Understanding the impact of asset failure on patient harm within an acute healthcare setting

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Abstract

The paper aims to explore impact of asset failure on patient outcomes within the National Health Service (UK). Through the application of qualitative systems dynamic modelling, system variables were identified and analysed to understand key interactions and leverage points within the system. The creation of model boundary, reference modes and causal loop diagrams permitted understand the impact of intervention employing key leverage points. The research found that, despite capital and revenue finance being a key variable in the resolution of the state of the built environment, the feedback loops of information supporting financial decision making is key. Understanding the impact of asset failure, both from an operational response and a patient outcomes perspective, has a significant influence on the application of available funds. Further work needs to be undertaken to develop the qualitative models into specific quantitative analysis. There has been very little research undertaken in the healthcare environment on the impact of the deteriorating assets on the wider healthcare system. With numerous studies are undertaken annually on clinical practice, healthcare research needs to increase the importance placed on the environment in which care is given.

***Keywords* –**Healthcare; Patient Harm; Infrastructure; Operations; Asset

1.0 Introduction

The recent global pandemic caused by SARS-CoV-2 highlighted significant shortcomings in the infrastructure of healthcare estate across the National Health Service (NHS) (Brooks, 2021; Davies and Atkins, 2020). A report commissioned by the Institute for Government 'How Fit were Public Service for Coronavirus' stated that "*The NHS could have entered this crisis with a more resilient health infrastructure if it had invested more in recent years"* (Davies and Atkins, 2020, pg27). However, while the pandemic has added additional stresses to the infrastructure, this is not a new issue.

In January 2021, the National Patient Safety Agency (NPSA) released data which states that clinical service incidents citing work and environmental factors in 2019/20 had doubled since 2011/12 (NHS England, 2020), amounting to over 115,000 incidents reported. In the same year the latest Estates Returns Information Collections (ERIC) (NHS Digital, 2021) highlighted that for five years in a row the cost to eradicate backlog maintenance within the NHS has grown, reaching an all-time high of £9.034bn, and in 2023 this reached £11.6bn (NHS Digital, 2023). As an estate infrastructure ages and clinical standards increase, greater funding is required to keep pace with planned maintenance and asset replacement However, both capital and revenue funding within the NHS have not kept pace with the demand, creating the level of backlog seen today.

The source of patient risk from infrastructure failure can originate from two main sources – active and latent. The active source is that of a primary cause/effect relationship, such as environmental factors which cause a patient to trip (NPSA, 2007). These incidents are captured within the 1,311,708 reported incidents on the National Reporting and Learning System (NRLS) system since 2003.

The secondary, latent cause is noted within the literature (Dickerman et al., 2008), but is not a subject that has been greatly explored. Environmental factors such as heat and noise caused by failing equipment have the effect of causing distraction and subsequently harm to patients (Edwards, 2016; Leape, 1994), or the concern around poor ventilation increasing the likelihood of cross contamination within hospitals (Eames et al., 2009). Equally, a failing environment or plant may be the primary cause of hospital acquired infection in some instances, when all too often attention is drawn to the primary care giver and hand hygiene techniques as a simpler cause/effect explanation (Braithwaite, 2018).

However, it is not currently possible to quantify how much of a genuine risk to patients the lack of maintenance of the infrastructure is. While there have been anecdotal reports, such as reports on the internet that 88 people were injured between 2015/16 and 2016/17 in hospital fires (Alexander, 2018), or the report on unsuitable buildings causing inefficiency within the NHS (Triggle, 2010), there has been no published work on the effects of NHS estate on patient outcomes.

One of the key premises of this research is to overcome the lack of relational data between the infrastructure and patient harm outcomes, as it creates a disconnect between the understanding of risk and subsequent funding to address said risk. This is echoed by "*dysfunctional macro-organizational behaviour … can be caused by systematic misperceptions of feedback at the micro-individual leve*l" (Gary et al., 2008, pg 413). It is the intent of the research to understand what impact the failing infrastructure is having on patients of the NHS and seeks to understand what needs to change to reverse the failing infrastructure position.

The research uses systems dynamics modelling to explore the feedback loops and describe the qualitative relationships between infrastructure and healthcare operations. With the lack of statistical data available to analyse estate infrastructure within the NHS, it is only possible at this stage to apply causal loop modelling to this research. The application of causal loop diagrams provides significant insight into the impact of infrastructure failure. The modelling tests the generality of key relationships and provide key evidence to policy makers (Gary et al., 2008). It is argued that qualitative systems dynamics modelling is suited to healthcare issues (Brailsford, 2008) specifically due to its heterogeneity and lack of comparable data.

2.0 Literature Review

The built environment

In 1994 the paper 'Error in Medicine' was published which not only drew on prior studies within and outside of the healthcare sector but challenged the medical professions approach to error prevention and management (Leape, 1994). Looking at error management from outside of the medical profession, Leape applied the theories of error management developed by Reason (1990) and Rassmussen & Jensen (1974). The paper states that the attitude within healthcare was that errors are regarded as an individual's fault due to lack of attention or lack of caring, but Leape argues that the individual has been set up to fail by poor design, maintenance, or management decisions. Using the mechanism of cognitive errors, slips and mistakes, described in prior research (Rasmussen, 1982; Reason, 1990), Leape argues that due to the complexity of errors there cannot be a universal way of reducing errors, but requires responsible parties at each stage of the system process to create safe methods of error reduction, including system development, design, construction and maintenance.

Published in 1994, the paper 'Operating at the Sharp End' put forward that there are two ways of interpreting errors (Cook and Woods, 1994). The conventional way is the cause and effect of operator / error at the 'sharp end,' or there is a view that accepts the influence of both sharp and blunt ends on the potential error. This view allows the system to recognise the effect of the blunt end on the sharp end. This argument has been further supported by research undertaken in the aviation industry. Presented at the International Aviation Safety Conference in 1997 (Soekkha, 1997), which argues that it is not pilot error which cause the majority of problems, but that of maintenance related activities.

A number of authors have identified that not only is the system more influential on errors occurring than sharp end interactions, but the physical environment - its design, construction and maintenance, can have a significant impact as an active or latent contributor to potential patient safety incidents (Cook and Woods, 1994; Gibson et al., 2020; Leape, 1994; Reason, 1990), with the latent impact taking several forms.

When looking at patient harm research within the built environment, there is a very strong tendency to focus on the design rather than the management of the estate. It has been established that good Evidence-based design can significantly improve the environment in which patient care is given (Ulrich, 2004) and, by extension, improve health outcomes. However, the current impact of EBD within the NHS is limited due the lengthy replacement cycle involved in embedding EBD into the NHS.

There is a small body of evidence that recognises the importance of the support role that management and maintenance of the built estate plays to clinical services and the patient. There is a general acceptance that maintenance is crucial in healthcare settings, and that the failure of key infrastructure systems – heating, water, ventilation, electrics – could have significant impact on patients (Dejaco et al., 2019). However, the lack of research into the impact of failing infrastructure is hard to assess (May and Pinder, 2008) due to the source of the impact quite often being latent. There is a sufficient body of evidence to indicate that an aged estate is having a detrimental effect on patient health (Brambilla et al., 2019), but this is often couched in clinical research with estates impact being incidental rather than the focus. In 2020/2021, 123 people lost their lives at work. In the same period an estimated 309 patients lost their lives in English NHS hospitals due to direct infrastructure failings (NHS England, 2020). The impact of latent harm is currently unknown.

Systems Dynamics

A methodology of Operational Research(OR), Systems Dynamics has a history of application within healthcare research (Brailsford and De Silva, 2015). From the generalist call for healthcare to systematically build safety into the processes of care (IoM, 2000), to the specific application of systems thinking in producing and refining theories to improve public policy (Agyepong et al., 2012), systems dynamics permits the distillation of key variables and defining of boundaries (Brailsford, 2008) to analyse key interactions of a system.

With both a soft and hard modes of intervention, SD modelling can be used for qualitative and quantitative research (Kunc, 2017). Considered the main tool of systems thinking (Senge, 1990), the mapping of a system using causal loop modelling creates a mental model of a known system (Forrester, 1994), and a 'micro world' (Torres et al., 2017) where systems feedback can be analysed and tested (Schaffernicht, 2010). The hard perspective of SD modelling uses stocks and flows to quantify the systems and allows the testing of hypothesis and sensitivity analysis of the system to support policy decisions (Epstein, 2008; Kunc, 2017). Through the development of hard SD models it is also possible for other researchers to replicate and build on the research (Epstein, 2008). The soft perspective of SD modelling consists of a broad understanding of the system behaviours driving the process, employing causal loop diagrams (CLD) to describe the system without the use of quantitative data (Kunc, 2017), but in a scientifically structured manner (Luna-Reyes and Andersen, 2003), especially as soft SD is seen as a precursor to full simulation using hard SD modelling (Coyle, 1999).

Summary

Healthcare systems have been described as a 'complex adaptive system' meaning that looking at the individual facets of the system in isolation will not explain the system function (Braithwaite, 2018). Being characterized by different features, such as non-linearity (Holland, 1995), micro, meso, and macro layers, (Liljenstrom and Svedin, 2005), and cause and effect which are distant in time (Sterman, 2000). The increasing complexity of the healthcare systems gives greater opportunity for error to increase (IoM, 2000). Furthermore, the systems within the estate infrastructure are intertwined with, affect, and are affected by the clinical services provided within the care setting (Pantzartzis et al., 2016).

Given the paucity of research previously undertaken on the effects of infrastructure impact on patient harm, the application of qualitative systems dynamics permits the analysis of key variables interactions over time (Rutherford, 2019). This shifts healthcare away from the tendency towards a narrow focus on isolated events (Taylor and Dangerfield, 2005) and towards analysing the key mechanisms responsible for the system behaviour (Kunc, 2017).

3.0 Research Methodology

Sterman sets out a clear methodology for undertaking systems dynamic modelling (Sterman, 2000, pg 86). The qualitative aspects of the framework have been adapted for the following methodology used to create, test, and verify causal loop diagrams:

- ***Problem articulation:*** Understanding the specific issue, its key variables and understanding the initial problem definition, recognising its dynamic nature, and the system boundaries will support a deeper understanding of what are the key endogenous factors to be considered, what are exogenous factors which need to be understood, but not modelled, and what factors are outside of the boundaries of the study.

- ***Formulation of dynamic hypothesis:*** through the initial hypothesis generation, the mapping of the model boundaries and of initial sub-system diagrams, the formulation of the dynamic hypothesis permits the analysis of key relationships and feedback loops and to test basic assumptions prior to the creation of the causal loop diagram.

- ***Causal loop diagram creation:*** Built using four key elements: Asset, Finance, Patient Harm, and Staffing, the diagram was developed iteratively which permitted the review of each key element as it was added to the model. Key leverage points within the system were also identified.

In most literature, the causal loop diagram, from problem articulation through to verification is undertaken with a set of stakeholders who are part of the system, an objective facilitator and involving key experts throughout the process. However, this study involves only one stakeholder, who is the main researcher and is already a key expert, facilitated by the other two authors, who are experienced system dynamicists and supervisors of the main research. Section 5 presents the next stages related to model validation.

4.0 Research Findings

While J.D. Sterman states that "*There is no cookbook recipe for successful modelling, no procedure you can follow to guarantee a useful model. Modelling is inherently creative.*" (Sterman, 2000, pg87), it is also noted that successful models follow a similar process (Peters, 2014; Sterman, 2000). This is articulated in the following sections.

4.1 Problem Articulation

Key theme selection

Identifying what the precise issue is, and understanding what impact the issue has, will support the focus on the key variables for causal loop diagrams. The research set out to understand how the level of backlog maintenance within the NHS affects patients harm levels. The level of backlog maintenance (whereby maintenance work that is required to be undertaken on the built infrastructure has not been completed, or lifecycle replacement not undertaken) has grown significantly in the last decade. The cumulative state of healthcare's built environment is causing additional cost to the NHS, delays to patient treatment, and harm to patients and staff alike.

The main key factors for not achieving a continuous level of maintenance within a system are:

- Budget availability and prioritisation
- Trained resource
- Available data to prioritise tasks
- Impact to clinical services
- Availability of stock

In addition, the policy for asset management would play a key role in the levels of backlog maintenance.

Key variables

A review of key variables was undertaken, highlighting numerous potential variables from clinical requirement to patient harm. The list below summarises each of the key variables identified, accompanied by a summary of the factors that influence the key variables.

- ***Assets:***
  Healthcare assets from an estate's perspective are anything that maintains the built environment to a suitable level at which clinical care can be given. This includes (but not limited to) buildings (roof / ceiling / flooring / walls / windows / doors); electrical (from sub-stations to sockets / wiring / switchgear); and mechanical (ventilation systems / water systems / medical gas). Key influences on the asset are:
  - Design quality
  - Manufacture quality
  - Clinical requirements
  - Financial availability

- **Asset failure**
  When an asset no longer performs within its design parameters, it can be deemed as failure, whether this is complete failure of the asset or not achieving optimal performance, the asset would still deem to have failed. Factors influencing this are:
  - Planned maintenance.
  - Usage
  - Design & Asset construction

- **Capital funds available (CDEL)**
  The CDEL available to any Trust has a significant impact on the built environment. Constrained CDEL and high levels of demand lead to risk prioritised allocation of resources which allows backlog maintenance to build up over time.
  - Annual budget setting process (Trust level)
  - Allocation process (HM Treasury -> DHSC -> ICB)
  - Competing demands
  - Inflation impact

- **Clinical capacity**
  The capacity to treat patients within a hospital is critical. Insufficient beds available to treat presenting patients puts patients at risk of harm. With the NHS operating at 90% occupancy (NHS England, 2023), the ability for areas to be released for planned maintenance is constrained and in direct conflict with clinical need in the short term. The influencing factors of clinical capacity are:
  - Patient waiting lists
  - Reactive maintenance
  - Staff availability
  - Length of stay

- **Clinical Error**
  Defined as *"The failure to complete the intended plan of action or implementing the wrong plan to achieve an aim"* (Rodziewicz et al., 2024), clinical error has a direct impact on both the likelihood of patient harm occurring and an impact on length of stay, and is influenced by:
  - Asset failure (latent infrastructure impact)
  - Staffing workload
  - Poor communication

- **Clinical requirement**
  The need of the clinical team changes significantly over time (Brambilla et al., 2019), and quite often much faster than the pace change within the built environment. This then creates a disconnect whereby the asset / environment is classed as not functionally suitable. The main factors influencing clinical requirement are:
  - Time
  - Treatment options
  - Patient morbidity

- **Lifecycle Replacement**
  All assets have a defined life at point of design and construction. Failure to replace an asset at the end of its life will increase the likelihood of asset failure to a point where it is no longer repairable. Key factors include:
  - CDEL availability
  - Clinical capacity
  - Clinical requirement

- **Patient Harm**
  Iatrogenic Harm **– "***harm experienced by patients resulting from medical care*" (Sampath, 2022). Originally defined as harm unintentionally caused by a physician, iatrogenic harm is now widely considered as any harm inflicted on a patient during their connection with healthcare. The World Health Organisation has identified thirteen classifications of patient harm, from clinical process / procedure to behaviour and resources. From an infrastructure/building perspective, there are two key factors which affect patient harm:
  - Clinical error
  - Active infrastructure failure

- **Revenue funds available (RDEL)**
  Set by NHS England and the local Integrated Care System (ICS), the Trust RDEL availability affects what can be maintained, and to what level. Insufficient RDEL reduces the level planned maintenance which in itself increases the level of reactive maintenance, reducing RDEL further. The RDEL budget is influenced by the following factors:
  - Allocation process (HM Treasury -> DHSC -> ICB)
  - Annual budget setting (Trust level)
  - Competing demands (IT / Clinical / Medical Equipment)
  - Impact of inflation

- **Staffing Levels**
  Staffing has a dual impact on asset management and patient harm. Without appropriate levels of trained estates staff, asset maintenance would not occur; secondly insufficient clinical staffing increases staff workload and has the potential to cause harm. Influencing factors are:
  - RDEL availability
  - Staff turnover levels
  - Staff harm levels

- **Staff Harm**
  While patients are more vulnerable, they are not the only persons that are vulnerable to failing infrastructure. The impact on staff working alongside the patient must be considered.
  - Active infrastructure failure

When listing out the variables, four key 'themes' emerged: the asset, staffing, finance, and patient harm. During the modelling process, each of the key themes was reviewed further to understand their impact on patient harm.

Time horizon

The time horizon of an asset is difficult to assess in entirety. Building life can range from 40-100 years; Specific asset items can last over 25 years; Items within an asset system can last only 6-12 months. Any one of these items failing could cause system failure.

The revenue and capital time horizon is annual, but with an influencing political cycle of around five years.

The time horizon for the availability of staffing resource within the estates department is conversely linked to the construction industry. As residential and business construction increases, the NHS loses staff; as there is a downturn, the NHS attract staff. No specific time horizon can be attached to this.

Patient harm Is unpredictable. Over a three-year period, the level of reported patient deaths due to infrastructure iatrogenic harm per month ranges from 1 per month in April to 8 in December.

It is proposed that the given the most regular and predictable timeline is that of the annual budget setting of the NHS, an annual timeline be set.

Dynamic problem definition

Reference Modes - Behaviour over time

The level of backlog maintenance across the NHS over the last 10 years has increased by 2.88 times. Taking into account average inflation (ONS, 2024), the £4.01bn backlog level in 2013/14 should only now be c£5.543bn, but currently stands at £11.6bn (Kings Fund, 2024) . Therefore, the resulting £6.05bn can be put down to the deterioration of the estate.

The deterioration of the assets over its life is captured in figure 1. Despite regular planned maintenance on an asset, asset decay is seen as all assets have a limited reliable life (Reason, 1990). The asset lifecycle is seen further in figure 4. Over its life, the asset may have specific breakdown / failures that make it inoperable.

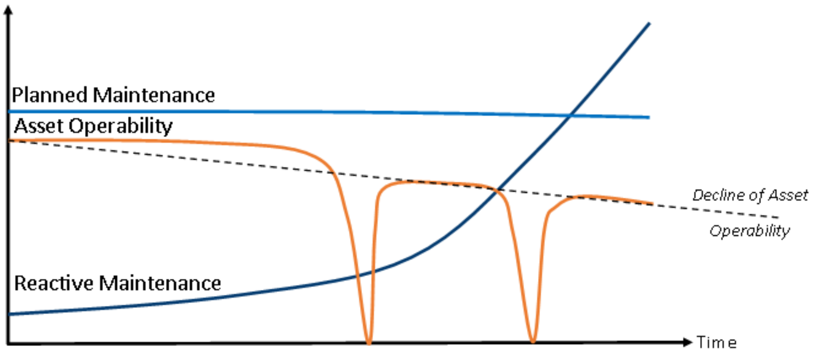

Figure 1 – Asset operability decline over its life.

The impact of assets over its life on the Trust's finances is depicted in figure 2. A steady growth in cost to maintain the asset occurs over its life. Asset breakdown / failure creates a spike in costs to bring the asset back online.

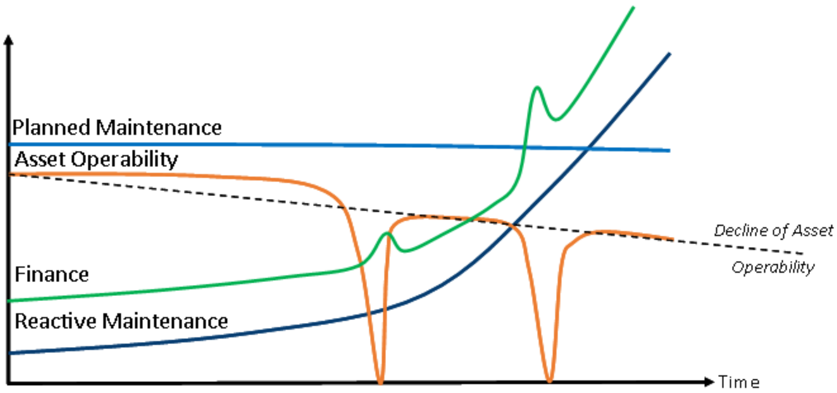

Figure 2 – Financial impact of asset decline

The human impact of asset decline is the increased propensity for patient harm to occur. This is starkly seen when an asset completely fails, the likelihood for patient harm spikes (figure 3). However, not all assets are 'on/off'. The deterioration over time of many assets also increases the likelihood of patient harm occurring. Whether this is the efficiency of filters in air handling units, the buildup of biofilm in water pipes, or deterioration of walls and floors in a clinical setting, all will slowly increase the likelihood of patients coming to harm.

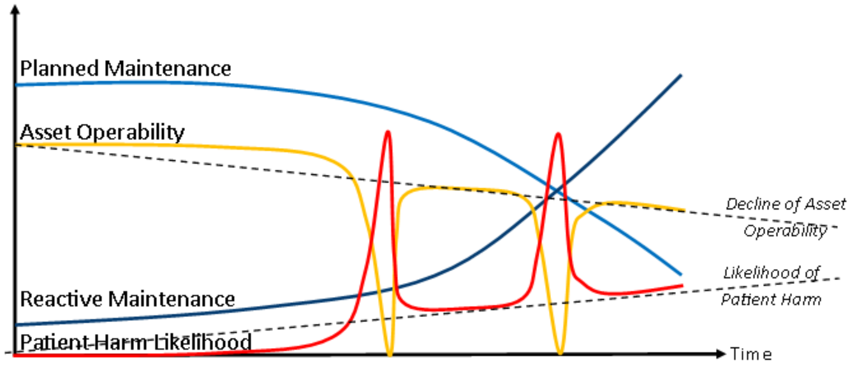

Figure 3 - Impact of asset failure on patient harm

Limits to Reduction in BLM

The main limiting factor in the NHS is that of availability of finances. This is based on the budget set by Treasury, the Department of Health and Social Care, and NHS England, as well as the individual Trust's. While the Treasury and DHSC set the overall financial envelope, it is NHSE that sets the Department Expenditure Limits (DEL)(Revenue RDEL and Capital CDEL). The DEL limits restrict the funding, regardless of the cash held by individual Trust's.

The next limiting factor is that the Trust's receive all the CDEL and RDEL allocation without ringfencing specific funds, leaving each Trust to decide where the funding goes to. A lack of information and awareness of the impact of Backlog prevents it from being prioritised. Estates departments do not consistently record the full impact of asset failure.

The third limiting factor is that of capacity, both from a Trust and contractor perspective. To undertake the work to deliver an £11.6bn reduction in backlog would require large swathes of the NHS to be closed and turned onto a building site – even if there were sufficient contractors to undertake the works. There is no simple solution to current position that NHS provider trusts find themselves in.

System Boundaries

A boundary needs to be set for each of the key variables to ensure that there is focus and clarity within the final model.

- **Asset**: The asset will be taken as a generic 'asset', following a standard trajectory of asset life as defined within the P-F Curve model (fig 4). It may be worth looking at the impact of individual assets in a case study. The maintenance of said asset will be seen as either 'planned' or 'reactive', dependent on the asset condition, failure rate, and input variables such as DEL availability, staff training and, clinical capacity.

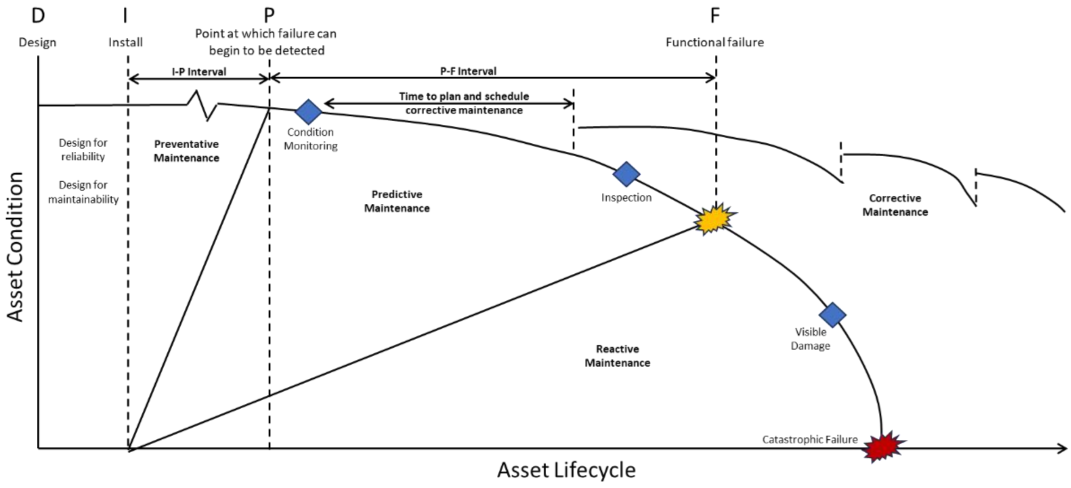

Figure 4 – P-F Curve model (wmargolin, 2020)

- **Asset Failure:** The asset failure, noted in figure 1, whether functional or catastrophic failure, is central the research and as such endogenous to the system. This can have an onward impact through Active harm or Latent Errors, affecting a wider system. The distinction between functional and catastrophic failure is not made at this point as the relevance is the failure itself, and not whether the failure is repairable.

- **DEL Limits (CDEL and RDEL):** The financial allocations (DEL) to the NHS are set by central government and HM Treasury. This is then allocated throughout the system. The difficulty with the boundary comes from looking at the trail of finance within the NHS, as well as the competing demands on the available resources. While there is a system loop from patient harm to HM Treasury and back through the NHS, this widens the potential scope of the system to the entire country's budget, making the modelling impractical. Therefore, the boundary has been set at a Trust's CDEL and RDEL budget allocation level (figure 5).

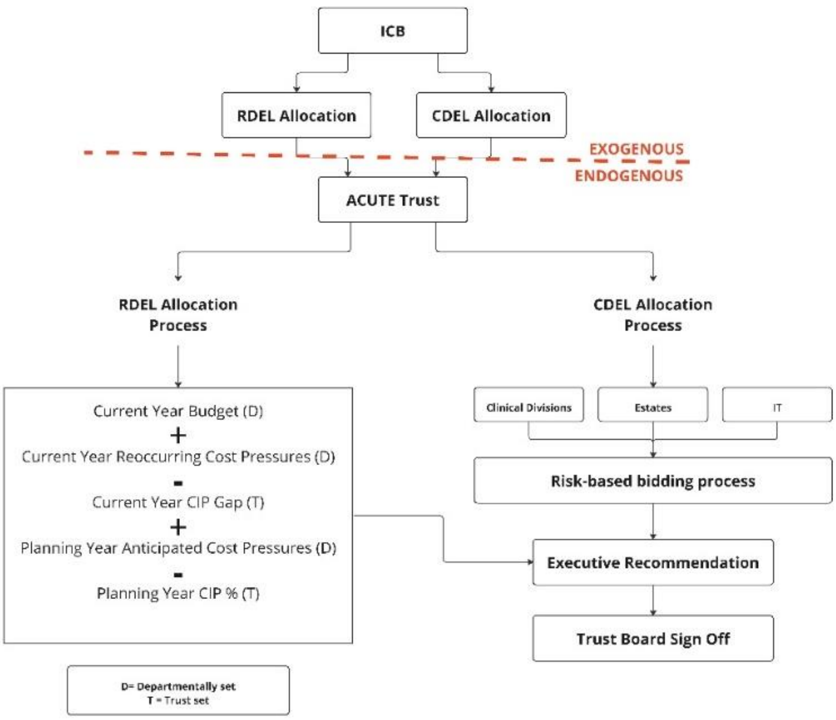

Figure 5 – DEL Limit System Boundary Diagram

- **Clinical Capacity**: The capacity of a hospital is a fixed volume. It takes significant construction over months / years to change, and thus from a modelling perspective would be considered 'static'. How the capacity is utilised is a key component and a significant limiting factor in addressing backlog maintenance. The capacity itself, however, would be treated as an endogenous factor in the modelling process given the potential impact that addressing backlog maintenance would have on capacity.

- **Clinical Error**: Affected by not only asset failure, but potentially many other factors, Clinical Errors has been considered endogenous, but all influencing factors, other than latent asset errors, are considered as either exogenous or outside of the model boundary.

- **Clinical Requirement**: This is as varied as assets, but their effects on the clinical capacity is significantly more complex. Therefore, clinical requirement will be treated as exogenous unless looked at within a case study. Clinical need will remain as a 'generic need' and expanded upon.

- **Lifecycle Replacement**: considered the 'end' of the asset lifecycle, the financial impact of lifecycle replacement is classified as endogenous, as with the design, build and installation of the asset.

- **Patient Harm**: The impact of active failure and latent error to a wider system, Patient Harm, is considered an output of the system and an endogenous factor of the system. Patient harm, however, can also be seen as key element of pressure on the system, causing less bed availability and an increase to waiting lists.

- **Staffing:** The impact on staff, predominantly clinical, should be considered endogenous. There is a link between active and latent infrastructure incidents and the impact on staff, whether it be direct harm, morale or feeling under pressure due to staff shortages. While there is an impact on estates staff, predominantly through the requirement to undertake greater levels of reactive maintenance, estates staffing levels are considered an exogenous influence on the ability to deliver the service at each state of the asset lifecycle.

The system boundaries are seen more clearly in section 2.3.1 in the Model Boundary Diagram.

Inputs and Outputs

The endogenous inputs and outputs to the maintenance of assets are set below in table 1. The impact of the inputs and outputs translates later within the causal loop diagram as cause-and-effect elements.

INPUTS	***OUTPUTS***
CDEL	Active Error
Clinical Requirement	Clinical Capacity
RDEL	Latent Error
Estates Staffing	Patient Harm
Asset Maintenance	Staff Harm
	Asset Failure

Table 1: Inputs and Outputs

Environmental Interactions

The environmental interaction of the system is delineated by internal (endogenous) factors and influencing external (exogenous) factors. The exogenous factors, such as political pressure on a system due to one cause or another, or the cyclical effect of the commercial construction industry, has the potential to exert equal if not more force on a system than some endogenous factors, such as how a Trust allocates capital funds or how the Trust reacts to a failed asset. Each of the key variable's endogenous' and exogenous' factors are summarised in table 2 below.

Key Variable	***Endogenous Factors***	***Exogenous Factors***
Active Failure	- Reactive Maintenance - Asset breakdown/failure	
Asset Maintenance	- DEL availability - Clinical capacity	- ACOP / Legislation changes - Trained staff availability
CDEL	- Competing demands ➢ Expanding clinical services ➢ IT development ➢ Medical device replacement	- HMT/DHSC/ICB CDEL allocation - Inflation
Clinical Capacity	- Patient harm levels - Asset failure	- Fit for discharge patients. - Service demands - Waiting lists
Clinical Requirement	- Age of Estate/ Fit for purpose	- Changing clinical practices
Latent Error	- Asset breakdown/ failure - Reactive Maintenance	
Patient Harm	- Active Asset Failure - Reactive maintenance	
RDEL	- Competing demands ➢ CIP requirements - Level of planned maintenance - Staff turnover	- HMT/DHSC/ICB RDEL allocation - Inflation - Service demands - ICB Partners capacity / demand
Staffing resource	- RDEL availability - Staff motivation - Staff harm incidents	- market fluctuation

Table 2 – Environmental interactions

4.2 Formulation of Dynamic Hypothesis

Cited as "a working theory of how the problem arose" (Sterman, 2000, pg95), the dynamic hypothesis has been mapped out using an initial working hypothesis, through a focus on endogenous factors and mapping the model boundary diagram, through to developing sub-system diagrams of the key factors.

Initial hypothesis generation

There are five potential hypotheses for why the NHS backlog position is today as high as it is.

Ageing Infrastructure: The NHS is over 75 years old and many of its buildings are aged. While there have been a number of new hospital building programs in the life of the NHS, they don't always tackle the most aged estate, with some of the infrastructure dating back to before the 20th century (NHS Digital, 2022). While in and of itself this is not necessarily an issue, combined with a lack of maintenance and planned asset replacement, the impact is an estate that is not fit for delivering clinical care in the 21st century.

- **Changing Clinical needs**: It has been noted that in the next 20 years 80% of the current knowledge about medicine and technology will change (Brambilla et al., 2019). Therefore, the environment within which the clinical services are delivered must change with it. Given over 80% of all of the NHS estate is over 20 years old, it raises the question as to whether the NHS estate is fit for purpose as an environment to deliver safe clinical care.

- **Funding Availability**: Both capital and revenue funding streams have been reduced in real terms. With capital allocations remaining almost static over the last 10 years, and with funds being directed towards new facilities to keep the pace with demand in growth, funds have been diverted away from asset replacement and repair.

  Revenue funding has seen a continual erosion of the estates budget over the last decade. With many trusts instigating a Cost Improvement Plan (CIP) amounting to between 3-5% per annum, estates departments have seen available funds drop from anything between 25% and 40% of operating budget, preventing activities such as planned maintenance works from effectively being undertaken.

- **Increased Service Demand**: Despite the number of inpatient beds reducing by 8% over the last decade, the usage of the facilities has increased. A&E alone has seen an increase in attendances by 22% in the last decade. All of this means that the NHS is providing more clinical care in a smaller space than ever before, effectively putting greater demands on the usage of the built environment.

- **NHS Governance:** Since the publication of the 2010/11 Health and Social Care bill in January 2011, and the subsequent Health and Social Care Act 2012, there have been significant changes to the structure of the NHS. The abolishment of the Strategic Health Authorities in 2012 due to a view emerging that 28 SHAs was too many, creating Clinical Commissioning Groups. In 2022, 48 Integrated Care Systems were established. Similarly, foundation Trusts were created in 2004, but with power being slowly centralised, such as control of capital expenditure limits, foundation Trusts are semi-autonomous at best. While the structure of the NHS does not directly impact the management of the built asset, the continual change distracts both and managerially, with NHS management focused on the changing structures rather than operational matters.

Endogenous focus

There are several endogenous factors that seek to explain the dynamic problem as defined above:

- **Clinical Capacity**: Even if Trusts had unlimited capital and revenue funding, or that Backlog Maintenance was considered top priority, without significant decant facilities it would not be possible to bring a hot site up to modern standards.

- **Financial**: While there are exogenous factors that limit the flow of DEL into a Trust, the apportionment of the funds is predominantly down to Trusts. Therefore, a choice is being made on what to invest in, and what to defer. This is an informed choice bounded by available data.

  Patient waiting lists have a clear deteriorating factor for many conditions. However, the deteriorating factors of assets is complex and not well known by decision makers within the NHS. The level of data being collected and analysed by estates departments does not permit the level of granular data on levels financial and harm impacts to support the case in investing in backlog maintenance.

- **Harm**: While harm is an outcome of the dynamic problem, it also exacerbates the issue, namely a patient suffers iatrogenic harm stays in hospital longer, thus the clinical demand on the hospital increases; less planned maintenance occurs; more asset failures occur; the likelihood of a patient being harmed increases.

- **Lifecycle replacement**: Failure to plan and deliver lifecycle replacement puts a trust in a position of operating a 'Run to Failure' replacement model. While considered acceptable in assets that are readily available and cheap to replace (e.g., lightbulbs), such a strategy would mean huge disruption and increased risk of harm in a healthcare environment. However, with minimal planned maintenance and no lifecycle replacement process, this is effectively what some NHS Trusts are implementing.

- **Preventative Maintenance strategies**: Increasing the level of preventative maintenance reduces the requirement for reactive maintenance, the likelihood of asset failure and potential for patient harm. Adopting either predictive maintenance strategies or evidence-based maintenance strategies could reduce the cost of preventative maintenance, and further reduce the likelihood of asset failure and subsequent reactive maintenance.

- ***Staffing***: A significant endogenous factor for the management of the effects of patient harm is staffing. Without a fully staffed, motivated team, the likelihood of turnover going up increases, staff turnover increases and the likelihood of patient harm due to staff pressure increases.

Model boundary diagram

Starting with the asset lifecycle as the core model loop, the setting of healthcare estate with clear endogenous factors were added. Expanding the model boundary further, exogenous factor was considered, followed by related, but factors that sit outside of the model boundary. Figure 6 summarises all factors, noting where they sit within the model boundary and their key theme.

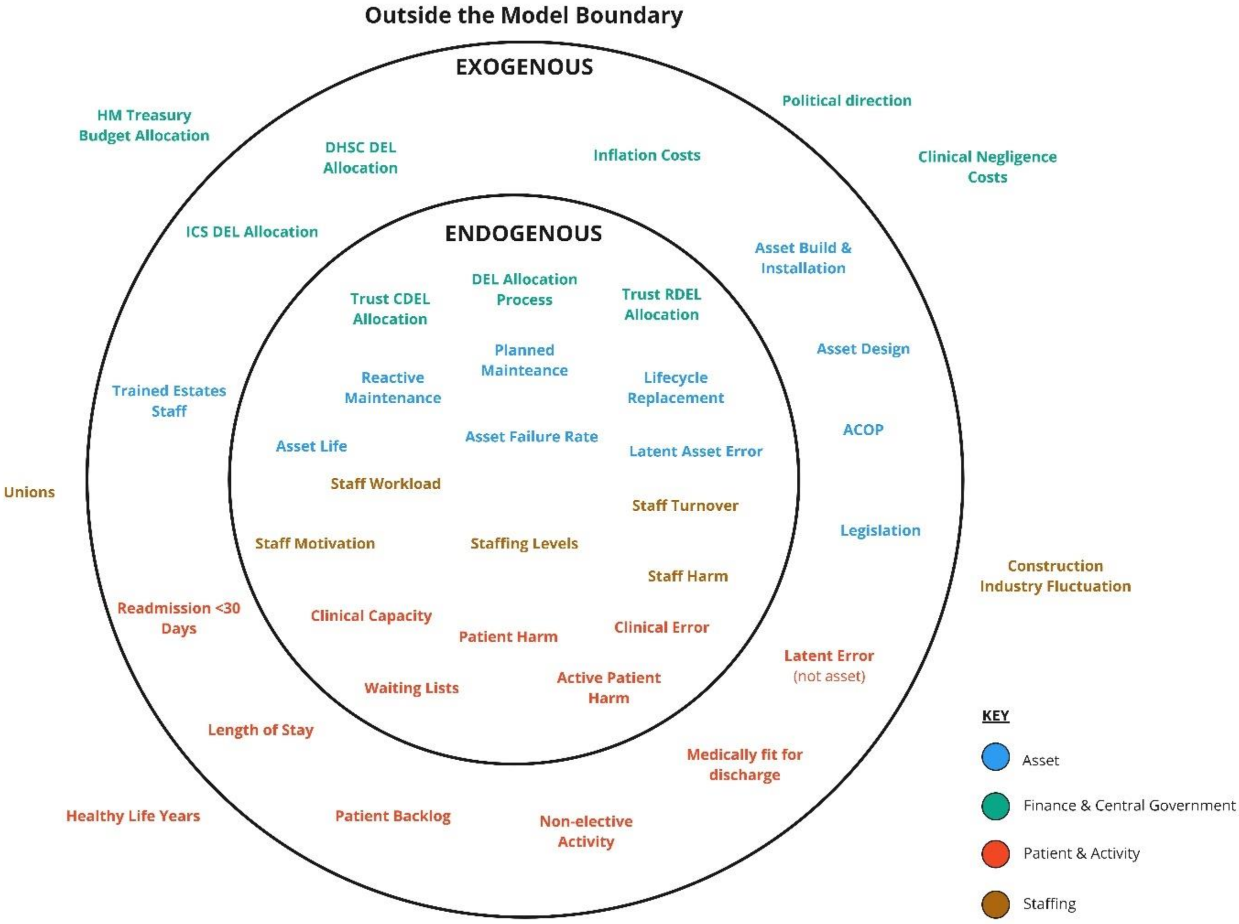

Figure 6: Model Boundary Diagram – Asset Failure

Causal loop diagrams

Without use of pre-existing template, the causal loop diagram is borne out of the understanding of how each of the key elements interact (Peters, 2014). Undertaken using Vensim™ software, the causal loop diagram was built in four stages, incorporating each of the sub-systems, and colour coded as per the model boundary diagram (figure 6) to clearly identify each of the key emerging themes.

View 1: The Asset.

The sub-system of Asset (figure 7) when mapped contains two loops. It is possible to see one reinforcing and one balancing loop within the asset lifecycle model.

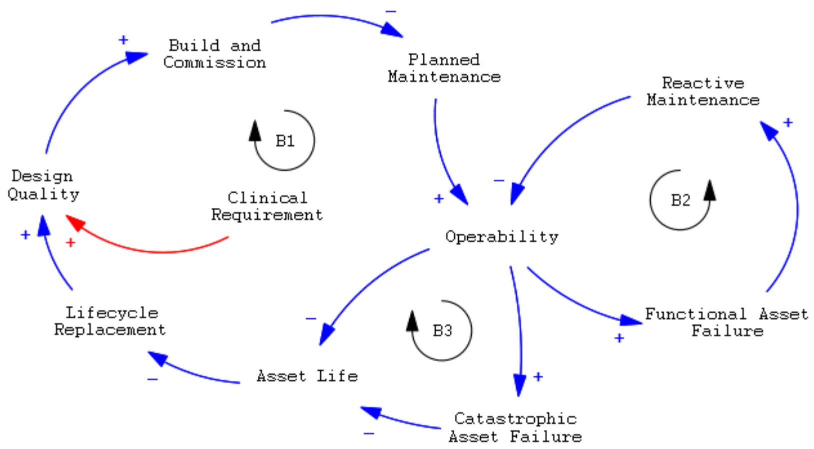

Figure 7: Asset Causal Loop Diagram

B1: The quality of design influences the build and commissioning quality which in turn reduces planned maintenance requirement. Planned maintenance creates downtime but increases operational life of the asset. Operability reduces the asset life. The longevity of the asset then negatively influences the requirement for lifecycle replacement. However, replacing assets through lifecycle positively informs the design process. In summary, improving design quality of hospitals leads to more operability but less experience about lifecycle replacement over time, which curtails the improvement of designs.

B2: The longer an asset operates, the greater the likelihood of functional asset failure which in turn increases the need for reactive maintenance. However, the more downtime the asset gets, the longer the asset life will be, which in turn decrease the likelihood for functional asset failure to occur. Thus, the longer an asset is operational, the greater the likelihood of asset failure and reactive maintenance intervention is required.

B3: As with B2, operability increases the propensity for catastrophic asset failure. This failure reduces asset life to zero, requiring lifecycle replacement. The replacement process improves design, build and commission quality which in turn reduces the need for planned maintenance. However, reduced downtime of the asset increases its operability which increases susceptibility for asset failure. Therefore, from an asset perspective, catastrophic failure not only improves design and installation quality, and reduces planned maintenance intervention, it increases asset up time, but has a downside of increasing likelihood of asset failure.

View 2: Finance.

Finance has a significant impact on the asset, both from a CDEL and RDEL perspective (figure 8). While most of the financial allocation process is exogenous (denoted by variables within hexagonal boxes), the allocation of the funds within the Trust is the responsibility of the Trust executive and boards.

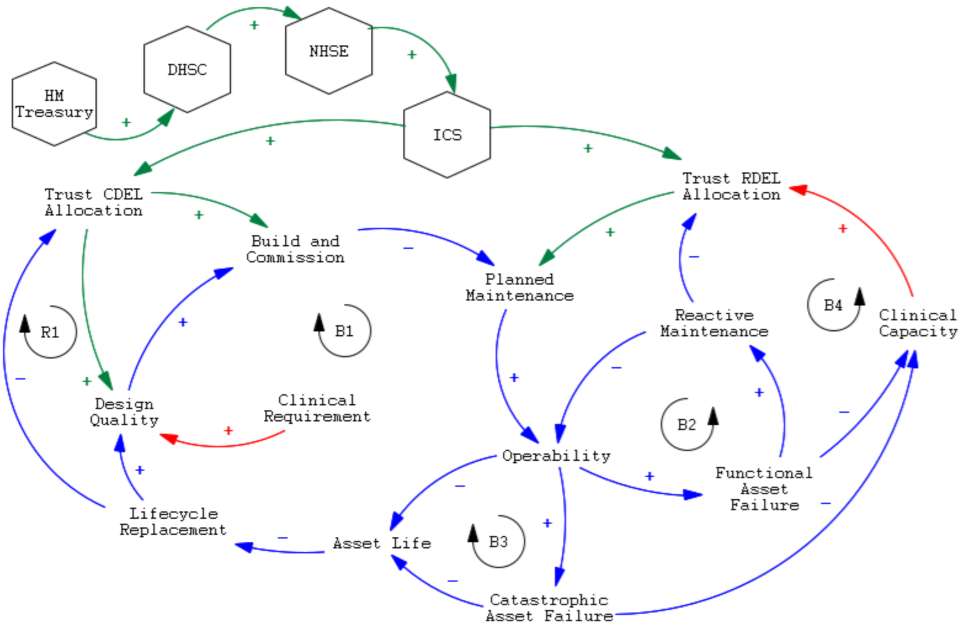

Figure 8: Asset and Finance Causal Loop Diagram

R1: Trust CDEL levels have a reinforcing impact on the asset. The greater the CDEL available, the better the design, build and commissioning of new assets is, which in reduces level of planned maintenance required, and increases the asset operability. Increased user time of the asset, reduces asset life, and increases the impact of lifecycle replacement on the Trust CDEL. In summary, the greater the level of capital funds available, the better the asset will perform, providing greater up time. However, continued running will impact asset life and lifecycle replacement, which in turn will have a negative effect on capital funds available.

B4: The Trust RDEL has a balancing impact on assets. Increased RDEL increases likelihood of planned maintenance, which increases operability. Continued operability increases possible asset failure, and the loss of clinical capacity, the cost of which generally far exceeds the reactive maintenance cost of the failed asset. Thus, while increased revenue funding improves operational up time of the asset, asset failure’s impact on clinical capacity will have a negative impact on the Trust’s RDEL position and its ability to undertake planned maintenance.

View 3: Patient Harm

The impact of the asset failure (functional and catastrophic) creates two clear loops that involve patient harm (figure 9):

B5(a&b): An increase in operability and increases the likelihood of functional asset failure (a) and catastrophic asset failure (b). This in turn increases the likelihood of an active incident, be it clinical or estate, which increases the chance of patient harm. Patient harm incidents negatively impact on clinical capacity, which consequently increases waiting lists, which in turn have a direct negative impact on Trust RDEL available. The reduction in RDEL reduces the Trust's likelihood to undertake planned maintenance.

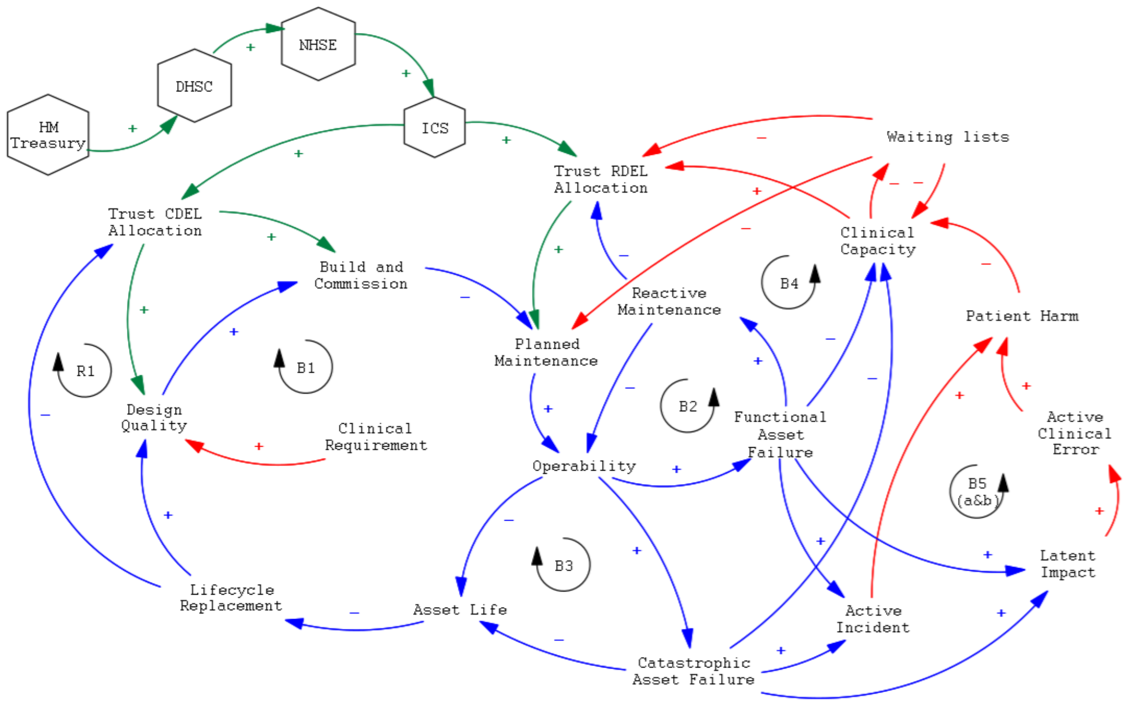

Figure 9: Asset, Finance and Patient Harm Causal Loop Diagram

View 4: Staff

The impact of staffing due to asset failure occurs in two distinct ways. Direct impact and motivational impact (Figure 10).

B6: The increase in operability increases the likelihood of asset failure, whether functional or catastrophic. The increase in asset failure increases the potential for staff to come to harm, which in turn negatively impacts staffing levels. A drop in staffing levels decreases staff motivation, but subsequently increases staff turnover. The increase in turnover has a negative impact on the Trust RDEL position which in turn decreases investment in planned maintenance and thus decreases operability.

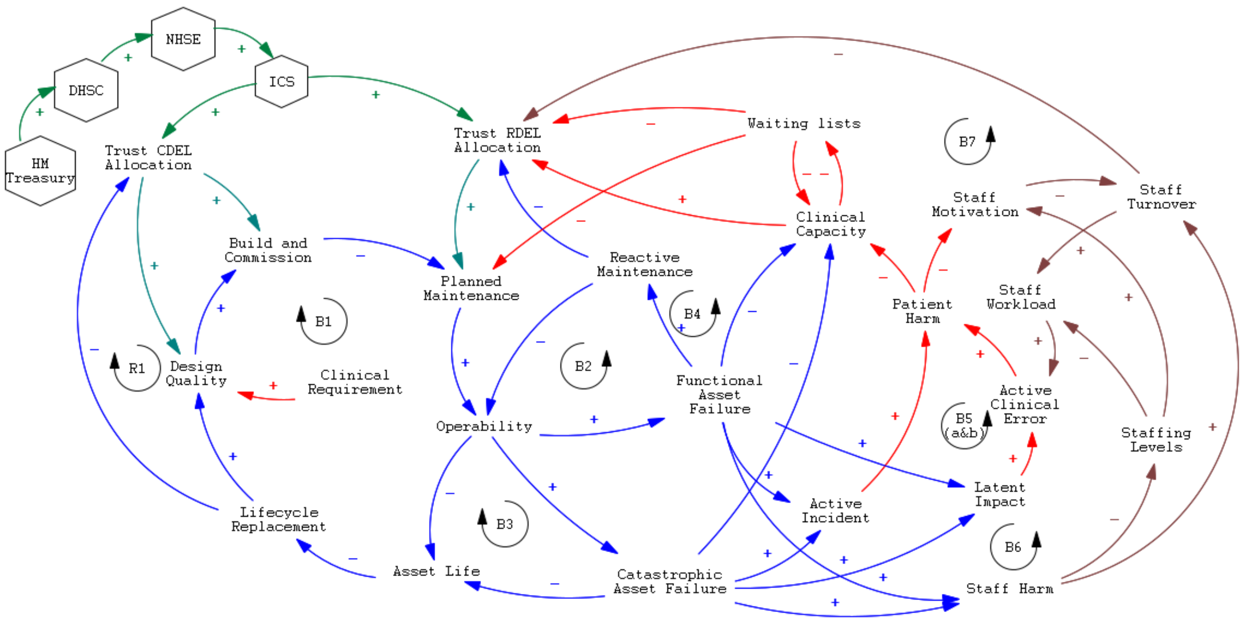

Figure 10: Asset, Finance, Patient Harm and Staffing Causal Loop Diagram

B7: Asset failure also has a latent impact on patient harm, via active clinical error. With operability increasing the likelihood of asset failure -functional or catastrophic – this positively increases the likelihood of active clinical error. An increase in active clinical error increases the potential for patient harm, which in turn reduces staff motivation. A reduction in staff motivation increases staff turnover which negatively impacts Trust RDEL, and planned maintenance and operability in turn.

Model Review

The model in and of itself is informative as it maps out key relationships within the dynamic relationship between the twenty-two endogenous variables. However, it is only by the analysis of the model will it greater inform the research at hand.

The way the model has been constructed, adding each of the key themes from assets to finance, patient harm, and staffing, has divided the model between cause and effect (figure 11). Finance as a key enabler can be seen as a positive or negative force for change, with the design, build, operating, and maintenance of the asset acting in a similar manner. The effect of these endogenous enabler variables impacts the remaining variables through two points – functional asset failure and catastrophic asset failure. Remove or reduce the likelihood of asset failure, the impact on patients and staff dramatically reduces.

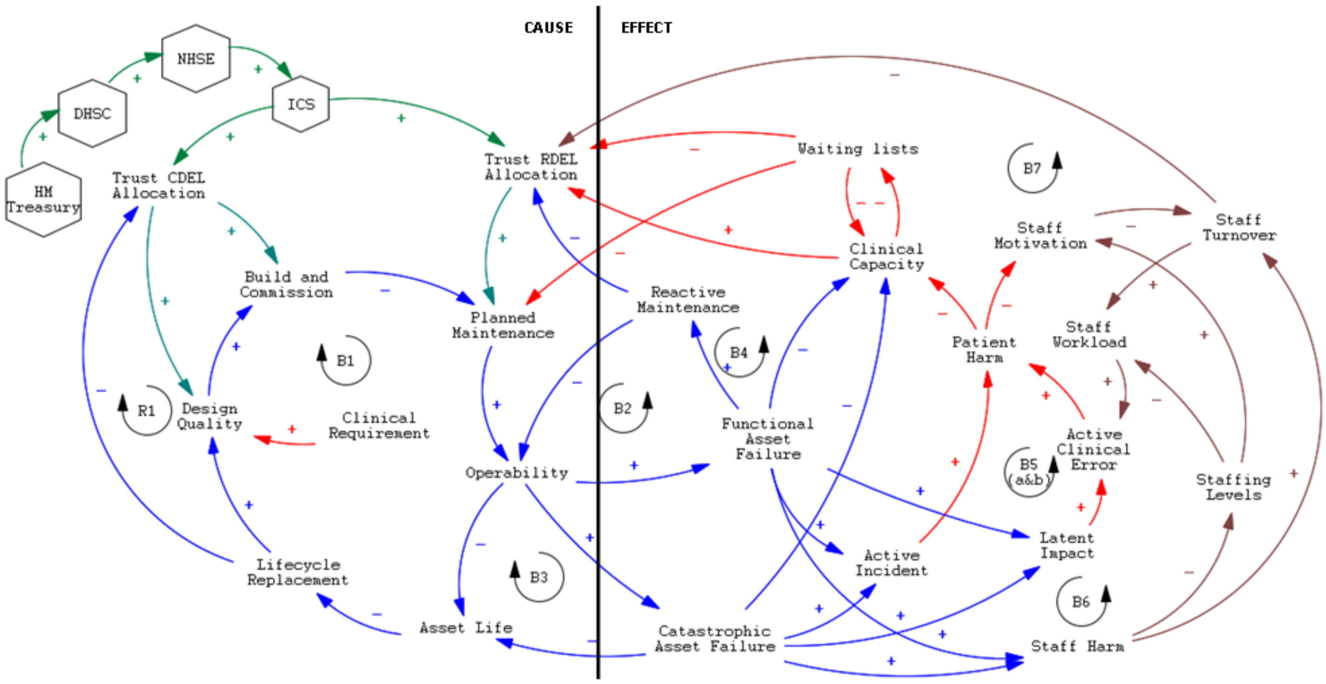

Figure 11: Cause and Effect split of the Causal Loop Diagram

It is also noted that there are 25 loops from lengths of 2 to 12 variables, with eight deemed as the most significant (see above).

Causal Loop Model - Structure Analysis

Through the use of a Java Script model assessment tool developed by Argonne (Martinez-Moyano, 2012), it is possible to bring greater transparency. The "System Dynamics Model Documentation and Assessment Tool" (SDM-Doc) is designed to work with Vensim™ software and provide modelling data on both stock and flow diagrams as well as causal loop diagrams. The Vensim™ model was uploaded to the SDM-Doc tool in Java Script, and the software ran. The data output produced information in three sections: information on the model, warnings, and omissions.

- ***Model Information***

The model assessment results (table 3) show 22 endogenous variables, and 9 exogenous (noting 4 are .Control variables). The table also highlights that there are 48 causal links within the model. The sub-system split of the causal variables is Assets = 21; Finance = 8; Patient = 11; Staffing = 8.

Model Information	Result
Total Number Of Variables	31
Total Number Of Exogenous Variables	9 (29.0%)
Total Number Of Endogenous Variables	22 (71.0%)
Total Number Of Feedback Loops No IVV (Maximum Loop Length: 5) [2, 5]	8 (3|5|0)

Table 3 – SDM-Doc Model Information output

When analysing the cause-and-effect relationship between all variables, 27 of the variables are seen to have a positive relationship, with 21 a negative one. The percentage split of the relationships within the sub-systems (figure 12) highlight that the patient sub-set is the only subset with a higher level of negative relationships. Table 3 also highlight that the Vensim™ model is neither fully formulated nor are the groups defined, but this is a function of not developing the variables for stock and flow analysis.

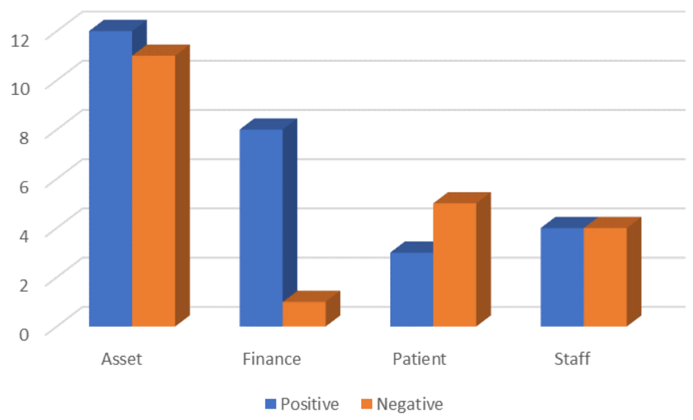

Figure 12: Breakdown of causal loop polarity by sub-system

In addition to the summary table, table 3, SDM-Doc summarises the level of connections that each variable is influenced by, and influences (table 4).

Group	Type	Variable	In/Out Counts	In/Out Ratio	In Links By Polarity	Out Links By Polarity
Master Patient Harm CLD Model	InOutLinks	Trust RDEL Allocation ()	5 | 1	5.00	2| 3| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	Functional Asset Failure ()	1 | 5	0.20	0| 1| 0	4| 1| 0
Master Patient Harm CLD Model	InOutLinks	Clinical Capacity ()	4 | 2	2.00	0| 4| 0	1| 1| 0
Master Patient Harm CLD Model	InOutLinks	Catastrophic Asset Failure ()	1 | 5	0.20	0| 1| 0	3| 2| 0
Master Patient Harm CLD Model	InOutLinks	Operability ()	2 | 3	0.67	0| 2| 0	0| 3| 0
Master Patient Harm CLD Model	InOutLinks	Waiting lists ()	1 | 3	0.33	0| 1| 0	0| 3| 0
Master Patient Harm CLD Model	InOutLinks	Trust CDEL Allocation ()	2 | 2	1.00	1| 1| 0	2| 0| 0
Master Patient Harm CLD Model	InOutLinks	Staff Turnover ()	2 | 2	1.00	1| 1| 0	1| 1| 0
Master Patient Harm CLD Model	InOutLinks	Staff Harm ()	2 | 2	1.00	2| 0| 0	1| 1| 0
Master Patient Harm CLD Model	InOutLinks	Planned Maintenance ()	3 | 1	3.00	2| 1| 0	0| 1| 0
Master Patient Harm CLD Model	InOutLinks	Patient Harm ()	2 | 2	1.00	2| 0| 0	0| 2| 0
Master Patient Harm CLD Model	InOutLinks	Design Quality ()	3 | 1	3.00	3| 0| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	Staffing Levels ()	1 | 2	0.50	0| 1| 0	1| 1| 0
Master Patient Harm CLD Model	InOutLinks	Staff Workload ()	2 | 1	2.00	1| 1| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	Staff Motivation ()	2 | 1	2.00	1| 1| 0	0| 1| 0
Master Patient Harm CLD Model	InOutLinks	Reactive Maintenance ()	1 | 2	0.50	1| 0| 0	0| 2| 0
Master Patient Harm CLD Model	InOutLinks	Lifecycle Replacement ()	1 | 2	0.50	0| 1| 0	1| 1| 0
Master Patient Harm CLD Model	InOutLinks	Latent Impact ()	2 | 1	2.00	2| 0| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	ICS ()	1 | 2	0.50	1| 0| 0	2| 0| 0
Master Patient Harm CLD Model	InOutLinks	Build and Commission ()	2 | 1	2.00	2| 0| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	Asset Life ()	2 | 1	2.00	0| 2| 0	0| 1| 0
Master Patient Harm CLD Model	InOutLinks	Active Incident ()	2 | 1	2.00	2| 0| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	Active Clinical Error ()	2 | 1	2.00	2| 0| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	NHSE ()	1 | 1	1.00	1| 0| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	DHSC ()	1 | 1	1.00	1| 0| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	HM Treasury ()	0 | 1	0.00	0| 0| 0	1| 0| 0
Master Patient Harm CLD Model	InOutLinks	Clinical Requirement ()	0 | 1	0.00	0| 0| 0	1| 0| 0

Table 4: Summary of links of each variable by polarity

Table 4 highlights that the variables that influence the greater number of other variables are Catastrophic Asset Failure and Functional Asset Failure, both influencing five other variables: Operability and Waiting lists, influencing three variables each, with nine variables affecting two other variables, and the remaining fourteen variables only influencing one other variable.

However, it is Trust RDEL that is affected by five other variables, and Clinical Capacity affected by four other variables. Planned Maintenance and Design Quality are affected by three variables Twelve variables are affected by two other variables, with nine being only affected by one variable, and two being influenced by no other variable (HM Treasury and Clinical Requirement).

This table demonstrates the importance of some of the variables. Those with high level of influence will have a greater impact on the system if positively influenced, whereas those with a lower level of influence may have little impact on the wider system. Conversely, those with a high-level of inputting variables will have a lower chance of being changed by one of the numbers of influencing variables.

Leverage Points

Based on system knowledge, there are nine initially identified leverage points which show key points within, and without, a system where slight change may generate wider system change. These are highlighted in figure 13 below as a yellow diamond.

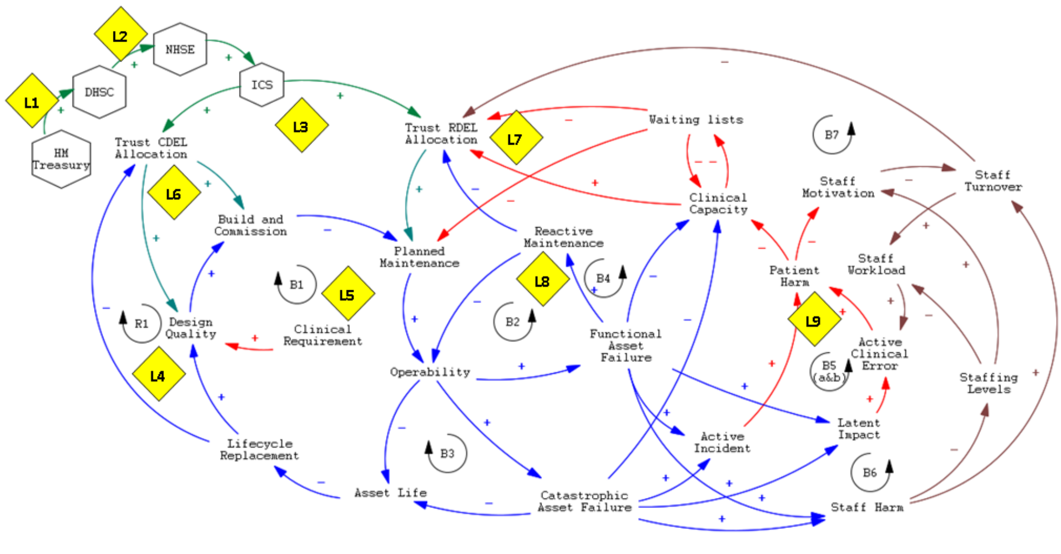

Figure 13: Causal Loop Diagram with key leverage points

L1 – L3 HM Treasury / DHSC / ICS capital allocation policy: the basis on which the NHS operates is derived from the financial allocations from HM Treasury. This allocation is done 'en-masse' for the DHSC and NHSE to use as appropriate, but with some targeted funding. This process is proliferated down to Trust level, whereby the use of the capital and revenue funds available are rarely ring-fenced, and open to the constant pressures of service and strategic demands.

Targeted central funding for addressing long-term backlog maintenance could have significant impact on the asset failure rate.

L4: ***Trust CDEL allocation:*** The allocation of CDEL for most Trusts is undertaken as an annual budget setting round, allocating on a risk profile basis. The articulation of the risk from an asset failure basis is significantly more difficult than that of clinical harm, predominantly due to data availability, and volume of cases on both fronts. Asset management needs to better articulate the risk and impact, both to finance and patient harm.

L5: ***Trust RDEL allocation process:*** As with CDEL, RDEL is an annual cycle round that starts with the prior year as a base, then seeks reductions due to budget savings and looks at an uplift on a case-by-case basis. The overall cost of managing the estate increases as the asset ages, but the budgets do not align with this assumption and deteriorate over time.

L6: ***Design Quality:*** Approved Codes of Practice, such as the Health Technical Memoranda and Health Building Notes within the NHS are *recommend* standards not regulatory. As such, each Trust designs and runs their estate very differently. However, it also has the side effect of permitting 'derogations' from the standards to suit the financial position of a Trust. These derogations can often put strains on assets, causing premature ageing and failure.

L7: ***Clinical Requirements***: Trusts often build an asset to a 'bare-minimum' standard, based on the clinical need they are currently faced with. However, this leads to inappropriate change of use later in the usable life of the asset, or greater pressure put on the asset than originally designed. Ensuring that, as far as practical, the future use for an asset is designed into the facility would reduce on the operability and planned maintenance.

L8: ***Cost impact of reactive maintenance feedback to Trust finance committees***: The cost of reactive jobs within estates is most often captured within its 'RDEL' budget allocation. It is rarely analysed or shared outside of the estates department. However, the cost impact of reactive maintenance should have a feedback loop back to the decision-making points L3 and L7. Not only should the estates cost of reacting to the maintenance be fed back, but the financial burden of the clinical impact also. It is only by understanding the full financial cost impact of asset failure can the worth of prudent asset management be measured.

L9: ***RCA and allocation of harm:*** One of the potentially largest leverage points is that of understanding the full and true impact of the asset failure. Undertaking full Root Cause Analysis of patient harm incidents could lead to a greater understanding of latent impact of asset failure on active clinical errors. However, this may be most difficult leverage point to manipulate.

When analysing the leverage points with the SDM-Doc model analysis, a couple of observations can be made. Other than Leverage point 5 - RDEL, which has 5 influencing variables, none of the other key leverage points correlate with a high number of other variables. This demonstrates how complex the issue at hand is, and that the adjustment of one leverage point will not resolve the level of backlog.

5.0 Next steps

The biggest potential flaw in the causal loop diagram above is its source. The CLD was developed by the author who is not only a PhD candidate but a director of estates in the NHS. This position creates both a unique insight and a potential bias at the same time (Fratini et al., 2012). While it is stated that one of the key characteristics of systems dynamics is its ability to be used by either a sole researcher or through group model building (Kunc, 2017), given the author's role within the NHS, a group model building approach would be preferential. Therefore, to challenge the efficacy of the model it is proposed that key stages of the modelling process are subject to scrutiny through the application of the Delphi Method.

The proposed analysis through the Delphi Method is proposed in two stages – Questionnaire and Focus Group (figure 14).

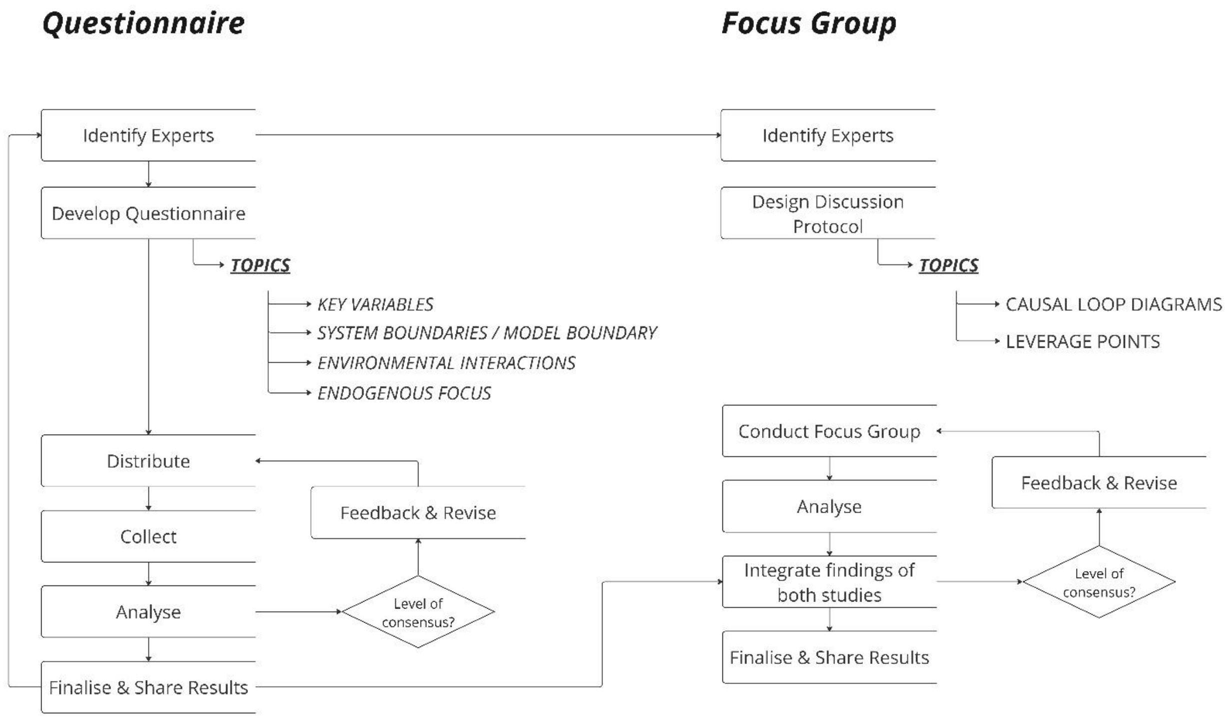

Figure 14: Proposed Delphi Method Approach to Analysing Efficacy of the Causal Loop Diagram

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