthcare services, such as general practitioners (GPs), nurses, and community health workers (CHWs), which frequently operate in normal residential buildings or transient in the community and are often the first point in contact for patients and community members. Like other service providers, these providers also depend on the availability of other systems, such as electricity, water and road infrastructure, as well as the availability of drugs and medical devices.

2.1.1 Hospitals

Hospitals are central components of the healthcare system and provide a broad range of services to different patients. This includes urgent (emergency) diagnosis, response and treatment, such as emergency surgery, burns treatment, cardiovascular treatments, amongst others. Hospitals also provide non-urgent treatments across a range of medical specialists. A selection of examples includes dermatology, cardiology, psychiatry, maternity, neurology, paediatrics, plastic surgery, and cancer treatment. Additionally, hospitals can contain other forms of clinical and nonclinical support services such as diagnostic and blood bank services, and house other healthcare assets, including pharmacies or training facilities.

2.1.2 Clinics and Primary Healthcare Centres

Clinics are important healthcare facilities in the healthcare system, categorized into general or specialized units. While there are urgent care clinics, they do not typically provide the emergency capacities of a hospital, however, many clinics are accessible by walk-in appointments. General clinics provide general medicine or general paediatric care, while other clinics can specialize in preventive care, such as gynaecology, orthopaedics, sexual and reproductive healthcare, podiatry, urology, gastroenterology, physical therapy, or dentistry. General clinics may also be known as primary healthcare centres (PHCs) – which are often present at the community level and represent an entry point for patients into the broader (public) healthcare system. Clinics can, amongst others, also offer prescription services, vaccinations, diagnostic services, and screenings. Clinics are typically connected to laboratories which process samples collected within diagnostic and screening services.

2.1.3 Mobile clinics

Mobile clinics may be utilised in contexts where there is a lack of infrastructure, geopolitical instability, or other lack of resources which render a fixed clinic unfeasible in a region. Their mobility enables individuals from a wider geographic range to access their services. Mobile clinics can provide preventive care, vaccinations, emergency interventions, dental care, and sexual and reproductive care, among other services.

2.1.4 Emergency vehicles

Emergency vehicles (for example ambulances) are the primary mobile urgent care units. These services include emergency interventions, pre-hospital acute medical care, patient transportation, basic life support, advanced life support, and crisis helplines.

2.1.5 Training facility

The healthcare system also contains facilities to train a range of medical staff. Primary training facilities include medical schools, which contain teaching hospitals and clinical training materials for trainees to prepare for general medicine, cardiology, surgery, and so on. Medical schools often have a research component to their facility, to generate innovative solutions in the spheres of medical engineering, medical technology, oncology, immunology, etc. Research is critical for the evolution of the sector, including to drive innovation within medicines, devices and care. Moreover, as a part of medical school training, there is often non-urgent patient care involved, such as preventive care or management of chronic conditions. Specialized training facilities include nursing school and dentist school, with smaller certificate programs preparing trainees for social work or pharmaceutical work.

2.1.6 Residential care homes

Residential care is a tertiary component of the healthcare system, catering towards individuals with chronic illnesses or conditions which necessitate assisted living. While residential care does not contain emergency services in the way a hospital does, it requires materials for live-in care involving permanent shelter which other facilities do not. Residential care includes nursing homes, assisted living facilities, adult disability support, geriatric care, psychiatric care, rehabilitation, and hospice.

2.1.7 In-home care

Like residential care homes, in-home care supports patients who require assisted living. However, the care provided by the healthcare system is delivered within the home of the patient. One or more healthcare personnel may support the patient and cater for their healthcare needs, either in a part-time or full-time capacity.

2.1.8 Pharmacies and drug dispensaries

Pharmacies are points of contact between medical suppliers and patients for the exchange of medical materials. This includes the exchange of medicines, but also medical supplies, equipment, and vaccinations. Services other than distribution can be provided at pharmacies, such as screenings, consultation, and preventive care.

2.1.9 Materials home delivery

Materials home delivery is the provision of healthcare materials directly to patients' homes. Materials can include medicines and other equipment, as might be available at pharmacies. However, some medicines may be restricted from delivery and instead require an in-person collect – to ensure safety. Delivery provides a useful way to access healthcare materials for those who may face access issues to pharmacies.

2.2 Healthcare system characterisation

The complex and interconnected nature of healthcare service provision highlights the need for a systems-based understanding of healthcare – to understand its characteristic behaviour, functional dependencies and systemic vulnerabilities. We propose healthcare systems characterisation (Figure 1) that centres around the 9 healthcare service access points that we introduced in the previous section of this report. Some of these services are delivered at buildings, whilst others through transportation modes. Supporting these key service-enabling assets are other assets within the healthcare system including the healthcare materials supply chain (that use storage and transportation assets), as well as healthcare personnel supply (that use housing and transportation assets).

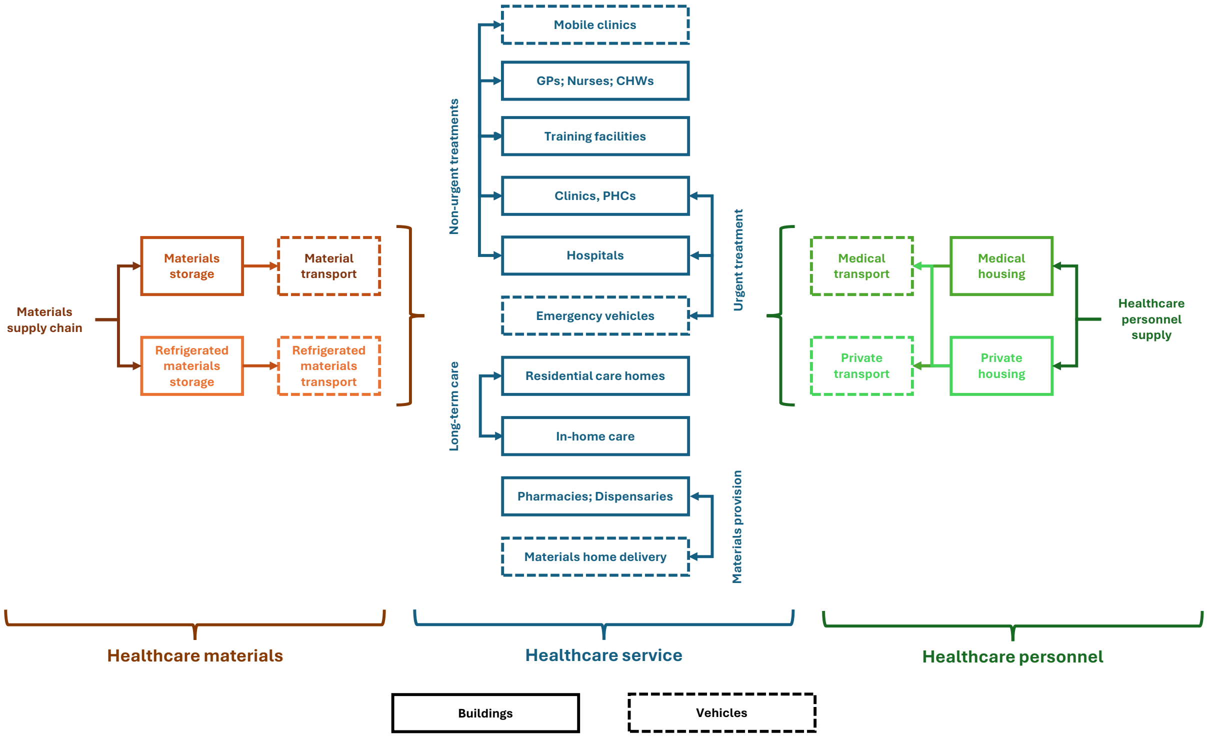

Figure 1: Generalized representation of the healthcare system, including key building and vehicle related assets and their interconnectivity.

The following sub-sections describe each of these assets in greater detail.

2.2.1 Healthcare service assets

Healthcare service assets are a central component of the system that facilitate patient access to a variety of different healthcare services (described in detail in Section 2.1 of this report). Broadly, these assets fall into two categories: Buildings – which are fixed assets and include hospitals, clinics, training facilities, residential care homes, and pharmacies; and Vehicles – which are mobile assets and include emergency vehicles, mobile clinics, and materials home delivery.

Building assets are typically built structures that are enclosed within a site boundary that has access restrictions that may be regulated through administrative and security systems. More broadly, the building may contain other monitoring and digital communication systems for staff. These can include internal control systems that manage lighting, heating, cooling, communications and ventilation. Medical gas management and refrigeration are also a central feature of such assets, enabling a variety of different medical services. Internal water, waste, electricity and sanitation systems provide and support other internal fixed-asset functions. Finally, food and housekeeping systems support clean and catered environments for staff and patients – which are essential for in-patient treatment and care.

Vehicle assets are typically purposefully designed vehicles that support the delivery of a limited range of healthcare services (compared to healthcare buildings assets) flexibly to different locations. They are typically able to carry a few healthcare personnel, alongside healthcare equipment, patients, and medicines. Vehicles may include refrigeration (for medicines), as well as supplies or water and electricity – to power certain equipment. Such vehicles may also include temporary structures that can be constructed besides the vehicle to administer services from, for example, vaccinations.

2.2.2 Healthcare materials assets

The healthcare system relies on many materials to ensure that services can be delivered to patients. Broadly, these fall into two categories: equipment and medications. Where medical equipment can include medical gases – used in surgery, imaging, or for those with respiratory dysfunction; electric equipment – including ventilators, defibrillators, as well as ultrasound and x-ray machines; non-electric equipment – ranging from wheelchairs to stretchers and syringes to beds. Medications are often split into two categories and include refrigerated medicines - such as insulin, vaccines, antibiotic liquids, injections, eye drops, creams, and others; and non-refrigerated medications - inhaler, contraceptives, anti-inflammatory, antihistamine, antipsychotics, amongst others. Refrigeration is required to maintain the efficacy and safety of many medications, with changing regulations indicating that increased medication is recommended to be refrigerated to ensure a certain temperature threshold is not exceeded, potentially compromising the medication.

Healthcare materials rely on the material supply-chain assets for their adequate provision and availability at healthcare service access points. Storage facilities are used to stockpile materials for distribution and across several healthcare assets. Such facilities are required to safe and secure, given the value and sensitivity of materials that they house. In the case of medicine storage, then refrigeration is required for several medicines. Such refrigeration must also extend through that medicine's transportation in vehicles between storage facilities and points of use. This refrigerated supply chain is commonly known as the 'cold chain'. Other, non-refrigerated vehicles are utilised to enable the transportation of equipment.

2.2.3 Healthcare personnel assets

Healthcare personnel are those staff involved in the operation of the healthcare system either at healthcare service access points or through the materials supply chain. Medical staff includes nurses, doctors, surgeons, laboratory technicians, emergency personnel, pharmacists, general practitioners, specialized medical staff (cardiology, neurology, etc.), and mental health frontline staff, amongst others. Medical trainees feed the flow of new labour into the healthcare workforce, and consist of medical trainers, trainees, nursing students, dentistry students, and medical school students. Non-medical personnel encompass the operations task force for healthcare assets and its supply chain, and includes administrative staff, buildings management, cleaners, logistics support, and drivers, amongst others.

Healthcare personnel rely on housing and transportation to support their work within the healthcare system. Whilst many medical and non-medical staff will rely on housing from the private market, some medical staff, such as visiting staff and medical trainees, many be provided medical housing. Such housing typically provides many of the services related to modern living (water, sanitation, electricity, communications), as well as easy access to buildings that they work in. Similarly, most healthcare personnel will reply on private transport to access work. This could be through their own vehicle, or via public transportation. However, in certain circumstances, medical transports are provided to take healthcare personnel between their residences and work.

3 INFRASTRUCTURE DEPENDENCIES

3.1 Healthcare system-of-systems characterisation

The previous section of the report provided a characterisation of the healthcare system comprised of different interconnected components. Importantly, each of these components is recognised as being operated and governed for the purpose of healthcare service delivery. This healthcare system is however dependent on the services provided by a broad range of external systems – which are not specifically operated and governed to provide healthcare services – but which are deemed as essential to enable them. These external services include those derived from infrastructure systems such as energy, transport, water, waste management and digital, which can be defines as external dependencies. Further to this, we observe that infrastructure systems themselves have dependencies on other infrastructure systems – that influence performance.

To understand the systemic vulnerabilities inherent within healthcare it is necessary to extend our understanding of healthcare from the systems level to the systems-of-systems levels – which not only includes healthcare, but also the external infrastructure systems on which they are dependent. Figure 2 provides a mapping of the 6 main asset types within the healthcare system and their external dependencies across 12 different infrastructure system sub-sectors.

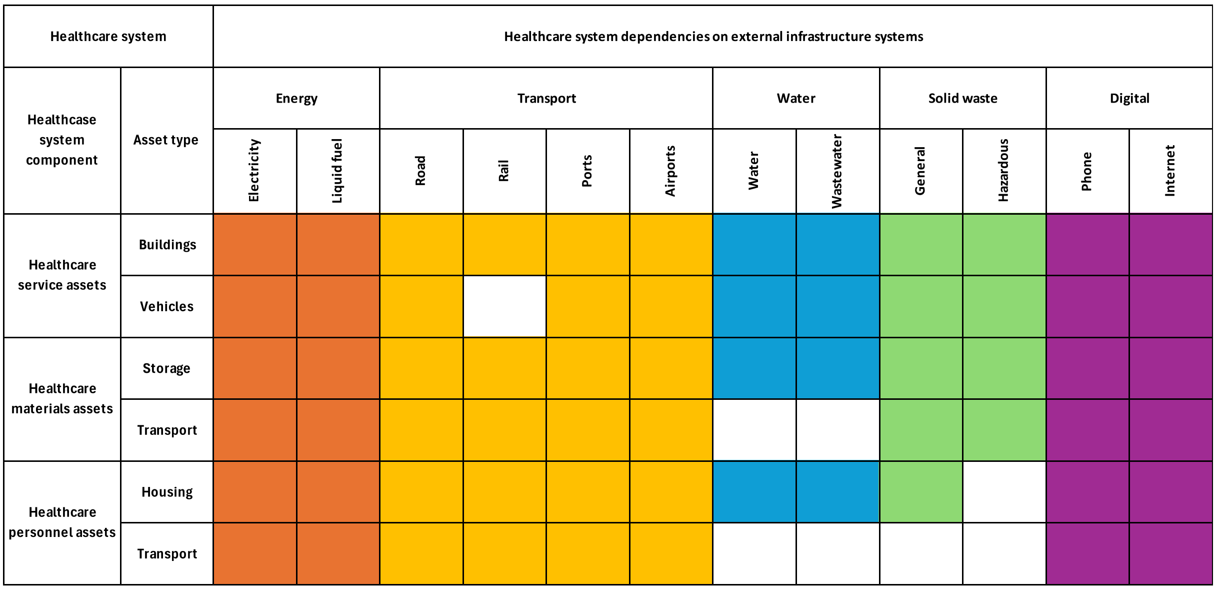

Figure 2: Generalized characterisation of the healthcare systems' dependence on a variety of infrastructure systems – creating a conceptual system-of-systems. Cell colouring represents where an infrastructure sub-sector has been identified as supporting a healthcare systems asset.

The following sub-sections describe each of these infrastructure dependency types in greater detail.

3.2 Dependence on energy

3.2.1 Electricity

Electricity is a vital input to all buildings that support healthcare service delivery. This includes in service providing assets such as hospitals and clinics, to power electrical medical devices and to provide access to administrative systems containing records and information. These administrative functions are also supported at storage facilities for inventory management and logistics, as well as in the home of personnel to keep track of and manage shiftwork. Electricity is vital for refrigeration found at all building types, to maintain medicines, blood and samples, as well as food – for staff and patients. Building related services are also enabled by electricity, including heating, lighting, cooling, communications and security and ventilation. In service providing assets and at storage facilities, these services may be managed by overarching building monitoring systems – which are in and of themselves electrical power dependent.

Electricity also plays an important role in transportation across the healthcare system. Both healthcare service vehicles (such as ambulances and mobile clinics), and materials transport vehicles (such as refrigerated lorries), rely on electricity to keep medicines and other items cool. Whilst the engine of the vehicle may support the provision of electricity, they can also rely on being plugged into the electrical grid whilst stationary – to maintain functionality. Electricity also enables several modes of transport for healthcare personnel, including from electric bikes to electric cars, and underground railway systems.

3.2.2 Liquid fuels

Liquid fuels are found to support all types of buildings within the healthcare system. Supporting functions include the use of diesel as a fuel for back-up electricity generators that are often found at hospitals and storage buildings – to maintain power in event of a power-cut from the grid. Propane is a liquid fuel that is used in many areas of the world for cooking and for the heating of water. Such uses are found across many building assets, from healthcare personnel homes, to training facilities and material storage location.

Liquid fuels, including petrol and diesel, are essential to fuel a large variety of vehicles within the healthcare system. This includes service-providing assets such as emergency vehicles, mobile clinics, as well as lorries for the movement of healthcare materials, and minivans that may function as medical transports for healthcare personnel. Liquid fuels such as diesel and petrol may be stored on sites, in the event of shortages.

3.3 Dependence on transport

3.3.1 Roads

Roads facilitate access to and from several buildings within the healthcare system. This includes enable materials such as food and medications to be delivered to hospitals and clinics and wastes to be removed through collection vehicles. It enables vehicle access to storage facilities – enabling operability of the materials supply chain, whilst also enabling personnel access to their homes after time spent at work.

Roads support all transportation asset types within the healthcare system. This includes by facilitating the access of mobile clinics to patients in a variety of locations, including the set-up of temporary structures – to deliver services. They also enable a variety of lorries and vans to collect and distribute materials from production sites, within and between storage sites, to points of use. Finally, roads provide connectivity for medical vehicles that connect residences, to places of work.

3.3.2 Railways

Railways can provide patient access to buildings such as healthcare training facilities and hospitals. Albeit this is most likely in urban contexts where rail is more commonly used for commuting purposes. The railways also support the long-distance transportation of healthcare materials, including medical equipment – enabling storage facilities to be functional. Finally, and again typically in urban contexts, the railways can be used as commuter transport for healthcare personnel – providing connection to medical housing.

Railways are in of themselves, essential components of the materials supply chain in many countries around the world. This includes shipments of food and medical supplies within and across national borders. From the perspective of transport, railways can provide access to medical transport vehicles and support commuting via multiple transport modes.

3.3.3 Ports

Ports support the materials supply chain, including the delivery of materials such as medical gases and electrical equipment into storage facilities that can be located at ports, or further afield. In remote contexts, such as small islands, ports may be used to support the travel of medical personnel to medical housing facilities on a temporary or permanent basis. This extends to patients, who might use parts as part of a journey to access healthcare services at specialist hospitals or other locations.

Ports are transport links that are part of the broader multi-modal transport system. They enable healthcare materials transport vehicle – such as trucks – by providing shipping containers carrying goods and supplies. Refrigerated containers are a vital part of the cold chain and support the transport of medicines from the water to land. Medical personnel may use ports as part of a multi-modal journey that includes medical transport vehicles. Beyond coastal ports, this can also include inland waterways that can support the movement of goods and people across freshwater lakes and rivers.

3.3.4 Airports

Air transportation enables rapid access to isolated and challenging environments, enabling medicines and materials (such as donor organs) to be transported to patients in remote hospitals. In emergency response, airports receive airlifts from remote locations to more centralized facilities. Aircraft can also enable the transport of larger equipment to storage facilities, albeit the ultimate size of the materials may be restricted in a way that transport via ports, rail or road would not be. Airports can support access for medical professionals to stay in medical accommodation – where they can then go on to provide services, including giving lectures at training facilities, or conducting research at medical laboratories.

Airports can support transportation infrastructure in the healthcare supply chain through the provision of healthcare materials – such as specialist medicines. Medical professionals arriving at airports support the use of healthcare transport through airport pick-ups and transportation to accommodation or places of work.

3.4 Dependence on water

3.4.1 Water

Water is a key dependency for all healthcare building assets. Water is required for drinking and sanitation purposes by patients, visitors and healthcare personnel generally, a use which extends to medical housing and storage facilities. In hospitals, clinics and residential care homes, food and housekeeping require water for most processes, including food preparation (e.g., cooking meals, washing produce), laundry (e.g., sanitizing linens and uniforms), and facility maintenance (e.g., floor cleaning, disinfection), in addition to sanitation.

Water can be used by emergency and mobile service vehicles to operate autoclaves, clean reusable tools, or prepare medications.

3.4.2 Wastewater management

Wastewater management is an important service within the healthcare system, supporting all building types. Pharmacies contribute chemical-laden wastewater through the cleaning of glassware and mixing tools that are used in certain medical preparations, that requires wastewater management. Storage buildings include toilets, sinks, showers, and medical washing stations, that create wastewater that requires treatment processing. Healthcare personnel housing also create wastewater through food preparation and cleaning.

Mobile clinics and ambulances may produce fluids through cleaning and other medical preparations that needs to be disposed of safely through wastewater management.

3.5 Dependence on waste management

3.5.1 General waste management

General waste management is required at all healthcare-related buildings. In clinics this includes through the disposal of medical supplies (e.g., used gloves, gauze, bandage wrappers), amongst others. At storage facilities and healthcare housing, general waste includes food waste and waste from sanitation, including hand towels and hygiene products.

Emergency vehicles produce solid waste that needs to be managed, including disposable thermometers and tongue depressors. This extends to supply chain transport that uses disposable items including protective coverings and straps to transport and secure medical equipment.

3.5.2 Hazardous waste management

Hazardous waste management is required at healthcare buildings that create hazardous waste. This can be residential care homes or hospitals that create pathological waste including human tissues, and body fluids (e.g., during surgery or wound dressing). At storage facilities, spillages of hazardous medicines, including sterilant like glutaraldehyde, disinfectants, cleaning agents, or radioactive materials (e.g., iodine-131 used in imaging, require specialised hazardous waste management systems to be in place.

Hazardous waste management is required at mobile clinics due to produce hazardous waste in the form of sharps (e.g., needles, syringes, scalpels). Materials including chemotherapy drugs (e.g., cyclophosphamide vials), if broken in supply chain transit, require specialist management.

3.6 Dependence on digital technologies

3.6.1 Phone

Phone connections are central to the operations that are undertaken at all healthcare building types. This includes phone lines at residential care homes to schedule patient visits or specialist care visits. Phones enable stock checks and logistic planning at storage facilities – supporting inventory tracking of key equipment. Phones at medical housing can be used to perform remote consultations, and shift management.

Phones are essential in emergency situations and drive the need for emergency vehicles to deploy trauma teams. Healthcare transport drivers use phones to coordinate arrives to unload and load medical materials. Medical transport coordinate via phone networks to collect key staff and take them to service delivering locations – such as accident and emergency wards.

3.6.2 Internet

The internet is used at healthcare service access points for several functions, including to facilitate patient booking, operate key equipment such as scanners and MRI machines, and to coordinate medicine home deliveries from pharmacies. Storage facilities rely on the internet for accessing cloud-based tools, communicating across teams, managing workflows, and delivering remote services. Internet connection is increasingly necessary due to the role of digital infrastructure, including artificial intelligence, accounting for things such as diagnostic services, patient records, and payroll. Medical accommodation that houses medical students use the internet to collect information from online and work on collaborative projects with others.

Emergency vehicles rely on mobile internet for navigation, patient data transmission, and coordination with receiving facilities. Healthcare material vehicles again use the internet for navigation, as well as transmitting shipment related data before and after drop-offs. The use of the internet for navigation extends to medical vehicles – to collect travelling passengers from locations such as ports and airports.

3.7 Infrastructure sector dependencies and interdependencies

Infrastructure systems also depend on one another to enable their functionality. Figure 3 shows how the 12 different sub-sectors have dependencies on one another – where cell colouring and comments are used to highlight example dependencies. Here we see that all infrastructure sub-sectors rely on certain other infrastructure systems for core functionality. This includes where sectoral workforces require electricity, water, wastewater, waste management, digital communications and road transport to support their jobs and keep the sectors in operation. Beyond this, we find other specialised dependencies that exist between sub-sectors, such as supply-chain related dependencies between road, rail, ports and airports. A further example includes waste and hazardous waste dependencies from multiple sectors – that are due to the use and production of waste through their operation and maintenance. Where 2 sectors are dependent on one another, the term interdependency is used.

Infrastructure system components		Infrastructure system depedencies on other infrastructure systems											
		Energy		Transport				Water		Solid waste		Digital	
		Electricity	Liquid fuel	Road	Rail	Ports	Airports	Water	Wastewater	General	Hazardous	Phone	Internet
Energy	Electricity		Required as a fuel for generators	Required for workforce and material access				Required for cooling and workforce	Required by workforce	Required by workforce	Required to manage certain fuel types	Required by workforce	Required by workforce and systems management
	Liquid fuel	Required by workforce		Required for workforce and material access	Required for material access	Required for material access		Required by workforce	Required by workforce	Required by workforce	Required to manage certain fuel types	Required by workforce	Required by workforce and systems management
Transport	Road	Required for traffic control and lighting	Required to fuel vehicles		Required for supply chain routing	Required for supply chain routing	Required for supply chain routing	Required by users and workforce	Required by users and workforce	Required by users and workforce		Required by workforce	Required by workforce and systems management
	Rail	Required for locomotion and control systems	Required to fuel vehicles	Required for workforce access and connectivity		Required for supply chain routing	Required for supply chain routing	Required by users and workforce	Required by users and workforce	Required by users and workforce		Required by workforce	Required by workforce and systems management
	Ports	Required for operation and control systems	Required to fuel vehicles	Required for workforce access and connectivity	Required for supply chain routing		Required for supply chain routing	Required by users and workforce	Required by users and workforce	Required by users and workforce	Required to manage certain waste products	Required by workforce	Required by workforce and systems management
	Airports	Required for operation and control systems	Required to fuel vehicles	Required for workforce access and connectivity	Required for supply chain routing	Required for supply chain routing		Required by users and workforce	Required by users and workforce	Required by users and workforce	Required to manage certain waste products	Required by workforce	Required by workforce and systems management
Water	Water	Required for pumping and monitoring		Required for worksforce and material access					Required for treatment and by workforce	Required for treatment and by workforce	Required to manage certain treatment chemicals	Required by workforce	Required by workforce and systems management]
	Wastewater	Required for pumping and monitoring		Required for worksforce and material access				Required for treatment and by workforce		Required for treatment and by workforce	Required to manage certain treatment byproducts	Required by workforce	Required by workforce and systems management]
Solid waste	General	Required for coordination and management	Required to fuel vehicles	Required for worksforce and material access				Required to manage dust and by workforce	Required for byproduct disposal and by workforce		Required for byproduct disposal	Required by workforce	Required by workforce and systems management
	Hazardous	Required for coordination and management	Required to fuel vehicles	Required for worksforce and material access				Required to manage dust and by workforce	Required for byproduct disposal and by workforce	Required for byproduct disposal and by workforce		Required by workforce	Required by workforce and systems management
Digital	Phone	Required for operating equipment		Required for worksforce and material access				Required by workforce	Required by workforce	Required by workforce	Required for disposal of asset byproducts		Required by workforce and systems management
	Internet	Required for operating equipment		Required for worksforce and material access				Required by workforce	Required by workforce	Required by workforce	Required for disposal of asset byproducts	Required by workforce	

Figure 3: Infrastructure sector dependency matrix detailing the dependencies identified (through cell shading and comment) by different infrastructure sub-sectors.

Figure 4 provides a generalized representation of the healthcare system-of-systems, based on a generalised infrastructure characterisation by Thacker et al. 2017.[13] At its centre is the healthcare system, with other infrastructure systems surrounding it. Each system is represented a series of interconnected assets that supply services. 3 different edge types (continuous line, dotted lines, and dashed lines) are used to showcase the connectivity within systems, dependencies of the healthcare system on infrastructure systems, and dependencies between different infrastructure systems, respectively. Such as representation provides an indication as to the complex functional relationships between sectors, that can also be considered as points of vulnerability and failure – which we characterise later in this report.

Readers wishing to learn more about this system-of-systems approach are advised to consult to Thacker et al. 2017[13]. The manuscript includes both a detailed mathematical characterisation of infrastructure system-of-systems, as well as a worked example for interdependent infrastructure in the UK – which was used by HM Treasury to inform the UK's first national infrastructure plan in 2018.

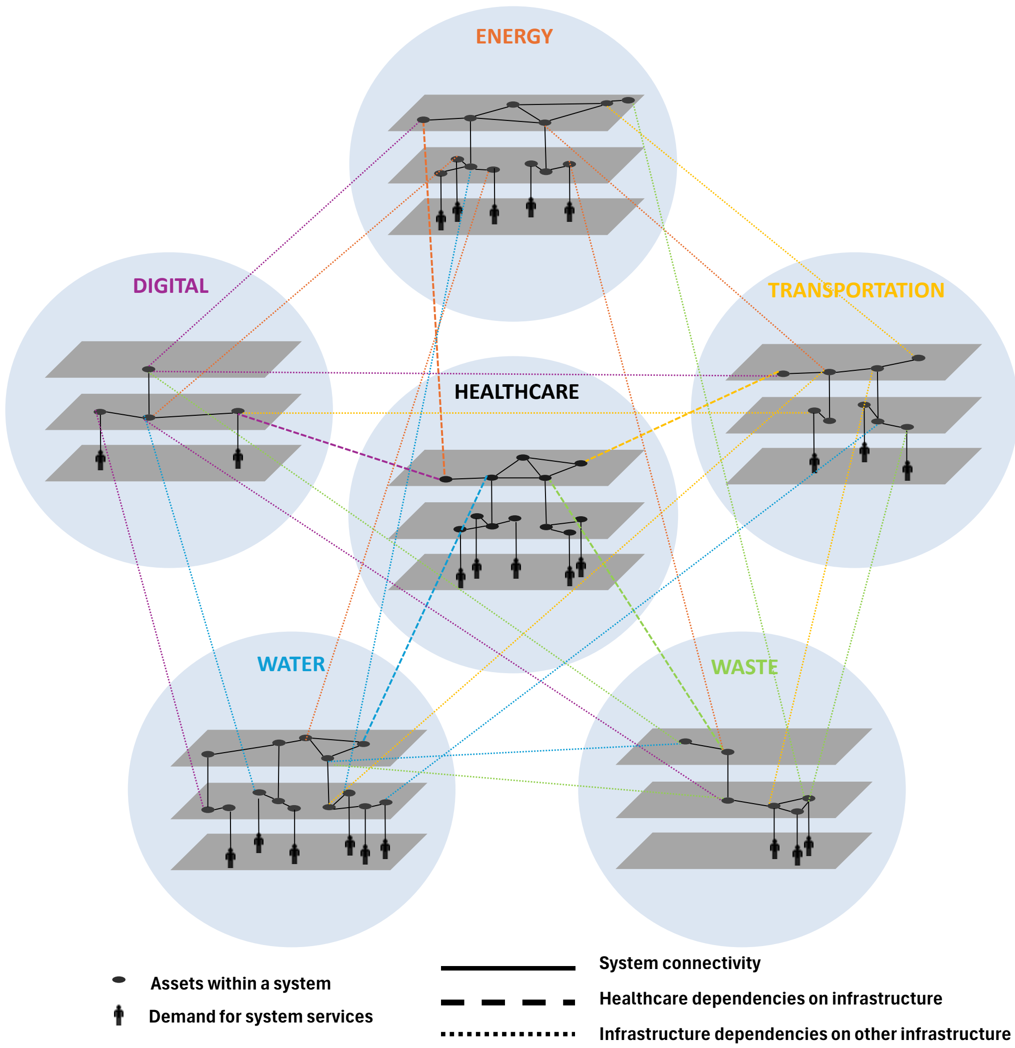

Figure 4: Generalized representation of the healthcare system-of-systems. Adapted from Thacker et al. 2017.

4 SYSTEMIC VULNERABILITIES

4.1 Characterising systemic vulnerabilities

The previous two sections of this report describe the healthcare system and how, through connection to external infrastructure systems, can be considered a 'system-of-systems'. Whilst this connectivity and interdependence enables patients to receive a broad range of services in an array of contexts, it also introduces a multitude of systemic vulnerabilities.[16] Where vulnerabilities can be established due to i) increased susceptibility to harm – where larger and more complex systems (for example, a system-of-systems) have more inherent points of failure and number of risks to be managed – many of which may be within exogenous systems (i.e. infrastructure services that are not operated or governed by the healthcare system); and ii) lack of capacity to cope / adapt (for example, through the installation of back-up services including electrical generators) – which may be more relevant in countries and contexts where resources are more limited. Through exposure of healthcare-system-of-systems assets to climate change related hazards, inherent vulnerabilities create risks that threaten to disrupt the quantity and quality of service provision that healthcare patients receive.

We characterise two types of failure vulnerability within the system-of-systems, which supports the systemic identification of risks, and subsequently risk management (through climate change adaptation) (Figure 5). Direct vulnerability – are those vulnerabilities that manifest directly within the healthcare system (as defined in Section 2 of this report). Indirect vulnerability – are those vulnerabilities that manifest outside of the healthcare system, within their indirect external dependencies on infrastructure (as defined in Section 3 of this report).

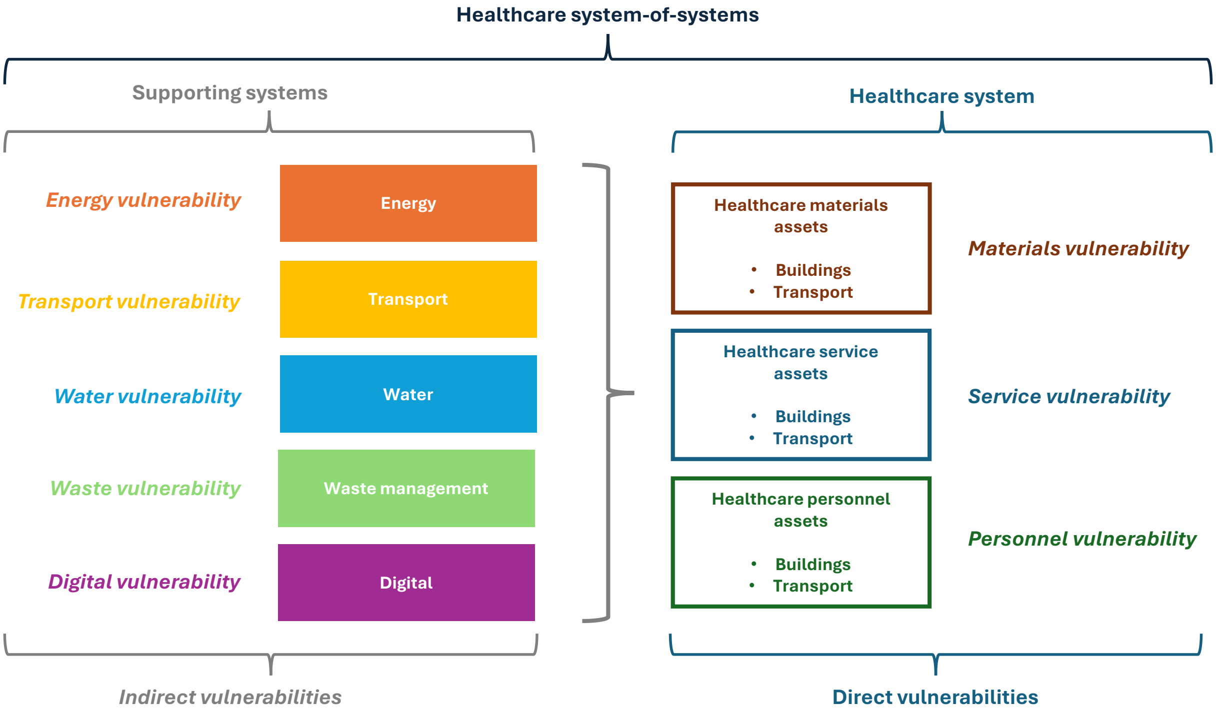

Figure 5: Generalized representation of the direct and indirect vulnerabilities within the healthcare system-of-systems.

[16] Where we adopt the IPCC AR6 definition of vulnerability: "The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope or adapt". IPCC (with Pörtner, H.-O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R. A., Betts, R., Kerr, R. B., & Biesbroek, R.). (2022). Climate change 2022: Impacts, adaptation and vulnerability. IPCC Geneva, Switzerland. p. 2927.

4.2 Direct vulnerabilities

Direct vulnerabilities are vulnerabilities that manifest in assets that are managed and controlled within the healthcare system.

4.2.1 Service vulnerabilities

Service vulnerabilities are those found within service providing assets including at buildings (hospitals, clinics, training facilities, residential care homes, in-home care, and pharmacies), as well as through vehicles (emergency vehicles, mobile clinics, materials home delivery). A non-exhaustive list of vulnerabilities includes:

Healthcare service buildings

- Vulnerabilities of the building including its structure, enclosure and access points.
- Vulnerabilities of internal services systems, such as ventilation, refrigeration, and inter-departmental communications.

Healthcare service transport

- Vulnerabilities of the vehicle including its structure, enclosure and access points.
- Vulnerabilities of internal services systems, such as temperature control, lighting and navigation.

4.2.2 Materials vulnerabilities

Materials vulnerabilities are those found within materials supply chain assets including materials storage (refrigerated and non-refrigerated warehouses etc.) and transportation (refrigerated and non-refrigerated lorries). A non-exhaustive list of vulnerabilities includes:

Healthcare materials buildings

- Vulnerabilities of the building including its structure, enclosure and access points.
- Vulnerabilities of internal services systems, such as security systems, refrigeration, and lighting.

Healthcare materials transport

- Vulnerabilities of the vehicle including its structure, enclosure and access points.
- Vulnerabilities of internal services systems, such as navigation, communications and refrigeration.

4.2.3 Personnel vulnerabilities

Personnel vulnerabilities are those found within personnel supply to the healthcare system including medical personnel housing (for example, medical trainee accommodation) and medical transportation (for example, staff buses). A non-exhaustive list of vulnerabilities includes:

Healthcare personnel buildings

- Vulnerabilities of the building including its structure, enclosure and access points.
- Vulnerabilities of internal services systems, such as lighting, heating, and cooling.

Healthcare personnel transport

- Vulnerabilities of the vehicle including its structure, enclosure and access points.
- Vulnerabilities of internal services systems, such as navigation, safety, and communications systems.

4.3 Indirect vulnerabilities

Indirect vulnerabilities are vulnerabilities that manifest in assets that are located outside of the management and control of the healthcare system.

4.3.1 Energy vulnerabilities

Energy vulnerabilities are those found within the energy system and between the energy system and healthcare buildings and transportation. This includes for the separate energy systems components of electric power and liquid fuels. A non-exhaustive list of vulnerabilities includes:

Energy system vulnerabilities

- Vulnerabilities that are inherent within the generation, transmission and distribution of electrical power systems.
- Vulnerabilities that are inherent within the extraction, processing, storage and distribution of liquid fuels.

Energy vulnerabilities of healthcare buildings

- Vulnerabilities of healthcare buildings due to a dependence on electricity, including for example, through a dentist practice dependency on electrical power to use electric drills.
- Vulnerabilities of healthcare buildings due to a dependence on liquid fuel, including for example, through a care homes dependency on propane to cooking patient meals.

Energy vulnerabilities of healthcare transportation

- Vulnerabilities of healthcare transport due to a dependence on electricity, including for example, through a refrigerated transport medical vehicle that requires electrical power to maintain refrigeration when the vehicle is parked during a journey.
- Vulnerabilities of healthcare transport due to a dependence on liquid fuel, including for example, through a medical transport dependency on diesel as a fuel for the vehicle.

4.3.2 Transport vulnerabilities

Transport system vulnerabilities

- Vulnerabilities that are inherent within the construction, maintenance, and operation of a road network.
- Vulnerabilities that are inherent within the development, construction, stocking, maintenance and operation of a railway network.
- Vulnerabilities that are inherent within the construction, management, and maintenance of ports.
- Vulnerabilities that are inherent within the construction, stocking, management, maintenance, and operation of airports.

Transport vulnerabilities of healthcare buildings

- Vulnerabilities of healthcare buildings due to a dependence on roads, including for example, through ambulances needing to access the healthcare facility to connect patients to services by using the road network.
- Vulnerabilities of healthcare buildings due to a dependence on rail, including for example, through the transportation of staff to healthcare facilities as a part of their commute.
- Vulnerabilities of healthcare buildings due to a dependence on ports, including for example, through the distribution of medical supplies from their origin of manufacturing.
- Vulnerabilities of healthcare buildings due to a dependence on airports, including for example, through the transportation of patients airlifted out of remote destinations.

Transport vulnerabilities of healthcare transportation

- Vulnerabilities of healthcare transport due to a dependence on roads, including for example, through mobile clinics requiring a road network to reach patients in rural areas.
- Vulnerabilities of healthcare transport due to a dependence on rail, including for example, through the distribution of liquid fuel necessary for facility backup power generation.
- Vulnerabilities of healthcare transport due to a dependence on ports, including for example, through the delivery of vehicle parts for vehicles required for the cold chain medicine distribution.
- Vulnerabilities of healthcare transport due to a dependence on airports, including for example, through the procurement of medical devices used in emergency vehicles.

4.3.3 Water vulnerabilities

Water system vulnerabilities

- Vulnerabilities that are inherent within the sourcing, treatment, storage, and distribution of water.
- Vulnerabilities that are inherent within the storage, collection, transportation, treatment, and reintegration of wastewater.

Water vulnerabilities of healthcare buildings

- Vulnerabilities of healthcare buildings due to a dependence on the water system, including for example, through the preparation of food for patients in a hospital facility.
- Vulnerabilities of healthcare buildings due to a dependence on the wastewater system, including for example, through the management of wastewater in a residential care facility.

Water vulnerabilities of healthcare transportation

- Vulnerabilities of healthcare transport due to a dependence on the water system, including for example, through the provision of water for medication administration in ambulances.
- Vulnerabilities of healthcare transport due to a dependence on the wastewater system, including for example, through portable washroom management within mobile clinics.

4.3.4 Waste management vulnerabilities

Waste system vulnerabilities

- Vulnerabilities that are inherent within the production, storage, collection, and disposal of general waste.
- Vulnerabilities that are inherent within the production, storage, collection, treatment, and disposal of hazardous waste.

Waste vulnerabilities of healthcare buildings

- Vulnerabilities of healthcare buildings due to a dependence on general waste management, including for example, through the maintenance of hygienic food preparation practices by disposing of facility cafeteria waste.
- Vulnerabilities of healthcare buildings due to a dependence on hazardous waste management, including for example, through the disposal of material byproducts of surgery.

Waste vulnerabilities of healthcare transportation

- Vulnerabilities of healthcare transport due to a dependence on general waste management, including for example, through the appropriate storage of the waste generated from medical supplies used in the provision of services, to maintain a hygienic environment in ambulances.
- Vulnerabilities of healthcare transport due to a dependence on hazardous waste management, including for example, through the safe containment of syringes after use in mobile vaccination clinics to prevent cross-contamination.

4.3.5 Digital vulnerabilities

Digital system vulnerabilities

- Vulnerabilities that are inherent within the development, material construction, network resourcing, and distribution of phone networks.
- Vulnerabilities that are inherent within the development, resourcing, and provision of internet.

Digital vulnerabilities of healthcare buildings

- Vulnerabilities of healthcare buildings due to a dependence on phone networks, including for example, through the building security systems to function as designed, relying on phone communication between staff at certain facilities.
- Vulnerabilities of healthcare buildings due to a dependence on Internet, including for example, through access to online patient medical records.

Digital vulnerabilities of healthcare transportation

- Vulnerabilities of healthcare transport due to a dependence on phone networks, including for example, through communication between emergency room staff and EMTs in emergency vehicles carrying patients.
- Vulnerabilities of healthcare transport due to a dependence on internet, including for example, through the necessity of internet in medical staff housing to enable the acceptance of shifts by staff members.

4.3.6 Infrastructure dependency vulnerabilities

Finally, we consider infrastructure dependency vulnerabilities as those that exist between the different infrastructure sub-sectors. These vulnerabilities align with the previously introduced infrastructure sub-sector dependencies and interdependencies that were showcased in Figure 3. For example, a vulnerability exists within the water sector due to its functional dependence on electricity for pumping and monitoring, as well as many other functions.

4.4 Climate hazard vulnerability

Systemic vulnerabilities inherent within the healthcare system-of-systems have the potential to create impacts to healthcare services at the different healthcare service access points. Disruptive events are initialised when a component within the system-of-systems is exposed to a level of intensity from a climate hazard that it cannot withstand. For example, a road asset that cannot withstand flooding of a given depth. This aligns with physical climate risk and adaptation methodology that has been developed and applied by OIA, the University of Oxford, and others.[12,13,14]

Figure 6 provides a generalized characterisation of the climate hazard vulnerabilities of the healthcare system-of-systems. This classification is indicative only, based on expert knowledge, and does not represent a definitive classification of climate hazard vulnerabilities – which are site and systems specific and should be underpinned by data for any given practical application. Additionally, it does not take into consideration the potential adaptative capacity of the healthcare systems-of-systems components to the hazard. Within the figure, we see the disruptive potential of flooding (coastal, fluvial and pluvial), wildfires and landslides – which are found to impact all assets within the system-of-system – whether they are located above ground or are buried beneath it. Precipitation is shown to create low and moderate vulnerabilities, with moderate vulnerabilities experienced on assets that rely on road infrastructure (due to precipitation impacting driving), as well as at airports (due to take-off and landing restrictions). Precipitation is one of many drivers of flooding, and the that is considered a different category in the table. In all but the most extreme contexts, temperature similarly can impact all aspects in low and moderate ways, where moderate vulnerabilities exist in rail infrastructure (due to line buckling and rolling stock impacts), the airports (through runway blistering and the perishing of freight materials), as well as electricity (where overhead power lines have thermal operating limits). Multiple sectors have high vulnerability to extreme winds, including electricity and phones (because of the use of overhead lines), as well as healthcare vehicles and the transportation assets, whose operability is heavily impacted by winds. Droughts have high vulnerability in the water sector (due to water availability issues), and moderate vulnerabilities with electricity and wastewater systems – which rely on water provision (for thermal cooling at some electricity plants, and to produce wastewater in buildings, such as toilet flushing).

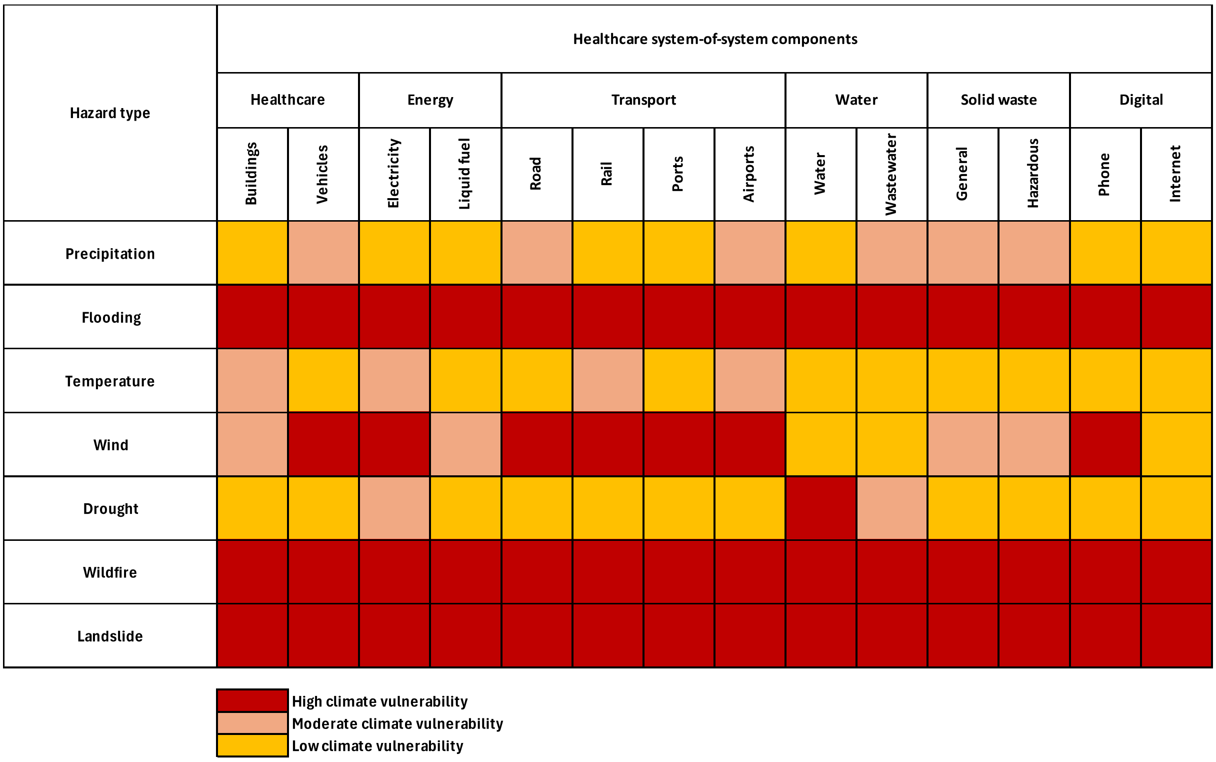

Figure 6: Generalised characterisation of the climate hazard vulnerabilities of the healthcare system-of-systems.

4.5 Failure pathways

The previous sections have characterized the healthcare system as a system-of-systems in the context of the five relevant external infrastructure systems and illustrated examples of vulnerabilities of the healthcare system to these external infrastructure systems as well as climate hazards. In this section, a throughline is drawn from the introduction of a climate hazard to risk within the healthcare system using failure pathways.

We characterise different failure pathway types in alignment with the various types of vulnerability identified earlier in this report. Direct failures (where a failure can be viewed as a reduction in the quantity or quality of service provision) occur when healthcare assets are directly impacted by hazard exposure. For example, flooding at a hospital that prohibits the use of equipment on the ground floor of the building). Indirect failures to the healthcare system can happen when a supporting infrastructure system is disrupted due to hazard exposure. For example, a regional telecommunications outage rendering emergency response coordination impossible. Indirect cascading failures involve cross-sectoral dependencies, where the failure of one infrastructure system sets off a chain reaction across multiple systems, such as a wind damaging transportation infrastructure, which delays supply chains, limits patient access, and jeopardizes healthcare services.

Figure 7 provides an illustrative, and non-exhaustive, example of a set of failure pathways for an extreme wind hazard. This climate hazard can result in six direct failure pathways, marked with solid lines: i) to healthcare buildings – threatening service delivery directly; ii) to materials storage buildings – threatening the supply chain; iii & iv) to roads and vehicle transport, as well as air transportation – threatening accessibility; v) to electricity – threatening energy access and availability; and vi) to internet provision – Impacting internet connectivity. The colouring of these lines represents the sectoral vulnerability to that climate hazard (from Figure 5) The supporting system impacts (iii-vi from above) can then impact the healthcare system through indirect failure pathways marked with dashed lines. Where healthcare impacts range from access restrictions for staff and patients – impacting the ability to give and receive treatment; material limitations through supply chain availability – impacting treatment types; to building services disruptions to electricity and the internet – impacting building and equipment utility – impacting care options. Finally, dotted lines are then used to represent cascading failure impacts that are possible between different infrastructure sub-sectors. As an example, where electricity outages can lead to cascading failures to internet provision (as power is required to operate data centres), as well as at the airport (where power and internet are required to operate control systems, as well as on roads, where power and internet are required for navigation and control. Collectively this represents the complex array of potential risks that manifest in such systems. Such failure mechanisms are highly context specific and difficult to identify. Not least, this is due to the complexity of these systems and the lack of visibility that any one decision maker has across the whole system-of-systems. Nevertheless, they are important to characterise, and where possible manage, where projects allow.

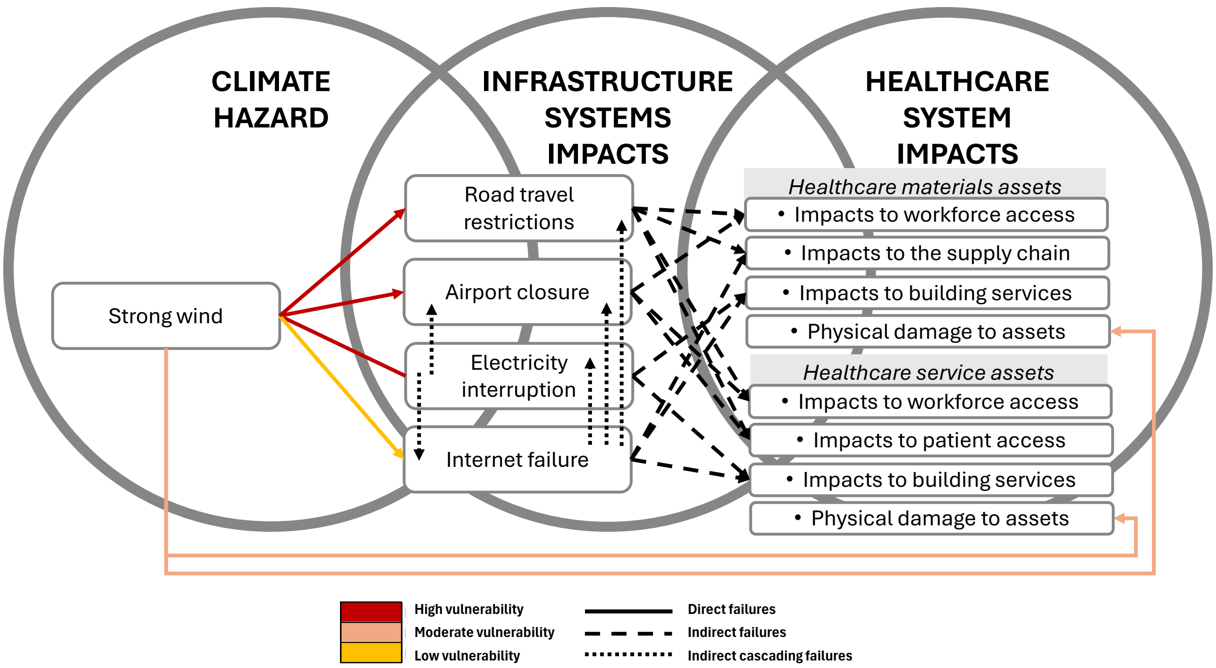

Figure 7: Illustrative example of a climate hazard (extreme winds) and various potential failure pathways through the healthcare system-of-systems.

4.6 Climate risks

Climate vulnerabilities can result in healthcare systems impacts in the form of i) damages – that we define as the monetary cost of repairing any material damage to healthcare system assets and materials in the event of hazard exposure; and ii) disruptions – that we define as the impacts of the loss of services to different patient types.[17] Damages can be estimated in different ways, including the use of vulnerability curves that describe how an asset is likely to be impacted (to what extent it is expected to be damaged) based on hazard exposure. In the case of flooding, depth damage curves are used to estimate asset damage fractions – based on expected (flood) depths at the asset location. Then, the asset damage fractions are combined with rebuild costs to estimate damages. Integrating damage estimations for a variety of probabilistic hazard maps allows expected annual damages to be calculated – which is the expected level of damage that could be expected, due to that hazard, for any given year.

Service-related disruptions can also be estimated using different methodologies.[17] In the case of calculating risks at existing infrastructure, this can be estimated using historical patient statistics (observed or expected) for any given asset. In the case of new and proposed healthcare infrastructure, this will need to utilise expected patient numbers that are often modelled based on geospatial access models – often using catchment areas around assets – to estimate potential usage. Whilst total disruptions can be considered as total potential patient service impacts, it can be beneficial to disaggregate these by gender and age, amongst other categories – to help inform risk and adaptation-based decisions and support the most vulnerable within our societies. To do so requires a recognition of the different healthcare service-based needs that different people have. A non-exhaustive description of person-centric healthcare services are given below to exemplify this point:

- Many women and girls have unique healthcare service needs (at clinics and hospitals) that relate to maternity and giving birth.
- 70% of HIV infections are found in men and boys, yet they are found to be less likely than women, to seek support,[18] and so require targeted service delivery at specific healthcare assets – including fixed and mobile clinics.
- Elderly people make up the main population within residential care homes and hospices.
- Pharmacies often require adults to collect medicines, rather than children.
- Children often receive immunizations that need to be at a variety of locations, from mobile clinics to pharmacies and hospitals.

4.7 Climate change adaptation

Adaptation options provide a means to reduce vulnerabilities that, as previously introduced, can become risks and the cause of systemic disruptions. Resilience enhancement can be introduced at various locations on the disaster management lifecycle: from disaster mitigation to disaster preparedness, disaster response and finally disaster recovery.[19] Climate change adaptation that is targeted at the mitigation stage of the lifecycle can have strong rates of return on investment (i.e. good benefit cost ratios) – and can be used to manage future potential risks.[20] Adaptation options can be deployed to target systemic vulnerabilities. As with the vulnerabilities described in the previous section, there are multiple hypothetical adaptation options that can be introduced to manage risks.

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[17]Peard, A., Raghav Pant, Jaramillo, D., Russell, T., Hall, J., & Thacker, S. (2023). Estimating investment needs for climate adaptation in the Eastern Caribbean..

[18] WHO. (2023, November 29). Reaching men with person-centred health services through evidence-based approaches and interventions. Departmental Update. World Health Organization.

[19] UNDRR. (2015). Sendai Framework for Disaster Risk Reduction 2015-2030. The United Nations Office for Disaster Risk Reduction. : 32.

[20] Hallegatte, S. Rentschler, M., Jun, E., et al. 2019. Lifelines: The Resilient Infrastructure Opportunity. The World Bank Group, Washington, D.C.

Figure 8 presents a non-exhaustive selection of adaptation options for the healthcare system to address vulnerabilities inherent within external infrastructure systems dependencies. Adaptation option types are generalized between material- and access-based service delivery from external infrastructure systems. Where adaptation generally includes storage, production and treatment for material-based infrastructure services, and access points and connection modes for access-based infrastructure services.

Healthcare system		Healthcare system dependencies on external infrastructure systems											
Healthcase system component	Asset type	Energy		Transport				Water		Solid waste		Digital	
		Electricity	Liquid fuel	Road	Rail	Ports	Airports	Water	Wastewate	General	Hazardous	Phone	Internet
Healthcare service assets	Buildings	Onsite generation, back-up generation and storage	Onsite fuel storage	Multiple access points				Onsite water storage Grey-water reuse	Onsite wastewater separation, storage and treatment	Onsite general waste storage	Onsite general waste storage and incineration	Multiple access points, and additional connection devices	Multiple access points, and additional connection devices
	Vehicles	Invehicle storage	Onsite fuel storage	Additional transport modes		Additional transport modes	Additional transport modes	Invehicle water storage	Invehicle wastewater storage	Invehicle general waste storage	Invehicle hazardous waste storage	Multiple access points, and additional connection devices	Multiple access points, and additional connection devices
Healthcare materials assets	Storage	Onsite generation, back-up generation and storage	Onsite fuel storage	Multiple access points				Onsite water storage Grey-water reuse	Onsite wastewater separation, storage and treatment	Onsite general waste storage	Onsite general waste storage and incineration	Multiple access points, and additional connection devices	Multiple access points, and additional connection devices
	Transport	Invehicle storage	Onsite fuel storage	Additional transport modes						Invehicle general waste storage	Invehicle hazardous waste storage	Multiple access points, and additional connection devices	Multiple access points, and additional connection devices
Healthcare personnel assets	Housing	Onsite generation, back-up generation and storage	Onsite fuel storage	Multiple access points				Onsite water storage Grey-water reuse	Onsite wastewater separation, storage and treatment	Onsite general waste storage		Multiple access points, and additional connection devices	Multiple access points, and additional connection devices
	Transport	Invehicle storage	Onsite fuel storage	Additional transport modes								Multiple access points, and additional connection devices	Multiple access points, and additional connection devices

Materials based services: Asset location storage, production and treatment
Access based services: Asset location access points and connection modes

Figure 8: Adaptation options for the healthcare system to address systemic external dependency vulnerabilities. Generalized between material- and access-based service delivery.

Healthcare system-of-systems adaptation can include onsite battery storage, renewable generation and diesel back-up generators for the electricity sector. Liquid fuels (such as diesel, petrol and propane) can be stored onsite to act as a back-up source of fuel. The healthcare sector can address road vulnerabilities through the provisional of additional access points at healthcare building locations (in case one is inaccessible), whereas the healthcare sector may change the modality of the vehicles they use for service delivery, as well as storage and personnel transport, to allow multiple transport mode options in the event of a hazard. For example, port, airport and road -based emergency vehicles can be substituted (additional modes) during hazard events, should the local context allow it.

Onsite water storage, using water tanks, can help address water access vulnerabilities. The reuse of grey-water (for example, rainwater for toilet flushing), helps to reduce the demand for water and can help maintain an operational buffer in a climate hazard – by making the water in storage tanks last longer. Wastewater can be separated into foul (sewage) and storm water, and stormwater can be managed onsite at building through soakaways (which can be nature-based solutions), to be manged locally and reduce the need for wastewater treatment. Wastewater can also be stored locally on site, and in healthcare service vehicles – such as medical helicopters.

Both general and hazardous waste can be stored onsite or in vehicles at locations that it is present. Onsite incineration facilities provide an additional means by which to process both waste streams, albeit may be more appropriate for certain forms of hazardous wastes if incineration at that site is capacity constrained. Vulnerabilities with digital technologies such as phones and the internet can be addressed by utilising additional connection devices and access points (such as through multiple mobile phones and service provider networks) – in doing so, providing redundancy for accessing information and digital services.

5 CONCLUSION

This study provides a first-of-its-kind characterisation of healthcare system-of-systems vulnerability. Starting with the healthcare system, we provide a generalised description that contains the representation and connectivity of service access points, healthcare materials and healthcare staff. We expand this representation to describe the system-of-systems through inclusion of the infrastructure systems on which healthcare depends. This includes services from sub-sectors from energy, transport, water, waste and digital sector. Finally, we highlight the systemic vulnerabilities that can occur in the system-of-systems - that can occur directly and indirectly through potential failures in healthcare and supporting infrastructure components, respectively. We extend the characterisation to include the indicative vulnerabilities of each of the healthcare system-of-system components to a variety of climate change related hazards and provide potential healthcare system adaptation options to address these vulnerabilities.

Whilst the study provides a comprehensive description of the healthcare system-of-systems, it should be recognised that this description will not be applicable to every country and context. Indeed, we observe a large variation in the nature, connectivity and interdependence of these systems at any given location. Technological innovation is also driving change within these systems and the way that they work, in concert, to deliver services. As such, the insights derived from this work should be considered indicative only – given the short duration of the study that they emerge from. We hope that the reader takes a general understanding from the work that they can take forward into any given project, context and country.

As highlighted by this report, the healthcare system-of-systems is a large and complex system with a wide variety of interconnected components. Whilst this short consultancy project has been able to provide new insights into the topic, it should be noted that much more resource would be required to further develop and enrich this understanding. There are multiple ways that this could be taken forwards, including the development of both theoretical and applied work. Areas for future work, amongst many others, could include: i) expanding the resolution of the healthcare system (number of its associated components); ii) expanding the scope and nature of dependent infrastructure systems; iii) expanding the scope of the failure mechanisms and systemic vulnerabilities; iv) provision of worked examples to support the theory, based on historic examples; v) integration of the this framework with a physical climate risk and adaptation methodology; and vi) and its application to a variety of contexts to inform applied decision making.

This report provides an innovative perspective, in an important and growing field, that is valuable for the research and practitioner communities. We expect healthcare sector practitioners and their patients to benefit from it, as well as practitioners from infrastructure companies (that are responsible for the dependent infrastructure), and governments (who administer these services), whilst also extending to international organisation and the IFIs – who support the development of resilient healthcare systems. More broadly, we expect insights from this work to transcend healthcare, into other areas of infrastructure service provision, including education, which, like healthcare, is not typically considered or analysed in this way. With the growing threat of climate change and the accelerating development, innovation, and uptake of healthcare systems, there has never been a more important time to understand their systemic vulnerabilities - to support the identification and management of risks through climate change adaptation.

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