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A systems approach to asset management for the Clifton Suspension Bridge Trust

A systems approach to asset management for the Clifton Suspension Bridge Trust

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Abstract

It is generally accepted that civil infrastructure systems are vital for enabling a nation and its population to achieve economic, societal and individual well-being (Little 2005). Large infrastructure assets, however, are typically expensive throughout their lifecycle (Vanier 2001) and there is therefore a need to elicit as much value from them over as long a lifecycle as possible.

The Clifton Suspension Bridge Trust (CSBT) manages the Clifton Suspension Bridge, with the purpose of both maintaining the bridge in perpetuity and enabling the public to enjoy it. The CSBT is a specific exemplar of the generic issues around how best to manage infrastructure assets for whole life value. While the CSBT expressed a desire for an asset management system to improve their ability to look after the bridge, the purpose of this research is to identify and develop the most appropriate methodologies to support the organisation.

By synthesising different approaches to and definitions of asset management, a classification framework has been developed. This has enabled the CSBT to explicitly identify their approach in relation to the alternatives available and determine whether it is the most appropriate for their purpose and context. This classification of AM is generic and of use to all infrastructure asset management organisations.

An extensive study was carried out within the organisation to explore the stakeholders' views on organisational purpose and value. The stakeholders' requirements were captured, as were their perceptions on the key challenges facing the organisation. The output of this study was used to guide the development of an integrated management system, rather than an asset management system.

Utilising systems thinking, models have been developed to explore the CSBT's asset management processes and some of the related issues, such as uncertainty and data management. These models bring together and structure a broad range of organisational elements crucial to asset management. They represent different world views, while externalising and formally capturing implicit processes and tacit knowledge inherent within the organisation.

Dedication

This thesis is dedicated to Chris, Mum, Dad, Aunt Margaret, and Uncle Henry. My family. I'm sure none of you will read this, but without you it would never have existed.

Acknowledgements

Prof Colin Taylor, for the ideas and discussions.

David Anderson, for all of the help and trips up the tower.

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All of the staff of the Clifton Suspension Bridge Trust, you made me so welcome. It was a privilege to work with you.

All of the Trustees of the Clifton Suspension Bridge Trust, for being open-minded and generous with your time.

Sophie Causon-Wood, for gentle nagging (and then less gentle nagging).

Janie Coffey, for putting a roof over my head and telling it like it is.

Dr Oksana Kasyutich, for convincing me to persevere.

Helen Dorgan, for Smurf who was a lifeline.

Declaration of Authorship

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

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1 Introduction

1.1 Context

1.1.1 Infrastructure

Infrastructure systems are the physical and organisational structures required for a society or an organisation to operate, such as transportation, utilities, buildings, healthcare etc (Aktan et al. 2016). It is generally accepted that these civil infrastructure systems are vital for enabling a nation and its population to achieve economic, societal and individual well-being (Little 2005). However, large infrastructure assets are typically expensive throughout their lifecycle, from conception to disposal (Vanier 2001). In addition, the United Kingdom has a high number of ageing infrastructure assets. This, coupled with the increasing need for new infrastructure to meet current and future demand, represents a huge cost for the government (Treasury 2016). There is therefore a need to elicit as much value as possible from these existing aging assets over as long a lifecycle as is feasible, in spite of increasing demand, changing requirements and shifting context.

1.1.2 Transport Infrastructure

Transportation infrastructure consists of all road, rail, air and shipping systems (including inland waterways). These systems are vital for enabling transportation of goods and services, allowing people to travel for work or pleasure, enabling people to access education and healthcare, and connecting communities. Historically, bridges have allowed populations to move and commercial activities such as trade to take place (Riveiro et al. 2011). In the USA, current economic well-being is argued to be dependent on the reliability, safety and security of its physical infrastructure (Spatari and Aktan 2012).

Transport infrastructure assets have a set of issues that are broadly common, both nationally & internationally. There is a growing proportion of transport infrastructure which has surpassed its original design life (Thurlby 2013). In some cases, these infrastructure artefacts were designed before the notion of design life was adopted. Public transport infrastructure has been chronically underfunded over the past few decades and a “sweating the assets” approach has been taken (Thurlby 2013). Today, there are significant quantities of assets requiring major investment in terms of maintenance, repair and renewal to continue performing (Frangopol and Liu 2007) or, as in some cases, replacement is the only option.

In addition to this, there are simply more people using existing transport infrastructure than ever before and the demand is only increasing. As populations continue to grow there is a need to keep up with the increasing demand and to connect communities that are not already integrated within existing transport networks. The current level of infrastructure is insufficient to meet the needs of the present, never mind the future demand (Shah, Jefferson and Hunt 2014).

As the reliance on infrastructure increases, so does the impact of unexpected and disruptive events on society. Sources of uncertainty are multifarious, including climate change, acts of terror, government policy, economic climate and ageing infrastructure. Asset managers need to consider how their assets and organisations will react to unexpected disruptions and plan for an uncertain operating environment (Montgomery et al. 2012).

1.1.3 Asset Management

There are many definitions of asset management and the definitions are generally dependent on the perspective from which the asset is being viewed (Ouertani, Parlikad and McFarlane 2008). Asset management is many things to many different groups but in essence and put simply, "Asset management is not so much about 'doing things to assets' but about using assets to deliver value and achieve the organisation's explicit purposes" (The Institute of Asset Management 2012). It is seen as important because it is cited as an approach that can support and enable organisations to address a range of issues, for example improve asset utilisation, reduce recurring and non-recurring costs, realise efficiency savings, improve overall performance, and achieve best practice (Taggart et al. 2014). However, the range of different definitions, with almost every text proposing a different version, does not necessarily help the asset manager to identify the most appropriate interpretation for their organisation. Harmonisation of the meaning and scope of asset management has been attempted by the PAS 55 standard and more recently by the ISO 5500x suite of standards.

1.1.4 The Clifton Suspension Bridge Trust

The Clifton Suspension Bridge (CSB) spans the Avon Gorge connecting Clifton with Leigh Woods. The grade 1 listed structure has formed part of Bristol's transport network since it first opened in 1864. The Clifton Suspension Bridge is an example of an aging asset that has been in service for over 150 years. While the bridge was originally designed before the age of motorised transport, today it must carry thousands of cars per day.

The CSB is managed by a Charitable Trust, the Clifton Suspension Bridge Trust (CSBT), set up under an Act of Parliament in 1952. The Trust has the dual purpose of both maintaining the bridge in perpetuity and enabling the public to enjoy it.

The CSBT receives no external funding and relies solely on the toll income. All finances raised by the collection of tolls for motor vehicles crossing the bridge are used for the ongoing maintenance and operation of the bridge. Therefore, to be self-sustaining in operation, conservation and maintenance of the structure, the Trust is reliant on the public paying to use the bridge.

Although this organisation only has one single infrastructure asset to manage, the issues that it faces are typical of those encountered by other asset management organisations. The CSBT, therefore, represents a specific exemplar of the generic issue of how best to manage infrastructure assets for whole life value. The organisation has to continue to operate despite changing operational requirements and in the face of future uncertainty.

Ultimately, the CSBT wishes to know how best to manage its assets in perpetuity, in order to achieve its overall purpose. At the beginning of the period of research, when the researcher joined the organisation, there was no demonstrable implementation of formal asset management. At this time, the CSBT expressed a desire for the implementation of asset management and the introduction of an asset management system. This was in order to improve their ability to classify risks, manage data, prioritise investment and look after the bridge.

From the researcher’s perspective, however, the purpose of this research has been to become embedded in the organisation in order to understand how it works. This has then enabled the researcher to uncover issues, to explore the problem space and to investigate and develop the most appropriate methodologies to support the organisation in achieving its purpose.

1.2 Purpose

The purpose of this thesis is to consider the broader issues of infrastructure asset management and look specifically at how they impact an organisation responsible for managing an infrastructure asset. The organisation in question is of particular interest as it maintains an ageing asset of significant historical and cultural importance that also forms an important part of the city's transport network. Therefore, although the organisation is relatively small, the challenges it faces are not trivial.

This thesis argues that asset management as a concept or management tool needs better definition to be usefully applied in a consistent manner across different organisations and industry sectors. Only through a better and more inclusive definition of asset management will all asset managers be able to identify and understand the potential approaches and associated benefits and in turn be able to select the most appropriate approach for their context.

Through the case study of the CSBT, this thesis aims to both explore the issues faced by an asset intensive organisation and to develop and test approaches to dealing with these issues. As many of these issues will apply to other assets and organisations, the work should be of general interest.

Initially, the research explores what is meant by asset management generally and then, specifically, the different paradigms present in infrastructure asset management. With this knowledge, the researcher then sets out to identify why the CSBT wanted an asset management system and what exactly was meant by this requirement. The research work draws on the International Standards Organisation ISO 55000 series of standards on the implementation of a management system for asset management. These standards show that the context, the stakeholders' requirements and an organisational strategic plan are the input to an asset management system. These have then been investigated and developed, where appropriate.

The research considers the implications and benefits of a systems thinking approach to exploring the issues around organisational and asset management. It introduces concepts that have the potential to offer benefits within infrastructure asset management. The purpose of this is to provide better understanding for asset managers, enabling them to question their current approach and challenging them to look at their systems from a different perspective.

This thesis then documents the work that has been carried out, the frameworks and processes developed, and the impact realised by implementing a systems approach to asset management for the CSBT. The thesis presents a range of ideas that have been developed as a result of the investigation into both infrastructure asset management and systems approaches. The intention is that, while not all of these may be generalisable or transferrable, they will prompt asset managers to consider alternative approaches and ways of thinking about their organisations and assets. This thesis is aimed at the asset manager and uses the CSBT case study to illustrate different ways of thinking about asset management.

1.3 Research Questions

The Clifton Suspension Bridge is a significant transport asset in Bristol and is maintained, managed and operated by a private organisation. While the organisation experiences many of the same issues and challenges as managers of larger asset systems or networks, it is on a smaller scale making it particularly suitable for an in-depth case study. The purpose of this work is to investigate the specific issues encountered at the CSBT, from a systemic, holistic and interdisciplinary perspective and to draw parallels where they could be applied to the wider problem situation of infrastructure asset management.

The work has been structured around addressing the following top-level questions:

1. What is asset management, particularly in the context of infrastructure provision?
2. Why does the CSBT want an asset management system?
3. Is asset management adequate to meet the needs of the CSBT and if so what are the key features and requirements of such a system?
4. How does a systems thinking approach to asset management help meet the needs of the CSBT?

1.4 Thesis Structure

Table 1.1 outlines the Chapters that address each of these research questions. Chapters 3 and 6 attempt to address the first research question of “what is asset management?”. They set the context for the work then go on to explore the history and development of infrastructure asset management. A method for classification of different approaches to asset management is introduced along with an approach to identifying different organisational archetypes that influence the adoption of asset management.

Chapters 4 and 7 explore why the CSBT wants an asset management system. Chapter 4 introduces the specific case study of the Clifton Suspension Bridge Trust and gives an overview of the organisation. Chapter 7 then presents a detailed study carried out by the researcher to determine the stakeholders' views on the need for asset management and their perceptions on the key challenges facing the organisation.

The third research question of whether asset management is adequate to meet the needs of the CSBT is explored in Chapters 5, 7 and 8. Chapter 5 introduces some concepts around what systems thinking means in the context of asset management and which approaches could be beneficial for the CSBT. The study presented in Chapter 7 also explores with the stakeholders what the key requirements of an asset management system should be. Through developing systems models of the CSBT that describe how the organisation operates, Chapter 8 identifies the elements necessary for a generic asset management model. This therefore highlights what would be required of an asset management system for it to adequately meet the needs of the CSBT.

The final question focuses on identification of the benefits of a systems thinking approach to asset management for the CSBT. This is addressed through several Chapters (Chapters 8, 9, 10 and 11). In Chapter 8, some different systems models of the CSBT are presented which identify the way in which the organisation currently operates to manage its assets and identifies some gaps which formal application of asset management could attempt to address. Chapters 8, 9 and 10 look to apply different systems approaches to structure the overall problem space, implement interventions in how the organisation operates and address particular technical challenges.

Table 1.1: Thesis Structure

Research Question	**Chapters Addressing Research Question**
1. What is asset management, particularly in the context of infrastructure provision?	Chapter 3: Literature Review Chapter 6: Asset Management Approaches and Organisational Archetypes
2. Why does the CSBT want an asset management system?	Chapter 4: CSBT Case Study Chapter 7: Exploration of Purpose

3. Is asset management adequate to meet the needs of the CSBT and if so what are the key requirements of such a system?	Chapter 5: Systems Approaches to Asset Management Chapter 7: Exploration of Purpose
4. How does a systems thinking approach to asset management help meet the needs of the CSBT?	Chapter 8: Systems Models of the CSBT Chapter 9: Organisational Interventions Chapter 10: Sustainability Assessment of the CSBT Chapter 11: Technical Projects

1.5 Contribution to Knowledge and Industrial Impact

From an academic perspective, this research work presented in this thesis addresses a number of gaps in knowledge. Firstly, there is no existing formal characterisation of the different philosophies and approaches in asset management. While work such as Kusumawardhani (Kusumawardhani, Gundersen and Tore 2017) explores and characterises research methods in asset management, and Frangopol (Frangopol, Saydam and Kim 2012) and Schraven (Schraven, Hartmann and Dewulf 2013) identify the research priorities in asset management, no work that characterises and classifies asset management approaches themselves has been found. The research work carried out attempts to fill this gap and structure a classification of asset management approaches. The work also proposes a framework for describing different organisational archetypes and how this influences their adoption of asset management.

The industrial benefit is to help organisations to understand different asset management approaches. This then enables them to determine where their approach sits within this classification and evaluate whether it is the most appropriate for them given their purpose, context and organisational structure and culture.

The development of a generic asset management model from the specific model of the Trust is another contribution to knowledge. This work represents a holistic approach to evaluating the organisational processes and attributes in relation to its purpose, in order to understand asset management performance. Furthermore, the development of a business archetype model based on Maslow’s work and application of it to the CSBT is novel.

For the CSBT, the work on modelling and structuring the organisational processes has resulted in a deeper understand of how the Trust operates and manages its assets. However, it is more difficult to measure the tangible impact of this.

There is relatively little published work on systems approaches in asset management. The majority of work that does exist is concerned with the development of modelling tools or methods. This thesis, however, contributes by demonstrating the impact of applying a systems thinking philosophy to the day to day asset management processes and problem solving.

For the Trust, the industrial impact of the implementation of systems approaches has been twofold. Firstly, there has been the progress in addressing specific problems such as asset management and data management. This has resulted in a better understanding of how these tasks contribute to purpose and the decision-making processes required. Secondly, as a result of taking a systems approach to the work, several interventions were carried out that had not previously been identified by the organisation. These include the CSBT's strategic plan and the development of an integrated management system. These were both prerequisites to the development and implementation of an asset management system. One particular outcome from this was the sustainability assessment, which was carried out using an adapted version of the Halstar framework. Using a holistic systems framework and including all areas of the organisation, has resulted in a much broader set of recommendations that go way beyond the environmental impacts of maintaining the Bridge.

Generally, there is potential for some aspects of the work to have a wider application and use in industry. The intention is that the thesis presents a range of ideas and applications of theory in a real-world context that could be useful for other asset managers. The researcher hopes that this work will promote and encourage a more intentional approach to management of asset intensive organisations.

2 Clifton Suspension Bridge Trust: The Case Study

2.1 Overview

The Clifton Suspension Bridge spans the Avon Gorge connecting Clifton with Leigh Woods. Isambard Kingdom Brunel was responsible for the original design of the bridge also oversaw construction of the towers. Redesign and construction of the remainder of the bridge was carried out by John Hawkshaw and William Henry Barlow after Brunel's death. The bridge was opened to the public in 1864 and still stands today, largely unaltered (Andrews 2008).

This grade 1 listed bridge is managed by a charitable Trust, set up under The Clifton Suspension Bridge Act 1952 (15 & 16 Geo. 6 & 1 Eliz. 2 1952). The Clifton Suspension Bridge Trust (CSBT) delivers the service of enabling people to cross the Avon Gorge, while maintaining and promoting the bridge as a historical and cultural icon for the city. The bridge is situated in a visually and environmentally prominent position in Bristol.

The 1952 Clifton Suspension Bridge Act sets out the main provisions regarding the operation of the bridge, the powers and duties of the Trustees and the requirement for building up and maintenance of a reserve fund. In addition to this, the Trustees aim to preserve the structure as a working bridge for the long term, rather than letting it decline to the point where it is only an historical monument. It currently forms a key part of the Bristol transport network, and has over 3.2 million vehicle crossings per annum (Clifton Suspension Bridge Trust 2012).

The only income available to the CSBT is raised by the collection of tolls from motor vehicles crossing the bridge. This income needs to cover all aspects of maintenance, operational costs and provide a reserve fund in case of unforeseen events. The Trust cannot use its income for any purpose other than to support the bridge and cannot distribute any surpluses to any other party.

In December 2014, the bridge was 150 years old and as would be expected of a structure of this age, there is an ever-increasing list of required maintenance work. In addition to this, there are many areas of uncertainty regarding the structure and its environment, which require investigation.

The Trust has expressed a perceived need for a systematic and holistic approach to asset and risk management. They believe this will enable them to maintain the bridge to the best of their ability and to achieve the requirements of their mission statement.

They believe that this will, in turn, enable them to deploy their limited funds most appropriately to mitigate risks and protect the long-term performance of the bridge.

2.2 Purpose and Objectives

The purpose of the CSBT is captured in its mission statement and is as follows:

"It shall be the mission of the bridge Trust to preserve the Clifton Suspension Bridge in perpetuity, to the highest possible standards, for the utility of the public, and to provide information and facilities for the enjoyment of visitors to the bridge."

The CSBT is committed to providing a safe and efficient crossing service and demonstrating value for money to the paying customers. The Trust considers itself to be responsible for both the physical upkeep of the bridge and also for maintaining and promoting the social, educational and historical value of the bridge. Infrastructure systems within the engineering sector often exist within a complex socio-technical context and engineering may even be considered as a primarily social process (Marashi and Davis 2007).

The crossing service connects the communities on either side of the Avon Gorge, particularly providing access into the City of Bristol for work, education and healthcare. The bridge therefore also has broader societal outcomes. Provision for visitors to the bridge and outreach in the community contributes to the bridge being an historical icon and focal point for the city.

In 2012 the CSBT applied to the government to increase the toll. Within the application the organisation states that one of their policies is that "the service provided to motorists, pedestrians and visitors should be maintained or improved" (Clifton Suspension Bridge Trust 2012). The document then continues with a list of objectives that describe what "service provided" means for the CSBT. These can be considered to be the top-level objectives of the organisation:

- The toll system should be easy to use, both for coin and card transactions
- The toll system should be reliable
- The system should be perceived to provide value for money
- Customer relations should be maintained or improved
- People in receipt of disability allowances should receive concessions
- The safety of the public and staff should be maintained or improved

- The bridge will be staffed by at least two members of staff (one at each end of the bridge) for 24 hours a day, 365 days a year
- That toll staff will seek to be accessible to members of the public at all times and to demonstrate a positive image of the Trust to all bridge users and visitors

2.3 Organisational Structure and Responsibilities

The Trust is managed by a board of twelve Trustees, comprising ten Resident Trustees, chosen for their technical and business expertise, and two Representative Trustees nominated by Bristol City Council and North Somerset Council (15 & 16 Geo. 6 & 1 Eliz. 2 1952). The board of Trustees also form three sub-committees, the Technical Committee, the Investment Committee and the Property Committee. These sub-committees have some delegated authority, they closely manage activities under their responsibility and report into the board.

The Trustees employ a Bridge Master who deals with much of the day to day management of staff, operations and technical issues. Some responsponsibility is further delegated to a Visitor Services Manager, Maintenance Chargehand & Office Manager. The Trust also employ external experts & consultants as required to provide speciallist advice, however the Trustees are ultimately responsible for all decision making.

Approximately twentythree full time and part time staff are directly employed by the Trust. This includes thirteen bridge attendants who are employed on a shift working basis to provide twentyfour hour coverage on the bridge. There are approximately sixtyfour volunteers who provide a range of services including working in the visitor centre and giving guided tours. The CSBT organisational structure is shown in Figure 2.1.

The responsibility for the overall management of the bridge and organisation lies ultimately with the Trustees. They are personally responsible for decisions made and as such are relatively risk averse, keen to avoid contentious decisions and rely to some extent on the advice of consulting professionals. The Trustees come from varying backgrounds and include engineers, an architect, a lawyer, an art historian, an estate agent, a finance and investments expert and several of them own or have owned their own companies.

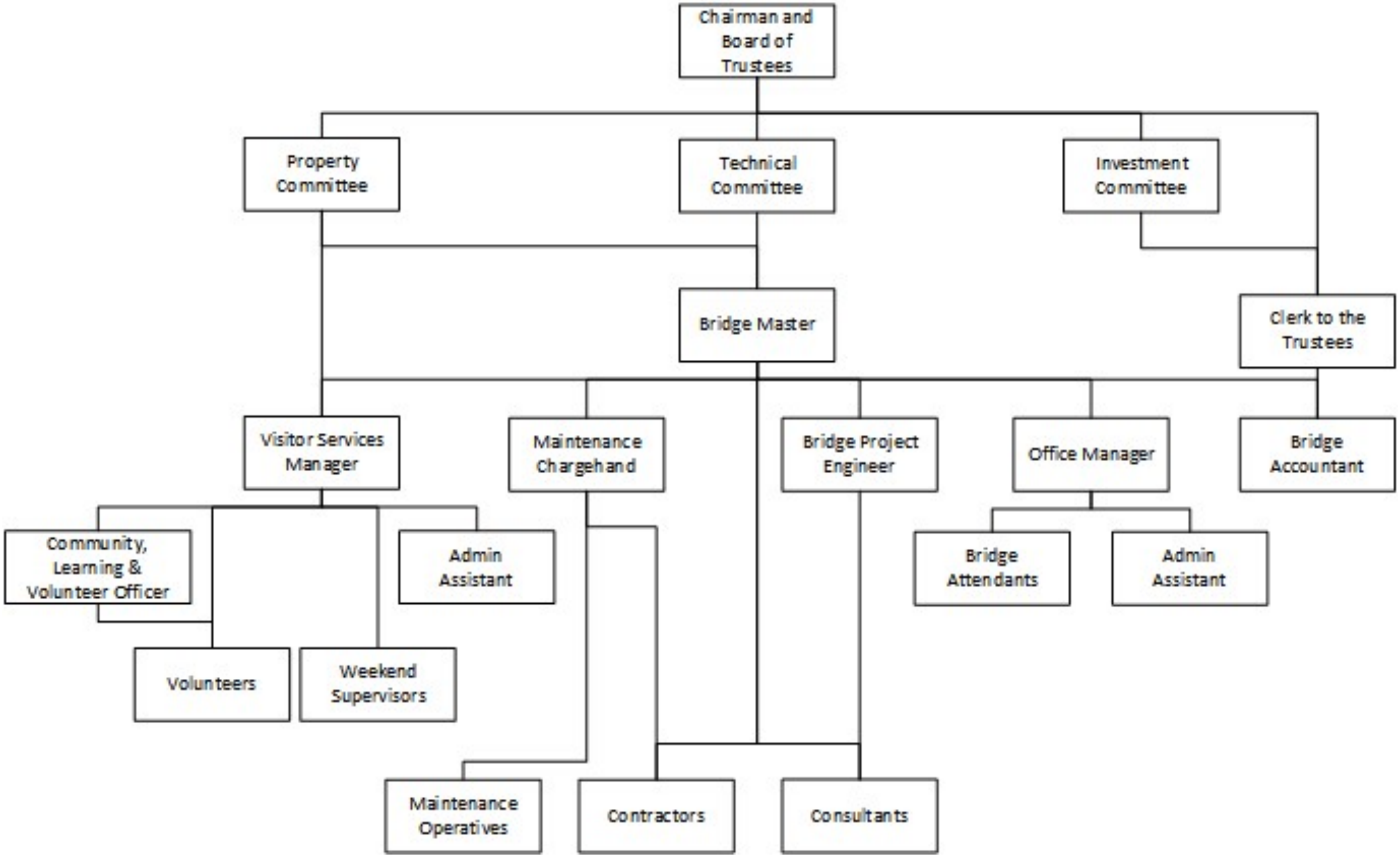

Figure 2.1: CSBT Organisational Structure

2.4 Governance and Acts of Parliament

There are three Acts of Parliament that concern the Clifton Suspension Bridge and the operation of the Trust. These are:

- Clifton Suspension Bridge Act 1952: constitution of the CSBT, incorporation of the Trustees and transfer of the undertaking of the Clifton Suspension Bridge Company to the Clifton Suspension Bridge Trust (15 & 16 Geo. 6 & 1 Eliz. 2 1952)
- Clifton Suspension Bridge Act 1980: making provisions relating to the investment of the Trust's finances (Elizabeth II 1980)
- Clifton Suspension Bridge Act 1986: authorising the Trustees to provide or assist in provision of a museum near the bridge (Elizabeth II 1986)

The 1952 Act of Parliament is the main legislation that sets out the requirements of the organisation and the Trustees themselves. This primarily relates to the following:

- The operation and maintenance of the bridge
- The powers and duties of the Trustees
- The building up and maintenance of a reserve fund

The organisation is responsible for all activities related to maintenance, management and safe operation of the bridge, while also providing visitor services and operating the visitor centre.

2.5 Assets and Services

The CSBT has a range of assets and utilises them to provide a number of services to its customers. There are two main asset groups:

- The operational assets, including the bridge and access systems, toll houses, operational and maintenance building, skills and expertise of staff etc.
- The visitor centre and heritage assets, including the visitor centre, collections and archives, historical knowledge etc.

The CSBT utilises its asset to deliver the following services:

- Provision of a safe and convenient crossing point across the Avon Gorge
- Free crossing to pedestrians, cyclists and emergency services
- Efficient collection of the toll
- Provision of the option for toll prepayment through crossing card

- Bridge tours, both revenue generating for groups and free for the public
- Education programmes, both onsite and offsite

2.6 System and Boundaries

The Clifton Suspension Bridge is a hard physical system sitting within the soft system of the organisation, the Trust. The bridge enables people to cross the Avon Gorge, while acting as a historical and cultural icon for the city. The organisation, therefore, also sits within two further city-wide systems; Bristol's transport network and the city's historical and cultural identity. This is represented in Figure 2.2.

These two city level systems could also be considered part of corresponding regional or national level systems. For the purposes of this study the system boundary has been drawn around the CSBT and its interactions with the two systems shown in Figure 2.2. Drawing a wider system boundary would detract from a detailed analysis of the CSBT.

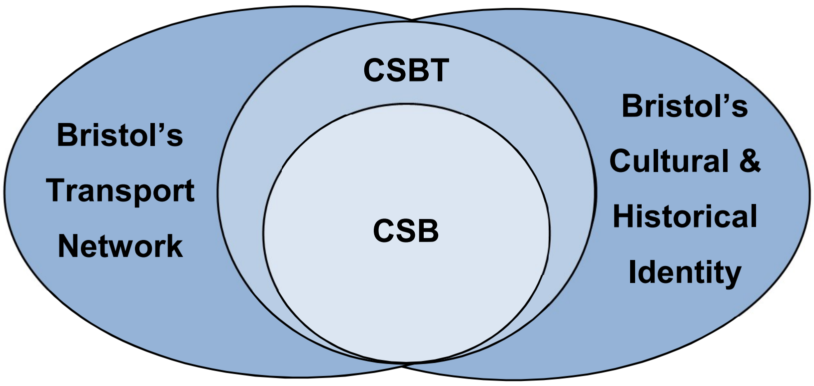

Figure 2.2: Clifton Suspension Bridge Trust System

In addition to the CSBT, there are other crossing points along the River Avon that enable people to access each side of the Avon Gorge. The next adjacent crossing points to the Clifton Bridge are the Cumberland Basin flyover and the Avonmouth Bridge. The Avonmouth Bridge is a motorway bridge and a 14 mile round trip from the CSB. The Cumberland Basin is a busy road interchange, close to the city centre.

There are also other historical and cultural landmarks for Bristol, however identification of them is subjective and will depend on the perspectives of individuals. One of the most likely candidates is the SS Great Britain, which is another Brunel project. The ship was brought home to Bristol in the 1970s and had extensive restoration work carried out. It now resides in the floating harbour is one of the other main tourist attractions in the city. Another symbolic icon of Bristol is the hot air balloons, due to the history of balloon manufacture in the city and the annual international balloon fiesta. Nevertheless, it is difficult to identify anything else which would fulfil the role that the bridge plays culturally and historically for the city of Bristol.

2.7 Stakeholders

The CSBT has a broad range of stakeholder groups, both internal and external to the organisation. A brief summary of these is shown in Table 2.1.

Table 2.1: CSBT Stakeholders

Stakeholder Group	**Concerns**	**Interest***	**Power***	**Management Strategy**
Trustees	Fulfil requirements of Acts of Parliament Manage to the best of their ability Be seen to be managing appropriately Achieve value for money Ensure security for the future	5	5	Manage Closely
Staff	Job security Safe working environment	5	4	Manage Closely
Commuters – paying	Value for money Safe crossing Efficient crossing Convenient service	4	2	Keep Informed
Commuters – non-paying	Safe crossing Efficient crossing Convenient service	3	1	Keep Informed
Visitors	Opportunity to learn about the CSB Space to enjoy the bridge in its setting	4	1	Keep Informed
English Heritage	Maintain the original fabric of the structure wherever possible	2	4	Keep Satisfied
Natural England	Be mindful of & protect the Avon Gorge SSSI	2	2	Monitor
Bristol City Council	Ensure traffic flow Attractor to the region Focal point for the city	3	3	Keep Informed

North Somerset Council	Ensure traffic flow	3	3	Keep Informed
Local Residents	Ensure traffic flow Preserve the aesthetic quality Minimise any disruption Low impact on community Low cost / value for money	4	2	Keep Informed
Public Interest / Community Groups	Ensure traffic flow Preserve the aesthetic quality Minimise any disruption Low impact on community	4	2	Keep Informed
Downs Society	Minimise impact on the Downs Preserve the aesthetic quality Be mindful of & protect the Avon Gorge SSSI	4	3	Keep Informed
Department for Transport	Requirements of Acts are fulfilled	1	4	Keep Satisfied
Investors e.g. Heritage Lottery	Requirements of funding agreements are met	1	1	Monitor
Charity Commission	Fulfil legal requirements Trustees carry out duties Publish accounts	2	4	Keep Satisfied

*On a scale of 1 to 5, 1 is low, 5 is high

It can be seen from Table 2.1 that only internal stakeholders have both a high interest and high influence. The CSBT does not have shareholders or investors to satisfy and the business model relies on many customers who each spend a small amount for the service received. Most external stakeholder groups have no power over the operations of the organisation despite a reasonable interest and the ones who do have power are only likely to exert it under specific circumstances.

The benefit of this is that the CSBT is not burdened with pressure from many stakeholder groups which could make decision making slow and difficult. They do not have to report to many authorities or conform to a wide range of regulatory standards. This results in cost & time savings and potentially a less bureaucratic organisation.

However, at the same time, this lack of accountability to external stakeholders could be problematic, both for the stakeholders and the organisation. For the people who use the service, it is difficult to ensure that it meets their needs or to have confidence in their feedback being taken on board. For the organisation, they are not being challenged about how they operate and as such have no pressure to review and improve their processes.

2.8 Issues

The issues that the CSBT faces are typically related to uncertainty. There is uncertainty over how the changing demand will affect the CSBT, with a noticeable increase in people using public transport, walking or cycling. If toll income is no longer sufficient, means of securing financial stability could become a major issue. The asset is old and there are elements of the structure that are still not well understood today. Examples of this are the ongoing geotechnical investigations and aerodynamic assessments, both a result of the bridge being designed and built in a time before these were understood.

Other issues are a result of competing and conflicting demands. Because of the dual nature of the bridge’s purpose, there will always be a tension between providing the service of a bridge and maintaining a historically and culturally significant icon for the city.

2.9 Problem Space

The problem areas expressed by the stakeholders at the beginning of the period of research were risk management, data management, and asset management. The overall goal for the CSBT from this research is to define requirements for and implement an appropriate asset management system to support the Trust in effective and economical decision making. Alongside that, strategies for managing and organising the vast quantities of data and archive material also need to be explored.

Initially it was not clear to the researcher what was meant by the need for asset management within the organisation, particularly when there are many divergent definitions, areas of research and examples of industrial implementations. After initial discussions with the stakeholders, it became clear that there were different perceptions of both what asset management was and what was required for the organisation. This raised two areas of study for the researcher. Firstly, to review the different areas, definitions, applications and research on asset management to develop a method of classification. This would then enable small organisations to begin to identify the types of approaches most suitable for them. This work is presented in Chapter 6. Secondly, a study was carried out to explore in more depth with the stakeholders what they felt the issues were within the organisation and what was needed to address them. This work is presented in Chapter 7.

The Trust defined several specific issues that needed investigation. One of the ongoing issues identified was the management and utilisation of the Trust's data. The organisation has material dating back from the early 1800s through to the present day. Much of this is still useful and interesting from a bridge maintenance and management perspective. Due to the historical and cultural importance of the bridge, this material has additional value and can be of interest to a wider audience. Difficult decisions needed to be made regarding what should be retained and for how long, how it should be stored, what should be made available to the public and how we ensure that the relevant information can be found at the right time for technical purposes. Effective, purpose driven data management is a common problem for asset managers. A study was carried out to review the extent of the issue, the types of material available, and typical use-cases. This information was used to develop solutions applicable across the whole organisation. This work is discussed in Chapter 9.

Another area of work identified by the Trust was related to hanger fatigue. The CSBT specified that they believed they needed a test programme to determine the hanger fatigue strength. However, by looking at how the problem related to the overall purpose, what decisions needed to be made and what information was already available, different outcomes were realised. An overview of this study is presented in Chapter 11.

More generally, throughout the project, systems modelling approaches have been used to try to frame the problem space. From this, framework was developed for categorising and exploring a set of organisational elements including context, purpose, processes, controls and capitals. This helped with understanding how different elements of the organisation are interconnected and what value flows occur between them. It is a systematic approach for thinking through all aspects that may contribute to an organisation's performance. It also enables identification and capture of implicit knowledge. This work is discussed in Chapter 8.

One of the key observations from the much of the published work on the industrial implementation of asset management was concerned with the importance of agreeing and capturing organisational strategy (International Standards Organisation 2014, The Institute of Asset Management 2012, Hooper et al. 2009). This includes the purpose and strategic direction of the organisation, stakeholders' requirements and how those filter down through the levels of the organisation. This then enables people in the organisation to have line of sight between what they need to do on a day to day basis and how that has a positive impact on the organisation's success. It was highlighted that this did not exist for the CSBT and so the researcher, with support and input from the rest of the organisation, created a Five Year Organisational Strategy document which was approved and implemented. This work is presented in Chapter 9.

Following on from the organisational strategy and as part of the asset management system, an integrated management system was developed and implemented by the researcher. This was in response to the requirements and concerns captured from the stakeholders about having confidence that the assets and organisation were being managed, maintained and operated in the most appropriate way to protect the future of both the organisation and the bridge. This system was implemented at the end of the period of research and the work is discussed in Chapter 9.

3 Literature Review

3.1 Introduction

Asset management describes a large body of work that spans industrial and financial sectors. There are many families of research within the field and many different applications in industry. There is no single accepted definition of asset management and what is considered an asset varies from one organisation to the next. Asset management has been applied in various ways within infrastructure management.

This Chapter aims to explore the body of research in the field of infrastructure asset management so as to identify the key gaps in knowledge and highlight opportunities for further work.

3.2 Assets

The term “assets” has many different definitions but generally can be considered as anything that has the potential for positive return (McKernan and Sherraden 2008). More recently, from the ISO 55000 standard for asset management, an asset is defined as an “item, thing or entity that has potential or actual value to an organization” (International Standards Organisation 2014). A similar definition is also given by the Institute for Asset Management but with the recognition that what constitutes ‘value’ will obviously depend on the viewpoint of the asset manager (The Institute of Asset Management 2012).

Assets can also be broadly classified as either tangible or intangible. Tangible assets include cash, financial securities, property, hard assets, machines and equipment, natural resources, and intellectual property. Intangible assets then would include human capital, cultural capital, social capital, organisational capital and political capital (Sherraden 1991). An alternative categorisation of assets is given in the Publicly Available Specification for Asset Management which states that there are five types of assets and that they must all be managed holistically to enable organisations to achieve their strategic plans. These are physical assets, human assets, information assets, financial assets and intangible assets. In this case, intangible assets includes reputation, morale, intellectual property and goodwill (The Institution of Asset Management 2008). Interestingly, this categorisation of assets groups intellectual property with the intangible assets.

There are some definitions of assets that only include consideration of the physical assets. Examples of such definitions state that assets are the physical components of a facility which enable the organisation to provide services, or that assets include plant, machinery, property, buildings and items that have distinct value to the organisation (Hooper et al. 2009). The ISO standard for asset management uses the phrase “asset portfolio” to describe the “assets that are within the scope of the asset management system” (International Standards Organisation 2014). Assets are then categorised in this document into either physical assets or intangible non-physical assets. Examples of physical assets given include equipment, inventory and property, while intangibles include leases, brands, digital assets, licenses, intellectual property rights, reputation and agreements.

Amadi-Echendu draws on the dictionary definition of asset to propose that any definition of asset should contain three key elements. These are an object (or property), a legal entity (person or company) and a value (Amadi-Echendu et al. 2010). Although Amadi-Echendu is concerned with engineering assets and considers these to be physical assets that are not financial, this can still be a useful way to think more generally about identifying assets.

It is unlikely that any general definition of assets will become usefully adopted. What is likely to be of more use to an organisation is the process of deciding internally. The organisation needs to think about the range of what can be considered to be an asset and then decide what makes sense to be included, in relation to their overall purpose and strategy. When thinking holistically, it makes sense to include everything of value as otherwise there will be a need for another separate approach to management of anything that does not fit under the umbrella of asset management. For the purposes of this work, drawing on the range of definitions discussed, the following is proposed:

An asset is any element managed by an organisation that has potential or actual value to a stakeholder, either directly or through its contribution to the overall purpose.

3.3 Published Standards and Guides

There are a range of published standards, policies and good practice guides on the subject of asset management. Standards are powerful as they can enable common agreement across organisations and systems, incorporating a range of user requirements with the overall aim of improving economic efficiency (Koronios et al.

2007). The first attempt at global standardisation of asset management was in 2004, through the development and publication of Publicly Available Specification 55 (PAS 55) for physical assets. This was revised and updated in 2008 with input from a large number of organisations across multiple sectors. The PAS 55:2008 specification was also aimed at the management of physical assets (The Institution of Asset Management 2008). In 2014, the International Organisation for Standardisation published the ISO 5500x series of standards for asset management and this comprises:

- ISO 55000 Asset management: overview, principles and terminology
- ISO 55001 Asset management: management systems – requirements
- ISO 55002 Asset management: management systems – guidelines for the application of ISO 55001

The ISO 5500x standards supersede the PAS 55 specification and expand the scope of asset management as follows:

"This international standard is intended to be used for managing physical assets in particular, but it can also be applied to other asset types." (International Standards Organisation 2014).

The Institute for Asset Management, who were instrumental in the development of PAS 55, also published a guidance document Asset Management – An Anatomy. The purpose of this was to act as a high-level guide to the fundamentals of asset management and acts as a companion to the asset management standards (The Institute of Asset Management 2012).

There are then many sector specific documents that are aimed at supporting asset managers in particular fields. Those that are particularly relevant to transport infrastructure asset management in the United Kingdom are as follows:

- Highway Infrastructure Asset Management Guidance Document (UK Roads Liaison Group 2013)
- Management of Highways Structures: A Code of Practice (Roads Liaison Group 2013)
- Realising a World Class Infrastructure: ICE's Guiding Principles of Asset Management (Institution of Civil Engineers 2013)

- Asset Management: Managing Assets in the Context of Asset Management (ISO 2017)
- Whole Life Infrastructure Asset Management: Good Practice Guide for Civil Infrastructure (Hooper et al. 2009)

The Management of Highways Structures and Highways Infrastructure Asset Management documents were both created by the Roads Liaison Group. This group brings together both national and local government from across the UK to explore roads infrastructure engineering and operations issues.

The Highway Infrastructure Asset Management Guidance is focused on the development and implementation of asset management for highway infrastructure. It is a high-level document that aims to support organisations that are trying to implement asset management according to the ISO 5500x series of standards. While the ISO 5500x standards detail the requirements or the "what to do", this guidance document support asset manager with the implementation or "how to do" (UK Roads Liaison Group 2013).

The Management of Highway Structure code of practice sits under the Highway Infrastructure Asset Management guidance, along with the other codes of practice for Well-maintained Highways, Management Well-lit Highways and Management of Electronic Traffic Equipment. It has a section dedicated to asset management planning and another on asset information management. It sets out guidance for organisations and asset managers to enable the implementation of good management practice. The code calls for a holistic approach to the management of highway structures, considering the broader network and environment within which the asset operates (Roads Liaison Group 2013).

The ICE's publication on Realising a World Class Infrastructure sets the context for the importance of infrastructure in creating economic prosperity and delivering societal outcomes (Institution of Civil Engineers 2013). This report outlines the key characteristics of civil engineering infrastructure assets including the uniqueness of most assets, the planned or required longevity of asset life, the complexity and multi-disciplinary nature of the asset systems, and the changes in use of assets over their lifespan. It calls for the need to view civil infrastructure assets as holistic and multi-disciplinary systems. A set of guiding principles are outlined that includes a list of aspects of best practice for asset management organisations. This calls for alignment of the whole organisation with asset management and also highlights the importance of line of sight between the organisational strategy and asset management policy and the people responsible for the day to day asset management activities.

The ISO Technical Committee TC 251 is responsible for standardisation in the field of asset management and produced the ISO 5500x series. To provide further guidance on particular areas of these standards, the Technical Committee are publishing a series of articles. Managing Assets in the Context of Asset Management is one of these and is of particular interest. It draws out the differences between a traditional approach to managing assets and the benefits of the more systemic and holistic approach to asset management. Table 3.1 outlines the differences in focus between the two paradigms (ISO 2017). This report explains that the ISO 5500x standards relate to asset management (rather than managing assets) and can help organisations who wish to take this approach.

Table 3.1: Managing Assets and Asset Management (ISO 2017)

Managing Assets	Asset Management
Lifecycle asset management and asset care Asset location, condition, deterioration & predictions methods Databases and IT systems KPIs including availability, reliability, safety Budgets and maintenance planning People, skills and work management	Organisational purpose Identification of assets required and why Understanding of how assets contribute to organisational value Value and long-term outcomes Risk and context Holistic approach to funding streams Collaborative behaviours internally and within supply chain

The Whole Life Infrastructure Asset Management Good Practice Guide for Civil Infrastructure document is the oldest of the supporting documents considered here and was developed as a companion to the International Infrastructure Management Manual. It also reads across to PAS 55. It is of interest however as it focuses on the strategic and tactical elements of asset management rather than operational processes such as maintenance and inspection. It also includes case studies to illustrate the points being made.

The documents discussed in this section have been limited to those applicable in the UK or internationally. However, for an organisation looking to implement infrastructure asset management, there is still a confusing number of documents aimed at informing and standardising asset management approaches.

3.4 Asset Management

The term "Asset Management" has roots in different sectors. It has been used in finance, related to the trade-off between risk and return (Brint, Bridgeman and Black 2009). It has also been used extensively within manufacturing, civil engineering and oil and gas (Woodhouse 2014). Amadi-Echendu presents a comprehensive review of what is meant by engineering asset management, drawing on global work in the field (Amadi-Echendu et al. 2010). Since the start of the 21st century, within engineering, there has been a gradual shift away from its origins in reliability and maintainability of equipment to a more holistic approach that considers "strategy, economic accountability, risk management, safety and compliance, environment and human resource management and stakeholder and service level requirements" (Frolov et al. 2010, Shah et al. 2014). This move towards a top down approach starts from the strategic purpose of the organisation and considers how the assets can be managed to enable the organisation to achieve this.

There is, as yet, no single definition of asset management and the definitions are generally dependent on the perspective from which the asset is being viewed (Ouertani et al. 2008). Some definitions include reference to lifecycle and achievement of organisational purpose e.g. "systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan" (Moon et al. 2008). Other definitions of asset management include:

- Strategic and systematic process of optimising decision-making (Too, Betts and Arun 2006)
- Alignment of asset with service demand (Too et al. 2006)
- Optimal and sustainable management of assets to achieve the organisational strategic plan (Bush et al. 2011)
- Balancing of cost, performance and risk over the life cycle (van der Velde, Klatter and Bakker 2012)

- A complex paradigm, requiring stakeholder consensus on the values and performance metrics and associated management trade-offs (Spatari and Aktan 2012)

From the asset management standards and documents discussed in section 3.3, there are a number of definitions as presented in Table 3.2.

Table 3.2 Asset Management Definitions

Source	Definition of Asset Management
PAS 55:2008 Asset Management (The Institution of Asset Management 2008)	"The systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan."
ISO 5500x:2014 Asset Management (International Standards Organisation 2014)	"The set of coordinated activities that an organisation uses to realise value from assets in the delivery of its outcomes or objectives. Realisation of value requires the achievement of a balance of costs, risks and benefits, often over different timescales."
Asset Management – An Anatomy (The Institute of Asset Management 2012)	"The co-ordinated activities of an organisation to realise value from assets"
Highway Infrastructure Asset Management Guidance Document (UK Roads Liaison Group 2013)	"A systematic approach to meeting the strategic need for the management and maintenance of highway infrastructure assets through long term planning and optimal allocation of resources in order to manage risk and meet the performance requirements of the authority in the most efficient and sustainable manner".
Management of Highway Structures: A Code of Practice (Roads Liaison Group 2013)	"A strategic approach that identifies the optimal allocation of resources for the management, operation, preservation and enhancement of the highway infrastructure to meet the needs of current and future customers."

Realising a World Class Infrastructure: ICE's Guiding Principles of Asset Management (Institution of Civil Engineers 2013)	"Asset Management creates this holistic focus, viewing our economic infrastructure over its entire lifecycle, and provides the basis for a coordinated and coherent approach. It ensures our essential infrastructure receives appropriate investment and attention, has the appropriate resilience to meet new challenges and can sustain our economic prosperity."
Whole Life Infrastructure Asset Management: Good Practice Guide for Civil Infrastructure CIRIA C677	"Asset management is the systematic and co-ordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan" "The combination of management, financial, economic, engineering and other practices applied to physical assets with the objective of providing the required level of service in the most cost-effective manner"
Asset Management: Managing Assets in the Context of Asset Management	Refers to ISO 5500x definition

In recent years, asset management of infrastructure systems has been attracting increasing attention. This is partly due to the growing pressures on infrastructure assets and also due to the reduced levels of government funding available to support and operate them (Moon et al. 2008). It is estimated that there will be a significant gap in funding for transport infrastructure of around £100 billion between 2010 and 2030 (Mills et al. 2011) This has resulted in a movement towards asset management to achieve maximum value for money. This incorporates the principles of sustainable management of assets including, where financially feasible, continued use of ageing infrastructure to reduce spending on new infrastructure assets.

In some communities, there has been a gradual shift in focus from the operation of the physical assets to the provision of service (Blom, Marco and Guthrie 2015, Miller and

Gransberg 2015). This requires asset managers to revisit the overall purpose, consider who their stakeholders are and identify their requirements. Then looking at the world context and environment within which they operate, it is possible to link the day to day asset management activities to the overall societal outcomes.

It is unlikely that there will ever be full convergence on a single definition of asset management. Within the research literature, the definitions are diverse and tend to reflect the nature and scope of the research described within. The issue associated with this is that if there is no accepted definition or means of bounding the area of research then it can lose focus and become so broad that it ceases to be useful. There is more synergy between the definitions from the standards and industrially focussed guidance documents as shown in Table 3.2. The consistency between definitions is that asset management:

- Is a series of strategic, co-ordinated, systematic activities
- Enables the organisation to manage its assets to elicit value
- Through generation of value, enables the organisation to achieve a strategic purpose
- Takes a holistic view
- Is concerned with the whole lifecycle

There may, however, be more acceptance of the definition given in ISO 55000 over time as organisations adopt the standard and seek accreditation. For the purposes of this work, and drawing on the range of definitions discussed, the following is proposed as a summary definition of asset management:

Asset management is the holistic and systemic approach to the sustainable continued achievement of organisational purpose and delivery of outcomes to stakeholders. This is realised through the coordinated and multidisciplinary management of all assets over their lifecycle.

3.5 Research Priorities in Infrastructure Asset Management

In addition to the wide range of standards and guidance documents, there are also many different branches of academic research in infrastructure asset management. The focus of asset management, both in industrial implementation and academic research, varies greatly despite increasing recent attempts at harmonisation through standardisation.

Many research studies seek to integrate different disciplines related to infrastructure asset management including civil engineering, economics, finance and organisational science (Schraven et al. 2013). In this paper Schraven also discusses the issue of scope creep within the contemporary research work on infrastructure asset management. Similarly to the point made on lack of cohesion on definitions of asset management, there is a risk that the research field itself is growing too broad, diluting focus and not creating a cohesive research community.

Frangopol et al carried out a review of papers related to maintenance, management and optimisation of infrastructure published in the Structure and Infrastructure Engineering journal from its launch in 2005 to July 2011 (Frangopol et al. 2012). The purpose of this was to try to identify recent areas of focus in infrastructure asset management research. These papers are grouped by one of the following sets of categories:

- Types of infrastructure: bridges, steel structures, reinforced concrete structures, railways, marine and offshore structures, aerospace structures, underground structures and special structures
- Deterioration mechanisms: identification of deterioration from inspection and monitoring data, probabilistic deterioration modelling, corrosion, and fatigue
- Quantification of uncertainties: probabilistic modelling and analysis in: decision making, assessment of financial benefits, structural performance, life cycle management, flood estimation; sampling-based uncertainty quantification, decision making with uncertainty
- Structural health monitoring (SHM): advances in techniques, damage identification and use of SHM data
- Life cycle analysis: general frameworks, life cycle performance assessment and prediction, reliability, maintenance and repair strategies and cost analysis
- Structural design, modelling, experiment and analysis
- Structural performance indicators: sustainability, redundancy, reliability, resilience, risk, robustness and vulnerability
- Extreme events: flood, earthquake and blast
- Rehabilitation and strengthening

Similarly, Schraven's study on research orientations in infrastructure management surveys articles from 1996 to 2013 that explicitly refer to infrastructure asset management in the title, abstract or keywords (Schraven et al. 2013). From the citation analysis carried out, knowledge groups were identified, and these showed a distinction between technical and non-technical aspects of infrastructure asset management. Those that are either general or applicable to bridges are as follows:

- Maintenance decisions, optimisation, and genetic algorithms, for replacement, rehabilitation, repair and inspection
- Multicriteria decision making
- Statistical deterioration models and probability concepts
- Condition prediction for concrete bridges
- Structure inventory appraisal
- Traffic and maintenance effects
- Portfolio selection, investment and pricing uncertainty
- Sustainability and infrastructure scores
- Performance measurement
- Reliability and maintenance standards
- Official guidelines for asset management and physical asset management
- Life cycle approach for bridges
- Bridge management systems
- Knowledge in organisations, information and data quality

From the researcher's own literature review, there were similar findings. The number and breadth of topics on infrastructure asset management were significant and to attempt to better understand the research space, a list of key research areas was created. This list contains some elements that are less general and more specific to the context of this research, particularly around systems thinking and cultural and historical value. This list is as follows with some examples of each:

- Decision making and prioritisation (Catrinu and Nordgård 2011, Gómez et al. 2011, Hall et al. 2004, Hsieh and Liu 1997)
- Performance monitoring and service level (Bush et al. 2011, Oswald et al. 2011, Too 2011, Chasey, Garza and Drew 1997, Blom et al. 2015)
- Risk management and uncertainty (Dester and Blockley 2003, Ezell, Farr and Wiese 2000, Fang and Li 2009, Ujjwal, Vadim and John 2012)

- Data and knowledge, asset databases and GIS (Chen, Chen and Chu 2009, Riveiro et al. 2011, Baskarada and Koronios 2013, Halfawy, Newton and Vanier 2006, Ouertani et al. 2008)
- Condition monitoring, deterioration prediction and modelling (Frangopol and Liu 2007, Brownjohn 2007, Kobayashi, Kaito and Lethanh 2012, Ellingwood 2005)
- General asset management issues and approaches (Schraven, Hartmann and Dewulf 2011, Koronios et al. 2007, Moon et al. 2008, Spatari and Aktan 2012)
- Asset and bridge management systems (Webster and Allan 2005, Miyamoto, Kawamura and Nakamura 2002, Vanier 2001, Kellick 2010)
- Lifecycle management (Popko et al. 2009, Frangopol 2011, Too and Too 2010)
- Cultural and historical significance and value (Holt 2014, Brühwiler 2012, Cossons 2012, Mike 2016)
- Resilience and robustness (Tariq et al. 2016, Fang and Li 2009, Blockley, Agarwal and Godfrey 2012, Brown, Seville and Vargo 2017)
- Governance and management (Kellick 2014, Lloyd 2010, Carron and Peter 2016, Weninger-Vycudil et al. 2015)
- Systems approaches to asset management (Blockley and Godfrey 2000, van der Velde et al. 2012, Marashi and Davis 2006, Wiewiora, Keast and Brown 2015, Baker-Langman 2003)

These three lists are presented in Table 3.3. The table highlights three areas of research priority, proposed by the researcher, that have not been identified by the other two sources. These are:

- Governance and management
- Systems approaches to asset management
- Cultural and historical significance and value

The identification of these is partly due to the time that has elapsed since the other two studies were published and also due to the nature of the current study on the Clifton Suspension Bridge. In any study of the Clifton Suspension Bridge, the cultural and historical value of it cannot be detached. Also, in recent years, resilience has emerged as a key priority for infrastructure management and systems approaches have been proposed as a means to at least begin to understand this further. In addition, there appears to be more consideration of organisational management and governance for effective asset management, particularly since the release of the ISO 5500x series of asset management standards.

Table 3.3 also presents a fourth list, titled General Research Priority Areas. This combines the three lists to propose a standard list of current research priorities in infrastructure asset management, particularly relevant to bridges. What can be seen from table 3.3 is that fourteen distinct groups of research have been identified. This is a significant number of different topics to consider and could be overwhelming for the asset manager considering implementing asset management in their organisation.

Moon (Moon et al. 2009) proposes a framework of paradigms for asset management from recent research, as reproduced in Figure 3.1. Moon's work suggests that the real gap to be addressed is the integration and relationships between the different paradigms and groups that represent them. Interestingly, the different paradigms are grouped into technological, organisational and societal as this is not a subdivision of asset management approaches or research priorities that has been noted elsewhere. However, it does suggest a holistic approach to considering asset management and structuring the elements it comprises. These three layers of societal, organisational and technological can be applied to the research priorities identified in Table 3.3.

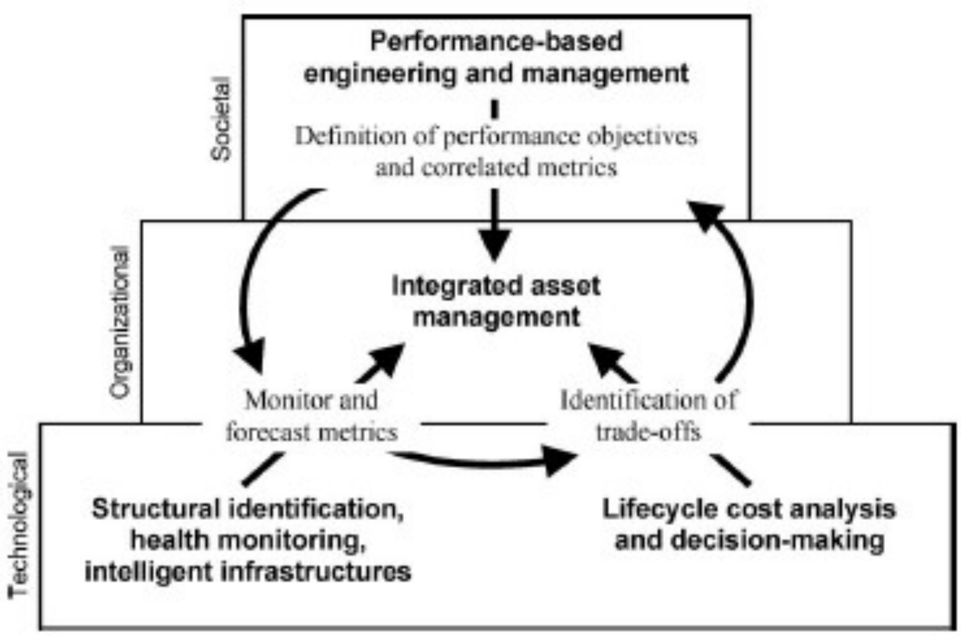

Figure 3.1: Integrated Asset Management and Related Paradigms

(Moon et al. 2009)

Table 3.3 Research Priorities in Infrastructure Asset Management

	General Research Priority Areas	Frangopol (Frangopol et al. 2012)	Schraven (Schraven et al. 2013)	The Researcher
Societal	Sustainability, resilience and robustness	Structural performance indicators: sustainability, redundancy, reliability, resilience, risk, robustness and vulnerability Extreme events: flood, earthquake and blast	Sustainability and infrastructure scores	Resilience and robustness
	Governance, strategy and leadership	-	-	Governance and management
	Cultural and historical asset value	-	-	Cultural and historical significance and value
Organisational	Performance service level monitoring and measurement	Structural performance indicators: sustainability, redundancy, reliability, resilience, risk, robustness and vulnerability Structural design, modelling, experiment and analysis	Performance measurement Structure inventory appraisal	Performance monitoring and service level
	Asset management issues, approaches and standards	-	Official guidelines for asset management and physical asset management	General asset management issues and approaches
	Asset and bridge management systems	-	Bridge management systems	Asset and bridge management systems
	Systems approaches to asset management	-	-	Systems approaches to asset management
	Risk and uncertainty management	Quantification of uncertainties: probabilistic modelling and analysis in: decision making, assessment of financial benefits, structural performance, life cycle management, flood estimation; sampling-based uncertainty quantification, decision making with uncertainty	-	Risk management and uncertainty
	Organisational knowledge and asset data	-	Knowledge in organisations, information and data quality Structure inventory appraisal	Data and knowledge, asset databases and GIS

Technological	Maintenance, replacement, rehabilitation, repair and inspection	Rehabilitation and strengthening	Maintenance decisions, optimisation, and genetic algorithms, for replacement, rehabilitation, repair and inspection Reliability and maintenance standards Traffic and maintenance effects	-
	Condition monitoring, deterioration prediction and modelling	Deterioration mechanisms: identification of deterioration from inspection and monitoring data, probabilistic deterioration modelling, corrosion, and fatigue Structural health monitoring (SHM): advances in techniques, damage identification and use of SHM data	Condition prediction for concrete bridges Statistical deterioration models and probability concepts	Condition monitoring, deterioration prediction and modelling
	Portfolio management and economic considerations	Quantification of uncertainties: probabilistic modelling and analysis in: decision making, assessment of financial benefits, structural performance, life cycle management, flood estimation; sampling-based uncertainty quantification, decision making with uncertainty	Portfolio selection, investment and pricing uncertainty	-
	Lifecycle analysis and management	Life cycle analysis: general frameworks, life cycle performance assessment and prediction, reliability, maintenance and repair strategies and cost analysis	Life cycle approach for bridges	Lifecycle management
	Decision making and prioritisation	Quantification of uncertainties: probabilistic modelling and analysis in: decision making, assessment of financial benefits, structural performance, life cycle management, flood estimation; sampling-based uncertainty quantification, decision making with uncertainty	Multicriteria decision making	Decision making and prioritisation

3.6 Gaps in the Literature

There is a lack of generally accepted semantics around infrastructure assets and asset management. There are many definitions, approaches and research priorities. There is a risk that if asset management remains poorly defined with no organising structure to link the different elements, the scope will continue to expand diluting the value and impact of work being carried out. For asset managers this could be a barrier to adopting and implementing novel approaches and could even hinder the effective application of any form of asset management.

There is no clear approach proposed for classification of asset management approaches or paradigms. Moon (Moon et al. 2009) makes an attempt, but this needs further work to become a useful guide for infrastructure asset managers.

While some of the literature reviewed contained practical applications and implementations of the research outcomes, there were no examples of larger scale studies taking a more holistic approach to asset management. No detailed case studies of an organisation's journey to implementing asset management were found. Lloyd presents a series of industrial case studies on the application of asset management. However, these were concerned with addressing a particular organisational problem through the improvement of asset management practices and are generally not detailed enough to be useful by themselves (Lloyd 2012). In addition, this series of case studies was published in 2012 and hence pre-dates the introduction of the ISO 5500x asset management standards.

It is felt that such an in-depth study could be beneficial in demonstrating the selection of an asset management approach for a particular organisation. While the standards set out the purpose of asset management (the why) and the requirements to be achieved (the what), they do not explain how the organisation should go about it. While there will never be one approach that works for all organisations, an illustrative example of the approach taken and decisions made could be beneficial. This work attempts to address these gaps through following the development and implementation of asset management for the CSBT.

4 Research Methodology

4.1 Introduction

The purpose of this Chapter is to give an overview of the research paradigm within which this research work was carried out. The specific methodologies employed in order to address the research questions identified are then discussed.

4.2 Research Formulation

The initially stated purpose of the work was to develop and implement an asset management system for the CSBT, which could also address the ongoing issues with data management. In order to form the research questions, two main sources were used in parallel: the CSBT itself and the literature review. Background information was gathered about the CSBT, including the reasons behind the trustees opening up their organisation to the researcher and the purpose of the research project. Information gleaned from many informal discussions with staff and trustees also fed into the development of the research questions. The literature review revealed the breadth and extent of research priorities within asset management. The research commenced before the launch of the ISO 5500x asset management series of standards and there was very little cohesion in definitions and approaches.

There was also a third influence in developing the research questions and this was the use of systems thinking principles to explore and structure the problem space. Rittel and Webber's proposes the concept of planning problems as wicked problems, along with ten distinguishing features of such problems (Rittel and Webber 1973). These ten features were later generalised by Conklin and reduced down to six for addressing areas other than planning (Conklin 2005). A number of these features are particularly relevant to this study and as such warrant a systems type approach to addressing.

1. The problem is not understood until after the formulation of a solution

At the outset of this work the problem was not fully understood and could not be understood until work commenced. It was an iterative process with the true requirements of an asset management system for the CSBT only becoming clear once the work was underway.

2. Wicked problems have no stopping rule

The requirements for this research were to enable the organisation to better manage its assets. It is unclear how much better is required and what better even means.

3. Solutions to wicked problems are not right or wrong

There are many different approaches that can be taken as evidenced by the wide variety of areas of research in asset management. The aim for this work is that a useful approach is found, that it has a positive impact on the organisation and that some of the findings may be useful more generally.

4. Every wicked problem is essentially novel and unique

Each infrastructure asset is different and so is each organisation responsible for managing infrastructure assets. There is no single approach to asset management that will suit every organisation, and this is reflected in the plethora of published research on implementations of asset management. This work attempts to address one specific case taking into account the specific features of its context.

5. Every solution to a wicked problem is a one-shot operation

Every time a solution is implemented, the wicked problem has been changed by it. As such, there is no opportunity to test out approaches. Any potential solutions need to be well developed and will involve stakeholder engagement to minimise potentially negative impacts on the organisation. This work largely focuses on providing the CSBT with the data to enable them to make decisions in collaboration with the appropriate experts.

6. Wicked problems have no given alternative solutions

There could be many different solutions to the problems this work is concerned with or there may be no solution, there is no definitive answer either way. It is down to the judgement of the researcher as to whether proposed solutions are valid or not and which should be implemented.

4.3 Research Questions

The purpose of the research work carried out is to investigate the specific issues encountered at the CSBT, from a systemic, holistic and interdisciplinary perspective to develop solutions to the real problems, not the perceived ones. The work has been structured around addressing the following questions:

1. What is asset management, particularly in the context of infrastructure provision?

The literature review has shown that there are many different definitions, standards and research priorities within asset management. There is a need to explore further what asset management actually means and to draw some general definitions and structures from the existing body of knowledge, before it can be then understood in the context of the CSBT. This work may also be beneficial to asset managers more generally.

2. Why does the CSBT want an asset management system?

From initial discussions and from the background information studied, there were clearly issues that needed to be addressed. There were a broad range of perceptions from the staff and trustees about what asset management is and what the organisation actually needed. It was felt that there was a real need to explore with the relevant people what the purpose of such a system would be, in the context of the overall CSBT organisational purpose.

3. Is asset management adequate to meet the needs of the CSBT and if so what are the key features and requirements of such a system?

Based on the outcomes of questions one and two, question three aims to explore whether asset management is aligned with the needs of the CSBT. If there is alignment, then what specifically would an asset management system look like in order to deliver on the benefits of asset management to address the challenges identified at the CSBT.

4. How does a systems thinking approach to asset management help meet the needs of the CSBT?

Finally, as stated, systems thinking principles have been influential in shaping the research. The aim is to utilise systems thinking principles throughout this research and evaluate whether they are beneficial for the CSBT in understanding, implementing and utilising asset management.

4.4 Research Paradigm

There are two main research paradigms, interpretivism and positivism (Collins and Hussey 2009). Positivism is typically used in natural science and relies on the perspective that reality is independent of the researcher, unaffected by the act of investigation. Positivism normally follows a deductive process of investigation and deals with quantitative data.

The interpretivist research paradigm rests on the assumption that social reality exists in our minds, that it is subjective and multiple. As a result, social reality is influenced by the act of investigating it. Undertaking research in this paradigm involves an inductive approach where patterns and theories are developed in order to understand phenomena (Saunders, Lewis and Thornhill 2008b). In inductive research, general inferences are induced from particular instances and theory is developed from the observation of empirical reality (Collis and Hussey 2009). The objective is to provide an interpretive understanding of social phenomena within a particular context. Interpretivism is associated with qualitative methods of analysis.

It can be more useful to consider these paradigms as on a continuum (Collis and Hussey 2009) and that the research may move somewhat between the two depending on the particular research question and element of work being carried out (Saunders et al. 2008b).

The interpretivist paradigm was selected as most appropriate for this study. The objective was to study a small-scale exemplar of the larger issues of infrastructure asset management, to understand what worked well and could be generalised to other organisations and contexts. The period of study took place over four years and was physically based within the organisation. Theories were developed from the data gathered in the given context. By joining such a small organisation, the researcher had an impact on the organisation itself and on the research carried out.

The features of an interpretivist approach, particularly relevant to this research, are as follows (Collis and Hussey 2009):

- Use of small samples
- Has a natural location
- Concerned with generating theories
- Produces rich, subjective, qualitative data
- Produces findings with low reliability but high validity
- Allows findings to be generalised from one setting to another similar setting

Primarily, an inductive approach has been taken, with the theories and frameworks being developed from the data gathered. However, there are also deductive elements where appropriate to test the theories developed. The methodologies used have been selected because they fit with the assumptions of the interpretivist research paradigm and also because they suit the nature of the research questions.

Systems thinking is concerned with seeing the whole, considering both hard and soft systems and identifying how they interact with their environment. Being able to reconcile stakeholders conflicting requirements and recognising individuals have different world views and mental models is crucial. This is all about the subjective and value laden nature of problems and sits well in the interpretivist paradigm.

4.5 Research Methodology

The main methodology employed in this research has been a case study of the Clifton Suspension Bridge Trust. Exploration of the issues around transport infrastructure management and ageing assets on a national scale, is too large a problem to be addressed in any detail given the time and resource constraints of this research. A case study is appropriate as it is a methodology used to explore a single phenomenon using a variety of methods to build up in-depth knowledge. The importance of the context and the phenomena in its natural setting is essential.

The case study methodology is used to explore a specific single phenomenon within its natural context, utilising multiple different sources of evidence (Saunders et al. 2008b, Collis and Hussey 2009, Yin 2009). The single case of the CSBT has been selected as the researcher is embedded within the organisation. It would be difficult to explore another case in the same level of detail, given the breadth and scope of the study and the available time and resources.

In addition, an ethnographic type approach has been taken. The researcher has been embedded within the organisation for over four years, working closely with the trustees, staff, consultants and volunteers there. The researcher has been carrying out work as part of the workforce in addition to the specific research outlined. The aim has been to gain a deep understanding of the organisational culture and values and identify how that shapes its activities.

4.6 Approach

Revisiting the research questions again and considering them in the context of the research paradigms and methodologies adopted for this work, Table 4.1 gives a summary of the approach taken, the methodology and the methods used. Figure 4.1 shows a chronological outline of the approach taken to addressing the research, which is influenced by Lewin's action research spiral (Lewin 1946).

Table 4.1 Research Questions and Approaches

Research Question	Relevant Chapters	Approach
1. What is asset management, particularly in the context of infrastructure provision?	Chapter 3: Literature Review Chapter 6: Asset Management Approaches and Organisational Archetypes	Inductive Theory building from literature review and ethnographic type approach
2. Why does the CSBT want an asset management system?	Chapter 4: CSBT Case Study Chapter 7: Exploration of Purpose	Inductive Theory building from case study of CSBT Semi structured interviews
3. Is asset management adequate to meet the needs of the CSBT and if so what are the key requirements of such a system?	Chapter 5: Systems Approaches to Asset Management Chapter 7: Exploration of Purpose	Inductive Theory building from case study of CSBT Semi structured interviews

4. How does a systems thinking approach to asset management help meet the needs of the CSBT?	Chapter 8: Systems Models of the CSBT Chapter 9: Organisational Interventions Chapter 10: Sustainability Assessment of the CSBT Chapter 11: Technical Projects	Inductive and deductive Application and extension of existing theory to the CSBT Case study of CSBT projects Survey of employees

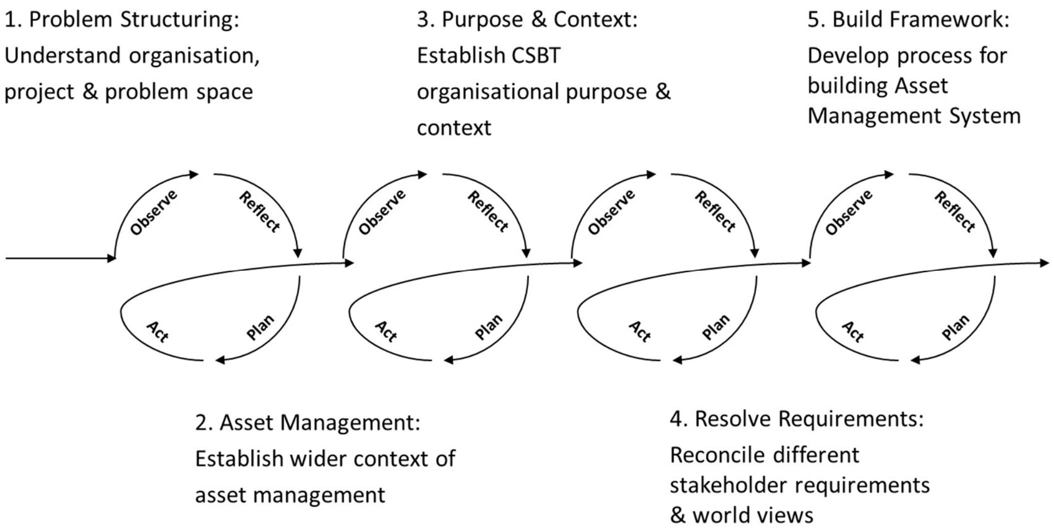

Figure 4.1: Research Approach

4.7 Ethical Issues

Ethical issues have been considered in the design and implementation of this research approach. Ethics refers to the appropriateness of the researcher's behaviour in relation to the rights of the people who are either the subject of the study or who are affected by it (Saunders et al. 2008b). The main ethical concerns in this work are related to anonymity and confidentiality, and informed consent. Informed consent has been addressed through the researcher being explicitly introduced to everyone within the organisation as a researcher and the broad topic of research being stated at the outset. This meant that everyone affected was aware of what was happening and if they did not wish to, they did not have to engage with the work being carried out. To ensure anonymity and confidentiality, the studies that sought out opinions and views of internal stakeholders were anonymised. In the case of the semi-structured interviews, participants were informed that the recordings and transcripts were for the researcher's use only and that data drawn out of these should not be able to be identified by anyone else. For the survey carried out, it was stated on the survey question sheet that responses were anonymous, there was no place for the respondents to put their name and they were to be returned in the provided envelopes.

One other relevant ethical consideration would be about how to report anything uncovered during the research that could bring the organisation into disrepute. One of the supervisors of this research was on the CSBT's board of trustees, one was an employee of the CSBT and one was independent of the organisation. It was felt that if such an issues arose then the supervisors would be able to provide support in negotiating the associated issues.

5 Systems Approaches to Asset Management for the CSBT

5.1 Overview

As outlined in Chapter 2, the CSBT expressed a desire for the implementation of asset management approaches and the introduction of an asset management system to improve their ability to classify risks, manage data, prioritise investment and look after the bridge. The organisation was concerned over whether it was adequately looking after its assets and in particular the management of its data and archives. The appropriate management of the assets is essential due to the governance models the organisation operates under, the risk appetite of Trustees responsible for the CSBT and the financial situation due to the private ownership and single income stream.

At the outset of this work, the CSBT had no formal asset management or other management systems in place. Annual inspection reports and structural risk assessments are carried out and documented, but the process and requirements themselves are not formalised.

The CSBT does not really know if it is a well performing organisation with well performing assets. There is a general feeling within the organisation that the bridge is well looked after and in good condition but there is little data on the performance of the service. In addition, this is an internal view and although complaints are typically recorded, external views are not normally solicited.

The Trust was looking for support in understanding what level of asset management was required and suitable for the organisation and what the current state of the art was. There was a need for a solution to the issues of data management, either as part of the asset management solution or separately. There were also some specific technical areas which the Trust was concerned about including the hanger fatigue and wind characterisation. The interest in these technical issues was two-fold. In addition to solving technical challenges for the Trust, this also afforded the opportunity to explore the process of addressing technical uncertainty.

As demonstrated in Chapter 3, there are many different definitions and research priorities within asset management. In an organisation where there is effectively an opportunity to start from the beginning, this offers an interesting case study and enables different approaches to be tested.

5.2 Systems Thinking and Systems Engineering

A system is a combination of interacting elements, organised to achieve one or more stated purposes (Haskins, Forsberg and Krueger 2007). Systems exhibit synergy which is when the overall result is greater than the sum of the individual elements. Systems exhibit emergent behaviour or properties which only occur as an output of the entire system. These emergent properties or behaviours can be intentional and beneficial but there may also be unexpected, unintended and detrimental consequences both for the system and its environment.

Systems thinking is both a way of viewing problem situations and an approach to tackling problem situations. Firstly, systems thinkers take the position that problem situations cannot be solved by reducing the system to its component parts (Checkland 1999). By applying a reductionist approach, the uniqueness and complexity of the system is lost (Edson 2008). Instead systems thinking is joined up thinking, where the detail of complex concepts and their interconnectivity are sought to be understood in the context of their greater environment (Senge 2006). Secondly, systems thinking is a process for working in problem situations, to bring about a positive change (Edson 2008). Systems thinking is about "getting the right information (what) to the right people (who) at the right time (when) for the right purpose (why) in the right form (where) and in the right way (how)" (Blockley 2010b). Systems thinking enables integration of people, process, purpose and performance (Godfrey 2010).

Systems engineering is a robust approach to achieving the successful realisation of systems. It is a common sense, logical, thorough approach that seeks to deliver on the shared understanding of purpose. "In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals" (Shishko and Chamberlain 1995).

Systems engineering is both multi-disciplinary and inter-disciplinary. Systems engineering considers both technical and business requirements with the goal of achieving the overall required performance (Haskins et al. 2007). Systems engineering approaches can apply to both hard systems and soft systems (those that include humans). Indeed it is argued that all hard systems exist within soft systems, for all hard systems have a purpose and exist in an environment that is defined by people. (Blockley and Godfrey 2000)

Systems engineers employ a number of techniques to enable the successful implementation of systems. These tools and techniques allow systems engineers to frame, understand, organise and manage complicated and complex situations. Some of the primary themes in systems engineering include:

- Identification of system purpose and performance
- Stakeholder engagement & management
- Identification of system, system elements and boundaries
- Requirement generation and management
- Ensuring a common worldview
- Holism, layers and hierarchy in process modelling
- System structuring and architecting
- Supported & evidence based decision making
- Uncertainty management
- Risk management

5.3 Systems Concepts in Infrastructure Asset Management

In infrastructure asset management there are many systems concepts used. Some are referred to explicitly whereas others simply embody the spirit of systems thinking. The similarity and commonality can be seen between the definitions of asset management and systems thinking. The Publicly Available Specification 55 (PAS55) for Asset Management gives the following attributes as key for asset management:

- Holistic
- Systematic
- Systemic Risk based
- Optimal
- Sustainable
- Integrated (British Standards Institution 2008)

All of these principles or attributes could equally be used in a description of systems engineering. It is proposed that a systems thinking approach may improve the current best practice in asset management. While asset management brings together useful tools such as risk and quality management, for them to be entirely successful there is a requirement to first establish a clear understanding of the system. It is argued that "[...] successful management of physical assets must consider not only the infrastructure, but also the wider system within which it is located. Only through 'systems thinking' can the performance of a complex asset be managed to meet the demand placed on it by its stakeholders" (Baker-Langman 2003). A number key parallels between asset management and systems engineering were found from the literature reviewed.

5.3.1 Stakeholder Engagement

Within both systems thinking and infrastructure asset management, there is a focus on stakeholder engagement and capturing their values and requirements. (Baker-Langman 2003), (Marashi 2006), (Hall et al. 2004). The aims of asset management include delivering on the purpose of the system and satisfying stakeholders. Stakeholder management and engagement is therefore an important part of asset management. To manage stakeholder expectations successfully and manage the asset itself, it is necessary to understand the system in question and moreover to ensure that there is common shared understanding amongst the concerned parties. Argumentation and discourse between stakeholders or within a team, can be used a means to developing a common view of the system as a process. (Marashi and Davis 2006)

5.3.2 System Modelling

A clear understanding of the system can be achieved by modelling the system in question. One approach to modelling of asset systems is to use hierarchical decomposition. The notion of hierarchical description of systems is fundamental to systems thinking and well established in practice for infrastructure management. (Marashi 2006)

Systems can be broken down into a series of interacting processes that can be organised in layers. The processes can then be connected in an appropriate way to reflect how the system achieves its purpose. These processes interact with one other to deliver success or to fulfil a role in a higher level process. They may also, in turn, be the result of lower level processes (Blockley et al. 2012). Reductionism is avoided by the careful exploration and capture of the interactions or connectivity between these processes.

Each of these processes can be considered to be a holon. The concept of holon was first introduced by Koestler in 1967 (Blockley 2010b, Koestler 1967) and describes the idea that everything is at once both a whole and a part. An example of this could be the Clifton Suspension Bridge, which can be considered to be a whole as it is an entire bridge. However, it is also a part of Bristol's transportation network, a part of Bristol's heritage and a part of Britain's Victorian engineering legacy. Within the bridge there are then many processes that together result in the successful operation of the bridge e.g. the toll collection system, the bridge deck etc. These processes, when viewed at a different level of granularity, could also be seen as wholes themselves.

Applying systems thinking, the whole or holon exhibits behaviours that are greater than or different to those of the parts. These emergent properties denote levels of hierarchy. Hierarchy fits with the idea of holons, where the wholes are built from parts which are themselves wholes at the next level down, and so on. (Marashi 2006)

Marashi states that creating a hierarchical process model of the system allows high level organisation objectives, mission statements and policy to be decomposed in increasing levels of detail to the sub-processes required to achieve the purpose. The process model should include soft and hard sub systems. The model should be structured in such a way that shows how the sub-processes interact with each other. In this context, process model refers to a hierarchically structured set of processes which are both wholes and parts (holons). Together these transform a 'purpose' to a 'purpose met'. (Marashi 2006)

5.3.3 Decision Support

"Civil infrastructure asset management decisions are a multi-disciplinary endeavour involving a complex set of technical, economic and environmental issues" (Hall et al. 2004). The most common approaches to asset decision making and bridge management are typically concerned with the optimisation of a single attribute, normally the reduction or minimisation of the life cycle costs (Lounis and Daigle 2012). There is also the added financial pressure of being required to use the available resources ever more efficiently. All of this means that asset managers face an increasingly difficult task when making decisions.

To enable decision making, analysis and evaluation of options can require organising and utilising large quantities of data. This data will take many forms including technical reports, expert judgements, numerical model results, perceptions and value judgements from the stakeholders (Hall et al. 2004). As modelling techniques and structural monitoring technologies advance, there is an ever growing quantity of data to be processed by decision makers. Decision makers need a method for bringing together different data types and levels of detail in a coherent structure, which enables all data to be used in decision making.

5.3.4 Uncertainty

There is also an increasing need to understand the impacts of uncertainty in this data. System modelling can be used to better understand the system and to help organise, and utilise the vast quantities of asset data generated, while understanding the uncertainties associated with them. Hierarchical process modelling combined with Italian flags can be used as a decision support tool to achieve this. Dealing with uncertainty in hierarchical models enables inclusion of both quantitative and qualitative data and enables propagation of performance to be evaluated.

Italian flags are based on interval probability. They give a visual indication of the dependability of the evidence for whether the process will be successful or not (Blockley and Godfrey 2000). Within the Italian flag the green area represents the amount of evidence in favour of the process being successful, the red area is the amount of evidence against the process being successful and the white area represents the uncertainty about the process performance either way. When used in a hierarchical process model, evidence can be propagated through from lower level processes up to higher levels. This can be particularly useful where evidence for a process is incomplete. This enables decisions to be made using all available data regardless of type or format and should highlight where there may be insufficient data to make an informed decision.

Systems concepts in asset management are seen as a way of doing things differently to how they have been done in the past. Systems thinking is a joined up, holistic, big picture view of the world. It is a means to formally incorporate the soft human aspects in the management of physical assets. Asset management using systems approaches will enable understanding of how the organisation achieves its purpose and what risks stand in its way.

5.4 Perceptions of Systems Thinking

Within academia, particularly at the University of Bristol, there has been a lot of work in development and application of systems thinking for civil engineering and infrastructure asset management (Blockley 2010b, Baker-Langman 2003, Marashi 2006). Much of the work carried out at Bristol is based on industrial case studies. Systems thinking is seen as a way of doing things differently and a means to formally evaluate hard systems within the context of soft systems in the management of physical assets. (Blockley and Godfrey 2000).

Within industry however, there can be diffidence or resistance towards what may be seen to be another management tool or strategy (Baker-Langman 2003). In the researcher’s experience some organisations introduce many initiatives to improve productivity, reduce costs, increase project delivery, improve employee engagement or to catalyse a culture change. This can result in initiative fatigue, particularly when they are not seen to be followed through or if the actual benefits achieved are never communicated back to the people at the front line.

The researcher has also noted that at the CSBT, while systems engineering is an unfamiliar term, many of the elements of systems thinking are recognised as potentially being beneficial, for example requirements capture and stakeholder management. In order to successfully implement systems concepts and convince people of their benefits, a performance focused approach will be required. If positive impacts of systems concepts can be demonstrated, then this will increase the awareness and interest within the organisation.

5.5 Systems Thinking at the CSBT

As stated, systems thinking is not an explicitly recognised concept at the CSBT and there is no formal implementation of asset management principles. However, the Trust wishes to develop an asset management strategy for the bridge, in order to help fulfil their mission statement.

The Clifton Suspension Bridge is a purposeful system. It is a man-made system that fulfils a purpose. This purpose, elicited from stakeholders, is twofold:

- To provide a safe crossing of the Avon Gorge between Clifton and Leigh Woods
- To be an icon for Bristol, recognisable as both culturally and historically significant

The focus on safety as the main feature of the crossing point, emerged from discussions with stakeholders and reflects the general focus on the condition of the bridge. It is interesting that features such as cost effectiveness or efficiency are not included as would be expected for other organisations.

If we consider again the proposed definition from Chapter 3:

Asset management is the holistic and systemic approach to the sustainable continued achievement of organisational purpose and delivery of outcomes to stakeholders. This is achieved through the coordinated and multidisciplinary management of all assets over their lifecycle.

Clearly, asset management has the potential to deliver value and enable achievement of the CSBT's purpose. This means that for the CSBT, asset management could enable safe passage across the bridge and also ensure and promote the bridge's status as an icon for Bristol. However, this implies a requirement to capture a measure of value based on the public's perception, awareness and affection for the bridge and their willingness to invest in it.

It is clear that the CSBT is not the only bridge or infrastructure asset that holds a purpose beyond the utility it was originally designed for. "Some of the most valued elements of worldwide cultural heritage are historic bridges" (Riveiro et al. 2011). This can be due to many reasons including the aesthetic qualities of the bridge, the geographical location, the story of the bridge itself or the story of the people involved with the bridge. Very little was found on infrastructure asset management that considered the purpose of an asset to be an icon. Sustainable development is a means of preserving cultural value as it includes preservation of the features, substance and appearance of a bridge. It also considers the relationship of the structure with its environment and surrounding landscape (Brühwiler 2012).

Within the CSBT, there is huge potential for the implementation of systems concepts. There are no systems concepts currently used and there is a desire to develop and implement an infrastructure asset management strategy. Initially, for the CSBT project, the most relevant concepts within infrastructure asset management are related to value, decision support, uncertainty, and performance measurement.

Due to the limited income that the bridge receives, and the increasing amount of maintenance and technical projects required, the Trust has to carefully prioritise the way it allocates its funds. The Trust believes that it is managing this to the best of its ability, however, it is always keen to challenge itself on best practice. Additionally, the Trust currently has no way to measure how successful it is in this.

5.6 Applications of Systems Approaches

Systems thinking approaches have been shown to have relevance and benefit to infrastructure asset management. This research aims to approach the problem space defined by the CSBT from a systems thinking perspective. The methods and frameworks developed are grounded in the existing body of knowledge and draw on recognised systems approaches and organisational and management science.

The issues are of wider interest as the UK has many infrastructure assets, some of which are also historically important, and there is insufficient money to adequately look after them all. There is a need and an interest to look at new & different ways of managing the infrastructure we already have and then to think about how we might enable provision of more infrastructure in future.

The intention throughout this work was to take a holistic and systemic approach to investigating alternative ways of thinking about infrastructure and to demonstrate the resulting benefits. The size and flexibility of the organisation has enabled novel approaches to conventional problems to be taken.

Systems thinking approaches have been applied throughout the period of research. There were a number of key themes from systems that were identified as useful and relevant. These are introduced briefly below and then covered in more detail in the proceeding Chapters. While specific to this context, these may have broader parallels for other asset managers.

5.6.1 Purpose & Problem Structuring

At the outset of the research, although the CSBT articulated that it felt it needed an asset management system, it was unclear exactly what the problem was and what the objectives of any interventions should be. The views expressed by the stakeholders within the organisation appeared to be based on individual's opinions and were not backed up with evidence.

Data and knowledge management is an issue for many organisations (especially those managing assets). Asset management is an extremely popular topic amongst civil infrastructure management due to the known challenges with ageing assets and limited funding and the fact that asset management claims to offer solutions to these issues. Approaches for asset management and knowledge management already exist but without clear definition on the intended purpose of such systems or detail about the problems encountered, any solution is unlikely to be successful. This led the researcher to question what the organisation and stakeholders needed, and why.

This is echoed by the guidance of the ISO 55000 series of standards for asset management (International Standards Organisation 2014), which suggests that the first step before developing an asset management system is to understand the organisation, its context and the stakeholders' needs and expectations. The actual elements of the asset management system can only be developed once this is clear as the asset management system should be a tool in enabling the organisation to achieve its purpose and satisfy its stakeholders.

To address this, a study was carried out with a sample of internal stakeholders, to investigate their views on a number of matters including the purpose of the organisation, why an asset management system was needed and what the key challenges are for the CSBT. This study and the outcomes from it are presented in Chapter 7.

5.6.2 Systems Modelling

Linked to problem structuring and exploration of purpose, a greater insight into problem situations and systems can be gained though modelling. In order to capture a snapshot of the CSBT organisation and understand the processes taking place, different approaches have been taken. The researcher, situated within the organisation, has developed both a Hierarchical Process Model (HPM) and a process map type model based on observations of the processes and interactions within the organisation.

The aim is that the process of capturing the models and the information contained within them should support the development of the asset management system. While the standards explain the requirements of an asset management system and give some guidance, they do not help an organisation actually implement asset management. They do not suggest any processes or methods that may be useful for capturing the current processes or identifying areas for improvement. By modelling the processes taking place within the organisation, it should highlight how the asset is currently managed and the gaps, risks and uncertainties that need to be addressed. The process of developing the models will also improve understanding of the system in question. The organisational models created are presented and discussed in Chapter 8.

5.7 Problems to be Addressed

5.7.1 Asset Management

While there are currently no explicit asset management processes in place at the CSBT, a risk management process has been developed in recent years, primarily focussed on the structural issues which could affect the integrity of the bridge. This aims to identify all potential hazards, evaluate the level of risk and support the prioritisation of the work required to mitigate the risks. The Trust has expressed a need for an asset management system to support them in a holistic approach to risk and decision support to enable them to achieve purpose. The aspiration is that an asset management system will encompass risk management and decision support and will cover both the physical and the intangible assets.

This area of work was approached in a number of different ways. Firstly, through an initial literature review of asset management (as presented in Chapter 3) it became clear that there were a number of definitions of asset management and many different approaches to implementation. There were a number of published guidelines from across civil engineering, construction, and infrastructure management. These have culminated in the publication of the ISO 55000 series of standards for Asset Management. For a small organisation, which has not yet adopted any formalised asset management, it can be overwhelming to understand the differences in definitions, approaches and systems. In order to start to address this, the researcher has looked at different means for classifying asset management to enable organisations to recognise what they need and what may be appropriate. This work is outlined in Chapter 6.

As part of the work into exploring the organisation's purpose and context (Chapter 7), the requirements for asset management were explored with the internal stakeholders. This study surfaced many requirements for an asset management system for the Trust and the reasons behind them. This study led to a number of outcomes for the Trust from an organisational perspective, including highlighting the need for the following:

- An organisational strategic plan
- A sustainability assessment

- An integrated management system

These are presented in more detail in Chapter 9.

In addition to more organisational work around asset management, there were two areas of technical asset management work that were also studied.

From a structural risk management perspective, a study was carried out into the interconnectedness in bridge components and systems. This applied a design structures matrix approach to the grouping of bridge components into subsystems.

The Trust had expressed a desire to test the spare bridge hangers after the failure of Leigh Woods North 3 hanger. The work carried out involved taking a systematic approach to the hangers overall, looking at the historical information available, the state of the art in wrought iron testing & material properties, information regarding previous hanger failures and the work that was carried out to investigate the cause of the recent failure. In addition, the purpose of testing the hangers was explored to try to determine what the uncertainties were and what the expected outcomes were. Both the structural risk assessment and hanger fatigue studies are presented in more detail in Chapter 11.

5.7.2 Data, Information & Knowledge

Data and archive management is a concern for the Trust as they own a large quantity of data in various locations and have a limited index. Work has been done to try to improve the accessibility and organisation of the information. Drawing on existing standards for data and archive management a data management policy for the Trust was created. This policy takes a holistic view on all data owned and generated by the organisation and considering a range of use-cases for that data. A detailed index of all archived data has been created to enable a range of people to find, access and use the information available. There are now up to date electronic records of all of the material and a regular review process will be implemented. This supports the Trust in its operational practices and audits but also aids with identifying the needs and expectations of data management. In addition to creating the detailed index, the review of the historical technical archives also enabled the researcher to gain an appreciation for the type of information contained within the archives and also the condition of them. This is important for the future use and sustainability of them.

The development and implementation of an integrated management system for the organisation was partly driven by the need to embed data management in the organisational processes of the Trust. Having such a system and processes in place would also help to start the process of capturing the implicit knowledge typically held in peoples' heads a turning it into formalised processes or archives that could be reviewed and improved over time. This work is presented in Chapter 9.

5.8 Conclusions

Infrastructure asset management has been introduced, as have the concepts of systems thinking and systems engineering. Systems approaches exist in infrastructure asset management, both explicitly and implicitly. Systems thinking and formal asset management strategies did not exist at the Clifton Suspension Bridge at the start of this period of research. The potential impact of the implementation of a systems approach to infrastructure asset management is significant for the Clifton Suspension Bridge and also for other historically or culturally significant infrastructures.

6 Asset Management Approaches and Organisational Archetypes

6.1 Introduction

As presented in Chapter 3, there are many definitions of assets and asset management and many different research areas within the field. This then makes it difficult for an asset manager to take a holistic view of the subject and understand which elements are most appropriate for their context. In addition, the asset manager needs to be able to understand their own organisation to identify how and where asset management could adopted.

A method for classification of the different approaches to asset management is developed and introduced. From an academic perspective, this fills a gap as there is currently no similar method for identifying and classifying asset management approaches. The industrial benefit is to enable organisations to identify where their approach sits relative to other approaches and evaluate whether it is the most appropriate for them given their purpose, context and organisational structure and culture. This section shall address the first research question.

A framework describing organisational archetypes has been developed, based on Maslow's hierarchy of needs and human motivation work (Maslow 1943, Maslow 1954). Maslow's work has been extended and applied to describe typical organisational processes, drawing parallels to the equivalent levels of human motivation. This is then used to consider which archetype the CSBT most commonly operates within and whether there is benefit in considering others, depending on the current context. Equally, this could benefit other organisations and represents a novel application of Maslow's work.

6.2 Classification Approach for Asset Management

By synthesising different approaches to and definitions of asset management, a simple classification methodology for asset management paradigms has been developed. Based on different examples of asset management approaches, thought was given to the characterisation of different types of asset management in different organisations. Even if accredited to ISO 55000 (International Standards Organisation 2014), asset management will look different in each organisation, so any classification relies on broad categories arguably reducing the use of the classification.

This approach distinguishes between two broad asset classifications and two broad models of responsibility of asset management within an organisation. It was felt useful and relevant to capture the apparent divide between whether organisations consider only hard physical traditional assets or whether they include all sources of value including intangibles. As shown in Chapter 3, in the various definitions of assets, this is not something that has been completely resolved although the move seems to be more towards treating everything of value as an asset. This distinction also draws on systems thinking concepts and the differences between hard systems, soft systems and the proposition that all hard systems sit within soft systems (Blockley and Godfrey 2000). In reality, an organisation may find that it does not completely fit in either box but somewhere in the middle. However, by having to determine where the organisation sits means that the asset manager has to explicitly think through what the approach currently is and whether this is where they want to be in future.

On the other axis, the classification is between how the asset management responsibilities are delegated within the organisation. One approach is to have a very functional approach, with a designated asset management function that holds all responsibility for assets and their management within the organisation. This includes ownership of all policies, systems and processes related to asset management. The alternative is that asset management principles and responsibility is embedded throughout the organisation. In this case, there may still be named asset managers and people for whom their full time job is still asset management. However, these people will be integrated with the rest of the organisation instead of sitting in a functional silo. In addition, and importantly, everyone in the organisation will be aware of asset management, what their responsibility is in contributing towards it and the importance of it to the organisation overall. Again, there may not be a simple answer to this question. An organisation could sit somewhere between these two approaches or be in the middle of a restructure with a plan to move one way or the other. As for the assets, what is important is the process of explicitly thinking through where the organisation currently sits and whether that is appropriate. Table 6.1 shows the overview of this classification approach.

Table 6.1: Classification of Asset Management

		Nature of the assets considered by organisation to be part of asset system	
		A hard systems view. Physical assets only e.g. plant, equipment etc.	A holistic, soft systems view. All organisational assets i.e. all sources of value e.g. people, knowledge, plant, equipment etc.
Who is responsible for asset management	Functional task, there is a manager and team assigned to asset management. Other departments / teams do not get involved.	**Functional Hard** Asset manager & team responsible for maintenance of factory machinery & reporting to senior management	**Functional Soft** Asset manager & team implementing policy throughout organisation & reporting into senior management
	Organisational undertaking, everyone is aware of their role in contributing to asset management outcomes.	**Organisational Hard** Entire organisation is aware of asset management for physical assets and the part they play individually.	**Organisational Soft** Entire organisation is aware of asset management principles and understands that all sources of value are assets to be looked after. They understand the part they play individually.

Using this classification approach there are then four main types of approach for an organisation. These are functional hard, functional soft, organisational hard and organisational soft. Functional hard is where the responsibility for asset management knowledge and activities remains within a dedicated team with a specific manager who reports into senior management. This team is responsible for asset management of the hard physical assets owned or managed by the organisation. An example would be a maintenance team who look after the machinery across an entire factory. The advantages of this approach are that there is a dedicated team to deal with these processes and there may well be good reporting of issues up through the management chain. However, in this case, any assets than are non-physical are being ignored. Due to the functional nature, there may be poor line of sight for people who sit outside of the asset management function in terms of understanding how the physical assets enable the organisation to achieve its overall purpose.

In functional soft asset management, the responsibility for asset management knowledge and activities also remains within dedicated team with specific manager who reports into senior management. This team is responsible for all manner of assets that the organisation has identified, including both hard and soft systems for example machinery, equipment, people, knowledge, and finance. An example would be a team responsible for implementing asset management policy throughout the organisation, most likely with people dedicated to different asset types. The advantage with this approach is that there is a dedicated team to deal with these processes and there may well be good reporting of issues up through the management chain. As the team is considering all types of assets, they are more likely to understand interactions between them. Additionally, all types of assets are being considered, which may offer benefits to the organisation. As for hard functional asset management, there may still be poor line of sight for people who sit outside of the asset management function in terms of understanding how the assets enable the organisation to achieve its overall purpose.

Organisational hard asset management is where responsibility for asset management knowledge and activities is dispersed throughout the organisation such that everyone is expected to have an understanding and to contribute. This approach is limited to the asset management of the hard physical assets owned or managed by the organisation. An example would be a physical asset intensive organisation that was set up in such a way that everyone is well aware of how their roles feed into the management of the assets. This might mean empowerment of individuals to carry out certain activities such as basic maintenance, data recording, and reporting of issues. It will certainly mean that all individuals understand the principles of asset management and how they apply to the physical assets and how those assets contribute to the performance and success of the overall organisation. This should result in more effective asset management of the physical assets as the activities simply become part of the day job.

Organisational soft asset management is where responsibility for asset management knowledge and activities is dispersed throughout the organisation such that everyone is expected to have an understanding and contribute. This approach is applied to all manner of assets that the organisation has identified, including both hard and soft systems, for example machinery, equipment, people, knowledge, and finance. An example would be where an organisation's structure, processes, and roles and responsibilities were set up entirely around asset management and all asset types are considered. This is likely to mean empowerment of individuals to carry out certain activities and it will certainly mean that all individuals understand the general principles of asset management as well as the specific processes implemented within the organisation. Individuals should have a good understanding of their place in the overall asset management system and how the organisation's assets enable the performance and success of the overall organisation. This approach extends the benefits of the organisational hard asset management approach to all assets that are managed by the organisation.

Classifying the CSBT according to this approach, at the outset of this work, it would sit within the functional hard sector. There is no specific asset management function or named asset manager within the CSBT. However, there are certain people within the organisation concerned with asset management and these are the trustees and the Bridgemaster. The rest of the organisation is unaware of anything explicitly related to asset management of the CSBT. The general view on the types of assets to be considered part of the asset system is that they should be hard assets only. There are a few different opinions amongst the trustees and Bridgemaster but the majority only consider the hard physical assets. There is a desire for the CSBT to move towards the organisational soft asset management approach. This better reflects the definition of assets given in the ISO 55000 asset management standard where an asset is defined as an "item, thing or entity that has potential or actual value to an organization" (International

Standards Organisation 2014). As the organisation is small (less than thirty employees) it does not have the resources to support a distinct asset management function. It will require a named person to be responsible overall for implementation of the principles of asset management (likely the Bridgemaster), but ultimately asset management activities will need to be shared amongst all employees.

This classification is generic and potentially of use to other infrastructure asset management organisations. As such it shall enable organisations to better understand their own approach to asset management in the context of the other approaches available. This should enable the organisation to make an explicit choice and select the most appropriate approach.

6.3 Organisational Archetypes

6.3.1 Background

Maslow's theory of human motivation (Maslow 1943) is a motivational scheme that considers a specific order and hierarchy in which human needs are satisfied. Maslow originally suggested that there were five levels, starting with the most basic and progressing to more complex needs as each of the more basic levels are sufficiently met. Maslow later proposed a sixth level (Koltko-Rivera 2006) at the very top, which is included in some reproductions and applications of his work. These motivation levels are summarised in Table 6.2 (Koltko-Rivera 2006)..

Table 6.2: Motivational Levels in Individuals

Motivational Level	**Description of Individual at this Level**
Physiological	Seeks food, sustenance, physical needs, basic necessities of life
Safety	Seeks law and order, security
Love	Seeks affiliation with a group
Esteem	Seeks recognition or achievement

Self-Actualisation	Seeks fulfilment of personal potential
Self-Transcendence	Seeks to further a cause beyond the self, experience communion beyond the boundaries of the self

6.3.2 Application of Hierarchy of Needs to Organisations

Understandably, this theory of motivation has been applied within management (Jerome 2013, Kaur 2013) and healthcare (Jackson et al. 2014, Zalenski and Raspa 2006). Outside of its original context, there are some other interesting applications. One of these is the Information Technology (IT) Value Hierarchy (Urwiler and Frolick 2008) where the model is used to structure the levels of IT requirements for organisations. This starts at the most basic level of infrastructure and connectivity needs and increases in complexity and sophistication with more innovative applications of IT. Another interesting application is in the context of Sustainable Data Infrastructure (SDI) development in developing nations (Yawson, Armah and Pappoe 2009). Yawson et al look to apply Maslow's theory to the motivations of governments rather than individuals. Parallels are drawn between Maslow's motivational levels and the equivalent needs of a nation. The justification for applying Maslow's work to governments rather than individuals is that governments are formed of groups of individuals. Yawson claims parallels between individuals and governments in relation to choice, rationality, decision-making and prioritisation (Yawson et al. 2009). Yawson's work draws on Hagerty's study on the development of nations over time (Hagerty 1999). Hagerty tests Maslow's Need Hierarchy as a framework for describing the need fulfilment of a nation.

Building on the work of Yawson and Hagerty, Maslow's hierarchy of needs framework has been applied to describe the operational processes and features of an organisation. An organisation is a collection of individuals working towards a common purpose and so its levels of needs could be seen to be analogous to the needs of an individual. In this case, each level describes an operational archetype within which the organisation may be operating. Depending on the world context within which the organisation currently exists, the operational archetype could be more or less suitable. Table 6.3 gives an overview of these archetypes and the following sections explore each in more detail. Process models have been created to illustrate a generic example of each archetype.

Table 6.3: Motivational Levels Applied to Organisations

Motivational Level (Individual)	Operational Archetype (Organisation)	Features for Organisations
Physiological	Survival	Cash flow, staff, customers, bridge, asset
Safety	Security and Planning	By laws, long term planning, USP, IP protection
Love	Affiliation	Sense of belonging, market, affiliation with professional bodies, affiliation with legislative groups, standardisation
Esteem	Recognition	Certification to an ISO management standard, external audit
Self-Actualisation	Fulfilment of Potential	(Basden and Klein) sense of purpose, future vision, measurement against achievement of performance, continuous improvement, audit
Self-Transcendence	Further a Cause	Community / social engagement

6.3.2.1 Survival Archetype

At the most fundamental level, the organisation is simply trying to survive. Survival means that the organisation is doing something (providing a product or a service) in order to generate income, enabling it to continue to provide the product or service. This may be driven by the need to keep people in jobs or to pay creditors. This could also be driven by extreme external factors such as natural disaster or war where there is a need to carry on providing a community with essential provisions, regardless of the disruption. The generation and collection of revenue enables the essential internal processes of the organisation to continue to enable this provision of goods or service. However, there is no review of whether the services or goods are in line with the purpose of the organisation or needs of the stakeholders. Potentially, the organisation could be doing anything to survive, notwithstanding its strengths, purpose or market position. This may be sufficient over the short term but could cause other unintended consequences over the longer term. The typical processes taking place within this archetype and the outcomes from those processes are shown in Figure 6.1. The processes are depicted in text and the arrows show the outcomes and where those outcomes feed into following processes.

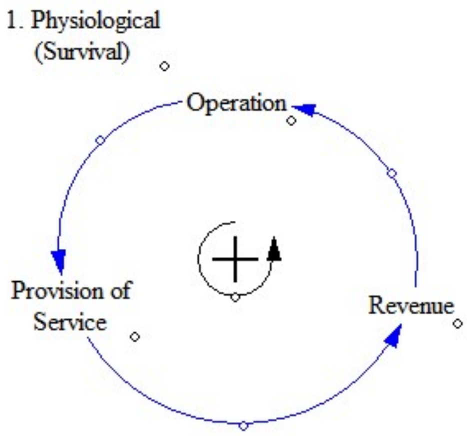

Figure 6.1: Survival Archetype

For survival, Table 6.4 describes each process that is taking place. An example of each process in relation to the CSBT is also given in addition to the typical outcomes.

Table 6.4: Survival Organisational Processes

Process	Description	Example	Outcome
Operation	Do something or create something that is desirable to someone else	Provide a useful service e.g. allow people to cross a river by bridge	Product or service
Operation to Provision of Service	Package up the product or service in such a way that someone can make use of it	Staff the bridge so that it is open, maintain the bridge	Enablers to exchange product or service for something desirable
Provision of Service	Point of provision of the product or service to the consumer or user	Provide access to the service e.g. commuters cross the bridge	Product or service received by consumer
Provision of Service to Revenue	Consumer or user exchanges the good or service they have received for something you need in return	Means of receiving payment in exchange for providing product or service, e.g. toll machines, toll collection	Desirable resource

Revenue	Income received in exchange for provision of service	Income is processed so that it can be used as an input to the operation e.g. toll money is counted and banked	Desirable resource in the appropriate format and place to enable further operation
Revenue to Operation	Use what you have gained from exchange to feedback into operation	Money to buy more input to the operation phase e.g. raw materials, human resource etc	Resource to continue providing service or producing product
Operation	Do something or create something that is desirable to someone else	Provide a useful service e.g. allow people to cross a river by bridge	Product or service

6.3.2.2 Security and Planning Archetype

The organisation continues to perform the same activities as required for survival. However, once the basic need for survival is satisfied, a new need emerges for safety and security. For the organisation, this will manifest in the need for longer term planning. This will typically include some financial planning for the future, resulting in a budget and investment. Decisions are made as to how much of the income will be spent on operation and how much is to be invested for the future.

Consideration is given as to how external regulation and legislation can provide security for the organisation. What this actually means will depend on the type of organisation and the environment that it operates within but could include the legal and regulatory requirements that need to be met if the organisation wishes to continue operating and may also include safeguards such as intellectual property protection. This provides security for the organisation through standards of best practice and ensuring that they are conforming to legal requirements. The typical processes taking place within this archetype and the outcomes from those processes are shown in Figure 6.2. The processes are depicted in text and the arrows show the outcomes and where those outcomes feed into following processes.

For safety and planning, Table 6.5 describes each process that is taking place. An example of each process in relation to the CSBT is also given in addition to the typical outcomes. For clarity, only the elements that are new for this archetype are shown in

Table 6.5. It can be assumed that all processes from the survival archetype are still continuing.

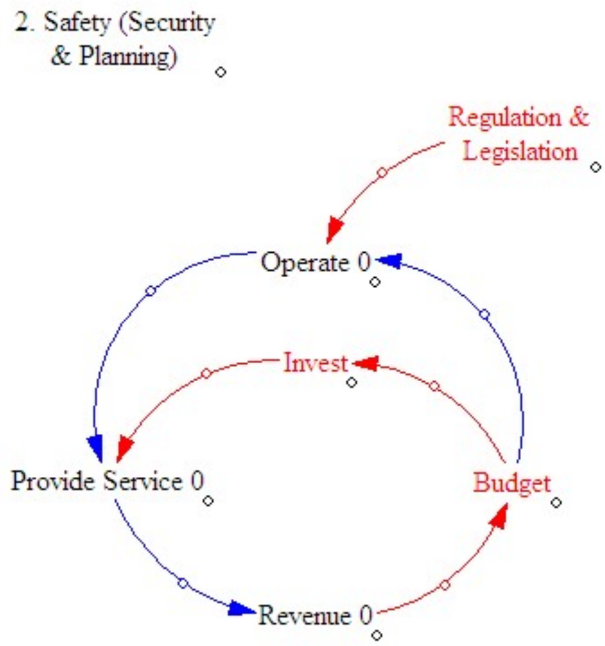

Figure 6.2: Safety and Planning Archetype

Table 6.5: Safety and Planning Organisational Processes

Process	**Description**	**Example**	**Outcome**
Revenue	Income received in exchange for provision of service	Income is processed so that it can be used as an input to the operation e.g. toll money is counted and banked	Desirable resource in the appropriate format and place to enable further operation
Revenue to Budget	Use the income received from exchange of service or product to drive decision making processes	Knowledge of how much resources are available and in what format is an input to budgeting decisions e.g. amount of toll money in the bank	Information on available resources
Budget	Decide what proportion of resources gained in exchange for product / service provided to use immediately	Budget allocation for available resources e.g. allocation of resources between continued	Clear resource allocation & plan

	to enable more operation and how much to save for later, take out as profit, dividend or use in some other way.	operation of bridge, longer term maintenance, and an emergency fund	
Budget to Invest	Process of transferring proportion of resources allocated by the budge to an investment of some type, for a given amount of time	Financial processes such as depositing allocated money in a reserve fund. Process of planning investment in physical or non-physical assets to expand capability, capacity or competency e.g. advertising for additional toll staff or planning to strengthen bridge deck	Process for transferring resource to selected means of investment
Invest	Allocated resource is somewhere where it is creating additional value	Allocated money invested in a fund gaining interest or process of procuring physical or non-physical assets to expand capability, capacity or competency e.g. new staff recruited or bridge deck strengthening complete	Realising the benefits of investment such as interest or additional capacity, capability or competency
Invest to Provision of Service	Process of feeding outcome of invested resource back into the provision of service or product	Newly strengthened bridge deck is open and operational and additional staff are in post. Interest from financial investment may be used to fund provision of product o service.	Continued or improved provision of service or product
Provision of Service	Point of provision of the product or service to the consumer or user	Sell good or provide access to the service e.g. commuters cross the bridge	Product or service received by consumer
Budget	Decide what proportion of resources gained in exchange for product / service provided to use immediately to enable more operation and how much to save for later, take out as profit, dividend or use in some other way.	Budget allocation for available resources e.g. allocation of resources between continued operation of bridge, longer term maintenance, and an emergency fund	Clear resource allocation & plan
Budget to Operation	Proportion of resources allocated by budget to feed into operation	Use allocated proportion of resources to continue operation e.g. pay existing staff salaries	Resource to continue providing service / producing product

Operation	Do something or create something that is desirable to someone else	Manufacture product e.g. car or provide a useful service e.g. allow people to cross a river by bridge	Product or service
Regulation & Legislation	Rules, standards, codes of practice, law etc. that impact on the organisation and its operations, both mandatory and optional	Compliance with H&S legislation is mandatory but as a result, there is some assurance of best practice and reduced risk to bridge staff and visitors	Processes that need to be followed, standards that need to be met, requirements and deliverables, security for the organisation as a result of complying
Regulation & Legislation to Operation	Implementation of standards, processes etc and compliance with requirements through operational activities & processes	Listed building consent applied for before works commence, operational processes in use that comply with H&S legislation	Reviewed & updated operational processes to ensure compliance
Operation	Do something or create something that is desirable to someone else	Manufacture product e.g. car or provide a useful service e.g. allow people to cross a river by bridge	Product or service

6.3.2.3 Affiliation Archetype

Once the organisations need for safety and security is sufficiently satisfied, a need for affiliation or belonging starts to emerge. The organisation will start to consider how it fits within the wider network and how its performance contributes to this. It may also begin to get actively involved in legislation and regulation, becoming a member of group of peers.

The organisation continues to perform the same activities and carry out the same processes as before but with the addition of network performance between provision of service and revenue, and the addition of connection from investment into regulation & legislation. The addition of network performance demonstrates the need the organisation has for belonging to a bigger group or family. In the case of infrastructure assets, the asset is considered in terms of how it contributes to the wider infrastructure network. For other organisations, this may involve recognising purpose, identifying allies and competitors and creating or joining alliances. The organisation may start to feed back into regulation and legislation through joining operators' forums or standardisation boards. The typical processes taking place within this archetype and the outcomes from those processes are shown in Figure 6.3. The processes are depicted in text and the arrows show the outcomes and where those outcomes feed into following processes.

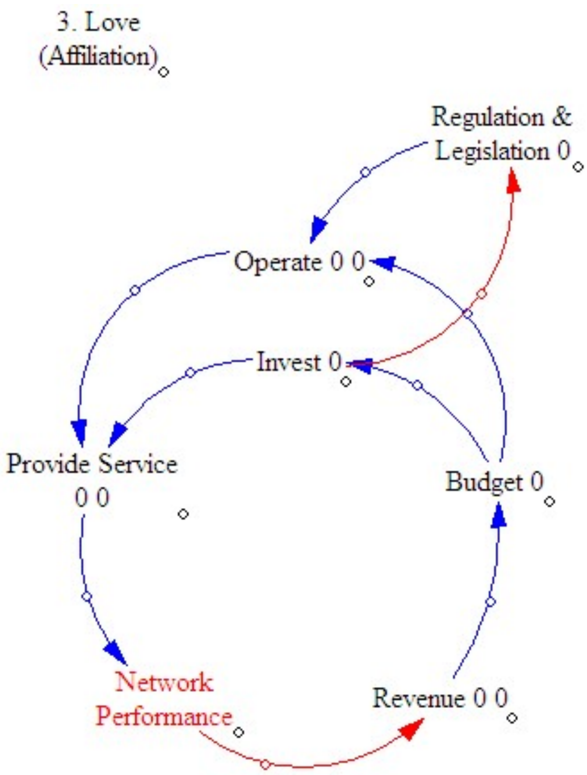

Figure 6.3: Affiliation Archetype

For the affiliation archetype, Table 6.6 describes each process that is taking place. An example of each process in relation to the CSBT is also given in addition to the typical outcomes. For clarity, only the elements that are new for the affiliation archetype are shown in Table 6.6. It can be assumed that all processes from survival, and safety and planning are still continuing.

Table 6.6: Affiliation Organisational Processes

Process	**Description**	**Example**	**Outcome**

Provision of Service	Point of provision of the product or service to the consumer or user	Sell good or provide access to the service e.g. commuters cross the bridge	Product or service received by consumer
Provision of Service to Network Performance	Gain feedback from customer about how well the provision of service or product has met their expectations / requirements	Quantity of crossings, customer satisfaction, cost, journey times etc	Indication of what is important to your customers
Network Performance	Measure of performance of wider network within which your organisation sits, performance of overall network linked to individual organisations' performance	Performance of Bristol's road network and contribution of CSBT to this	Overall network & individual organisation's performance targets and measures, membership of a network
Network Performance to Revenue	Consumer or user exchanges the good or service they have received for something you need in return. The better the organisation and network performs (against the customers' requirements), the more income will be generated.	Means of receiving payment in exchange for providing product or service, e.g. toll machines, toll collection. Better performing organisations & networks will generate more sales, resulting in higher income	Desirable resource
Revenue	Income received in exchange for provision of service	Income is processed so that it can be used as an input to the operation e.g. toll money is counted and banked	Desirable resource in the appropriate format and place to enable further operation
Invest	Allocated resource is somewhere where it is creating additional value	Allocated money invested in a fund gaining interest or process of procuring physical or non-physical assets to expand capability, capacity or competency e.g. new staff recruited or bridge deck strengthening complete	Realising the benefits of investment such as interest or additional capacity, capability or competency
Invest to Regulation & Legislation	Organisation invests resource in actively getting involved in regulation & legislation, helping to shape and define those standards & codes relevant to the particular industry / type of organisation	Employee of organisation sits on Eurocode committee, helping to shape future standards that organisation complies with, Bridgemaster sits on suspension bridge operators' forum to share experience & best practice	Input from organisation to development of regulation & legislation, recognition of the organisation being part of the wider (industrial) community
Regulation & Legislation	Rules, standards, codes of practice, law etc. that impact on the	Compliance with H&S legislation is mandatory but as a result, there is	Processes that need to be followed, standards

	organisation and its operations, both mandatory and optional	some assurance of best practice and reduced risk to bridge staff and visitors	that need to be met, requirements and deliverables, security for the organisation as a result of complying

6.3.2.4 Recognition

When the need for affiliation and belonging is sufficiently met, a need for recognition may then emerge. This means that the organisation will feel the need to be recognised for what it does or achieves. The organisation will want to be seen to be doing things well and so will start to look at how they are performing and what requirements they are measuring themselves against.

In terms of organisational processes, this will typically mean the addition of performance requirements and audit. Performance requirements are an input into the provision of service and enable the organisation to measure itself against targets. This can then be used to demonstrate to stakeholders how well the organisation is doing at whatever it is trying to achieve. An audit (or regular audits) may also be carried out on the organisation by an independent body to determine whether it meets self-defined standards or legal or regulatory requirements. This can then be used to demonstrate the performance of the organisation to the stakeholders. Other similar types of activities that the organisation may engage in include publishing papers in journals or at conferences or inviting external organisations in to benchmark their ways of working. The typical processes taking place within this archetype and the outcomes from those processes are shown in Figure 6.4. The processes are depicted in text and the arrows show the outcomes and where those outcomes feed into following processes.

For the recognition archetype, Table 6.7 describes each process that is taking place. An example of each process in relation to the CSBT is also given in addition to the typical outcomes. For clarity, only the processes that are new for this archetype are shown in Table 6.7. It can be assumed that all processes from survival, safety and planning, and affiliation are still continuing.

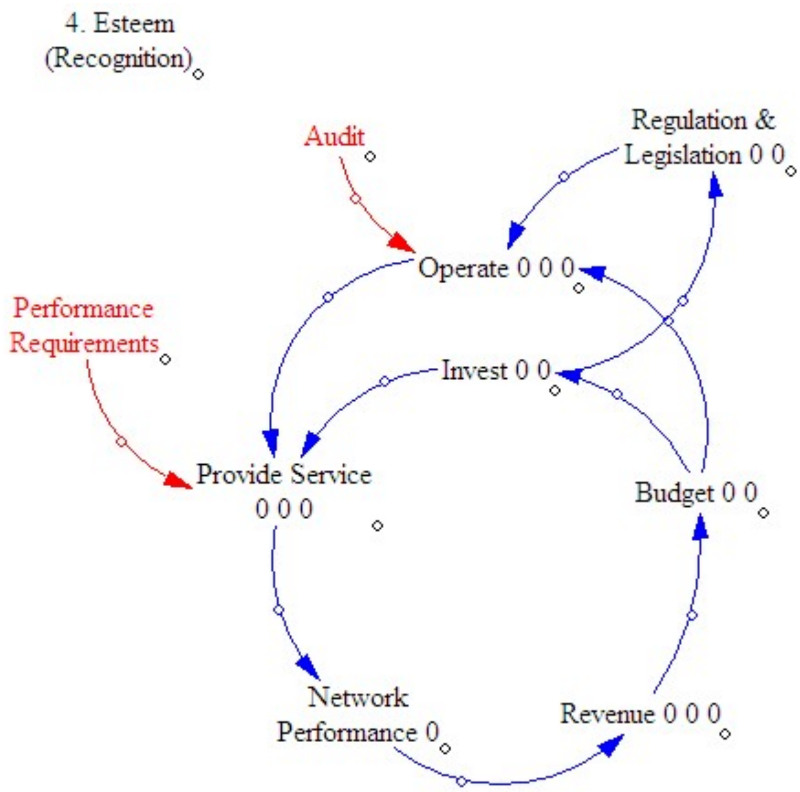

Figure 6.4: Recognition Archetype

Table 6.7: Recognition Organisational Processes

Process	Description	Example	Outcome
Audit	Organisation invites an external body to check compliance of their processes against some standard, enables organisation to demonstrate how well it is doing and get external feedback, some may be compulsory, but the purpose is to allow the organisation to demonstrate how well it is performing to its stakeholder group	Annual financial audit of CSBT accounts, safety audit of process compliance	Independent, objective assessment of performance against some criteria

Audit to Operation	Findings from the audit process will feed into how the organisation goes about its core activities	Suggestions for process improvements, areas where organisation is not following best practice or ability to demonstrate to stakeholders how well the organisation is doing	Use of independent assessment of performance to either improve operational processes or communicate success with stakeholders
Operation	Do something or create something that is desirable to someone else	Manufacture product e.g. car or provide a useful service e.g. allow people to cross a river by bridge	Product or service
Performance Requirements	Definition of what outcomes the organisation sets out to achieve and how it will know if it has achieved these	Reliability of service, production rates, rework rate	List of requirements & associated measures
Performance Requirements to Provision of Service	Implementation of performance requirements by using them to define performance measures to apply and use to measures and monitor achievement of requirements in the provision of service	Data on performance measures that inform on whether organisation is achieving requirements	Performance data
Provision of Service	Point of provision of the product or service to the consumer or user	Sell good or provide access to the service e.g. commuters cross the bridge	Product or service received by consumer

6.3.2.5 Fulfilment of Potential

Once the organisation has attained recognition, the organisation may then have an emerging need for self-actualisation or the fulfilment of potential. The organisation may feel the need for further growth or expansion. It will question and review its purpose, which will feed into the strategic planning, influencing the operation and budgeting. The organisation will also review its performance against the performance requirements to determine whether it is achieving what it is capable of. All of these additional processes are concerned with the organisation consciously reviewing what its purpose is, whether this is still appropriate and assessing whether it is achieving it. The typical processes taking place within this archetype and the outcomes from those processes are shown in

Figure 6.5. The processes are depicted in text and the arrows show the outcomes and where those outcomes feed into following processes.

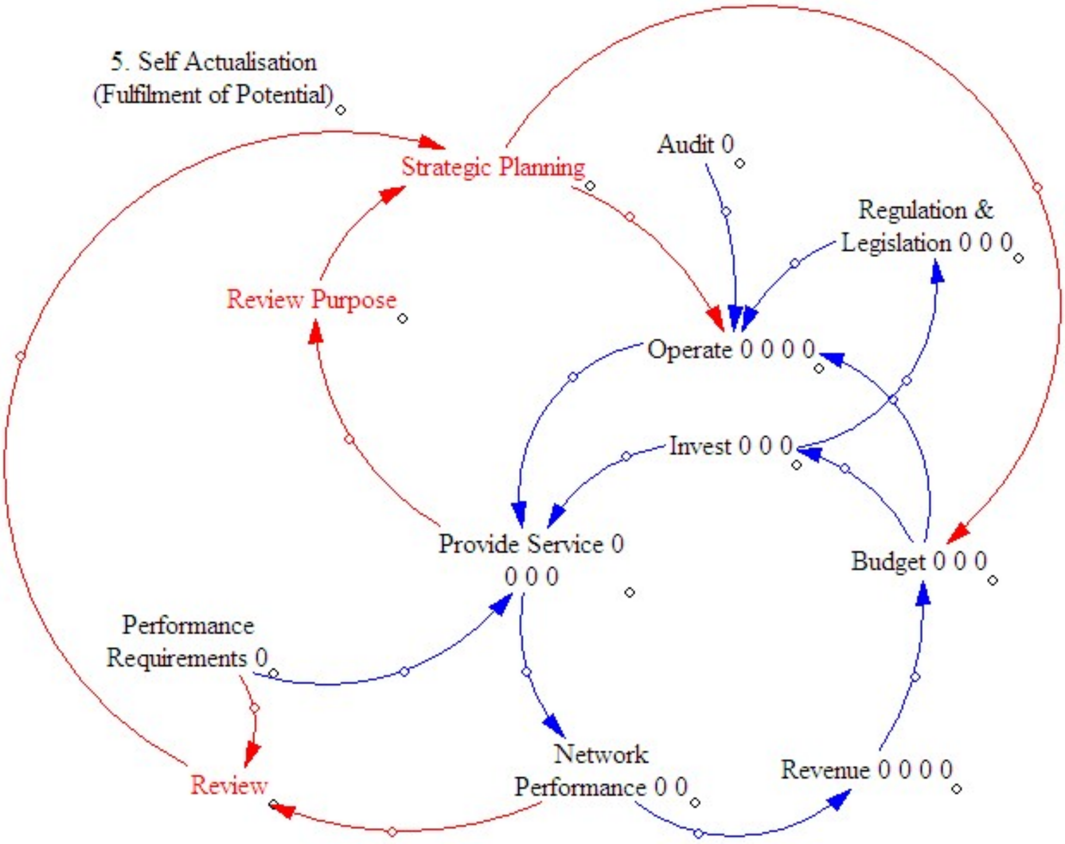

Figure 6.5: Fulfilment of Potential Mode Archetype

For the fulfilment of potential archetype, Table 6.8 describes each process that is taking place. An example of each process in relation to the CSBT is also given in addition to the typical outcomes. For clarity, only the processes that are new for the fulfilment of potential archetype are shown in Table 6.8. It can be assumed that all processes from survival, safety and planning, affiliation, and recognition are still continuing.

Table 6.8: Fulfilment of Potential Organisational Processes

Process	**Description**	**Example**	**Outcome**
Provision of Service	Point of provision of the product or service to the consumer or user	Sell good or provide access to the service e.g. commuters cross the bridge	Product or service received by consumer
Provision of Service to Review of Purpose	Input of data from provision of service enables organisation to carry out a review of its current purpose to determine if still appropriate	Sales, customer satisfaction, cost, journey times, customer feedback etc.	Data on provision of service to be reviewed
Review of Purpose	Organisation carries out a review of its fundamental purpose, and whether it is achieving it based on its provision of service or product	Review of whether provision of a crossing point for the Avon Gorge is still required and whether the service provided still meets stakeholders' expectations	Review of current purpose in environmental context & identification of miss-matches and gaps
Review of Purpose to Strategic Planning	Outcome of the review of purpose will feed into strategic planning, if purpose is no longer appropriate or not being achieved then strategic plans may be made to alter it	Purpose and outcomes are no longer in line with stakeholder requirements, need to address at strategic level to adapt to these changes	Data from the outcomes of review of purpose to be fed into strategic planning
Strategic Planning	Top level planning & decision making within organisation about future direction & purpose, balancing different stakeholders' requirements with the context of the organisation, including governance, long term financial planning, engagement with industry, government, local authority, strategy for R&D	Long term strategic plan for CSBT, including management structure, financial planning etc	Strategic plan for organisation, with supporting detailed plans to enable implementation
Strategic Planning to Operation	Implementation of strategic planning at operational level, implementation of strategic decisions, unpacked into more detailed specific actions for the day to day management and operation of the organisation	Long term strategic plan for CSBT broken down into maintenance plan which is then broken down into annual maintenance activities	Top level strategic plans translated into smaller, more specific plans to be implemented in everyday operational activities

Operation	Do something or create something that is desirable to someone else	Manufacture product e.g. car or provide a useful service e.g. allow people to cross a river by bridge	Product or service
Strategic Planning	Top level planning & decision making within organisation about future direction & purpose, balancing different stakeholders' requirements with the context of the organisation, including governance, long term financial planning, engagement with industry, government, local authority, strategy for R&D	Long term strategic plan for CSBT, including management structure, financial planning etc	Strategic plan for organisation, with supporting detailed plans to enable implementation
Strategic Planning to Budget	Implementation of strategic planning on financial planning processes, implementation & maintenance of strategic decisions, unpacked into more detailed specific actions for the day to day financial planning & management	Long term investment plan for CSBT	Top level strategic plans translated into smaller, more specific plans to be implemented in everyday financial activities
Budget	Decide what proportion of resources gained in exchange for product / service provided to use immediately to enable more operation and how much to save for later, take out as profit, dividend or use in some other way.	Budget allocation for available resources e.g. allocation of resources between continued operation of bridge, longer term maintenance, and an emergency fund	Clear resource allocation & plan
Network Performance	Measure of performance of wider network within which your organisation sits, performance of overall network linked to individual organisations' performance	Performance of Bristol's road network and contribution of CSBT to this	Overall network & individual organisation's performance targets and measures, membership of a network
Network Performance to Review	Network performance data is an input to the review process	Overall network's success at delivering on customer requirements and CSBT's contribution	Data on network performance

Review	Review of network performance against performance requirements, determine whether the organisation is achieving what it should be and whether this is still appropriate	Comparison of performance against requirements e.g. no of cars able to cross bridge per hour compared with requirement for crossings per hour or actual traffic volume in the context of Bristol's road network	Identification of gaps in performance or opportunities in network
Review to Strategic Planning	Data generated on gaps in performance or opportunities in the network are input to the strategic planning process	CSBT not meeting traffic volume targets due to toll equipment capacity, strategic planning needs to consider this and decide on options to address	Data on performance gaps and opportunities to be fed into strategic planning process
Strategic Planning	Top level planning & decision making within organisation about future direction & purpose, balancing different stakeholders' requirements with the context of the organisation, including governance, long term financial planning, engagement with industry, government, local authority, strategy for R&D	Long term strategic plan for CSBT, including management structure, financial planning etc	Strategic plan for organisation, with supporting detailed plans to enable implementation
Performance Requirements	Definition of what outcomes the organisation sets out to achieve and how it will know if it has achieved these	Reliability of service, production rates, rework rate	List of requirements & associated measures
Performance Requirements to Review	Performance requirements are input data to the review process to ascertain whether the organisation is meeting (or exceeding) its performance targets or falling short	Traffic flow requirements, product quality standards etc.	Data on requirements and associated measures
Review	Review of network performance against performance requirements, determine whether the organisation is achieving what it should be and whether this is still appropriate	Comparison of performance against requirements e.g. no of cars able to cross bridge per hour compared with requirement for crossings per hour or actual traffic volume in the context of Bristol's road network	Identification of gaps in performance or opportunities in network

6.3.2.6 Further a Cause Archetype

Once all other needs have been sufficiently satisfied, the need for furthering a cause may emerge. This is purely altruistic on the part of the organisation however it may result in some positive side effects, for example improving the public image of the organisation or raising its profile. Strategic planning will identify opportunities to carry out non-revenue generating activities that may have a positive impact on something or someone outside of the organisation. These activities will then be funded and supported by the organisation. The impact of these activities will be continually reviewed against the wider social, economic and environmental context to determine their appropriateness and efficacy. By this stage, the organisation's operation is stable, and it has at least partly satisfied all previous needs sufficiently. The typical processes taking place within this archetype and the outcomes from those processes are shown in Figure 6.6. The processes are depicted in text and the arrows show the outcomes and where those outcomes feed into following processes.

For the further a cause archetype, Table 6.9 describes each process that is taking place. An example of each process in relation to the CSBT is also given in addition to the typical outcomes. For clarity, only the elements that are new for this archetype are shown in Table 6.9. It can be assumed that all processes from survival, safety and planning, affiliation, recognition, and fulfilment of potential are still continuing.

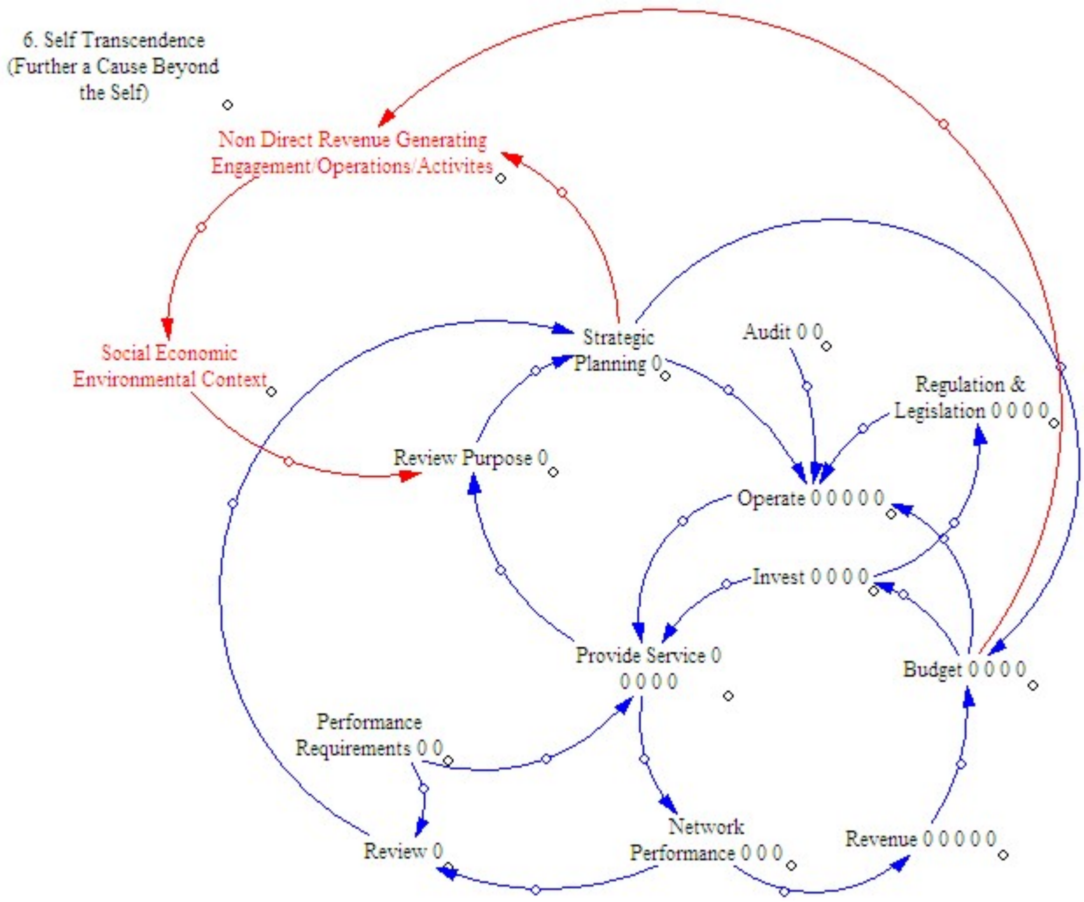

Figure 6.6: Further a Cause Archetype

Table 6.9: Further a Cause Organisational Processes

Process	**Description**	**Example**	**Outcome**
Strategic Planning	Top level planning & decision making within organisation about future direction & purpose, balancing different stakeholders' requirements with the context of the organisation, including governance, long term financial planning, engagement with industry, government, local authority, strategy for R&D	Long term strategic plan for CSBT, including management structure, financial planning etc	Strategic plan for organisation, with supporting detailed plans to enable implementation

Strategic Planning to Non-Direct Revenue Generating Activities	Outcome of strategic level decisions & planning results in decision to invest in some cause that does not return a financial (or otherwise) gain to the organisation	Organisation decides that it wants to engage with and support disadvantaged people in its community	Plan for implementation of non-revenue generating activities
Non-Direct Revenue Generating Activities	Philanthropic activities not core to the organisation in terms of operations & how it generates income, they primarily benefit people or groups external to the organisation, may be aligned to organisation's core values or related geographically	Funding community programmes, donating to charity, investment in kind, donation to charity, free bridge tours for the public, free access to the bridge visitor centre	Activities of benefit to others with no intended financial gain to the organisation
Non-Direct Revenue Generating Activities to Social Economic Environmental Context	Impact of these non-direct revenue generating activities on the social, economic & environmental landscape	Reduction in anti-social behaviour due to better community engagement and provision of free activities for young people	Measures of impact
Social Economic Environmental Context	Social, economic and environmental context within which the organisation exists, contributes to, and is affected by	Profile of context within which the CSBT operates and identification of opportunities to support that fit with the organisation's core values, etc	Definition of context within which the organisation exists, how this affects organisation and how organisation can impact on it
Social Economic Environmental Context to Review Purpose	Information on the social, economic and environmental context within which the organisation exists, contributes to and is affected by is input to review of organisation's purpose	Level of affluence, geographical setting etc	Definition of context within which the organisation exists, how this affects organisation and how organisation can impact on it as an input to the review of organisational purpose
Review of Purpose	Organisation carries out a review of its fundamental purpose, and whether it is achieving it based on its provision of service or product	Review of whether provision of a crossing point for the Avon Gorge is still required and whether the service provided still	Review of current purpose in environmental context & identification of miss-matches and gaps

		meets stakeholders' expectations	
Budget	Decide what proportion of resources gained in exchange for product / service provided to use immediately to enable more operation and how much to save for later, take out as profit, dividend or use in some other way.	Budget allocation for available resources e.g. allocation of resources between continued operation of bridge, longer term maintenance, and an emergency fund	Clear resource allocation & plan
Budget to Non-Direct Revenue Generating Activities	Budget allocation for activities that will not necessarily bring about any return on resource invested, altruistic investment in a cause the organisation believes in	Allocation of an amount of money for community project or allocation of resource to apply for external funding to resource	Resource to engage in non-direct revenue generating activities
Non-Direct Revenue Generating Activities	Philanthropic activities not core to the organisation in terms of operations & how it generates income, they primarily benefit people or groups external to the organisation, may be aligned to organisation's core values or related geographically	Funding community programmes, donating to charity, investment in kind, donation to charity, free bridge tours for the public, free access to the bridge visitor centre	Activities of benefit to others with no intended financial gain to the organisation

6.3.3 Implications for the CSBT

This hierarchy of needs model for organisational archetypes has been developed with the CSBT processes in mind although there will be parallels with other organisations. It is unlikely that an organisation always remains in any one of these levels. What is more likely is that organisations will move between several archetypes depending on the temporal context of the organisation and the current stakeholders' requirements. The usefulness of the model is that it provides an explicit framework to enable organisations to identify where they currently are. Once the organisation has a better idea of where it is, it can review whether it has the necessary support, controls and measures in place to enable the relevant processes. The organisation can also look at where it is on the hierarchy and consider whether this is the most appropriate archetype, given current circumstances and make appropriate plans for the future.

For the CSBT, the organisation is typically operating in the recognition mode. There is audit of the finances, annual inspection of the structure carried out by external consultant engineers and investors in people assessment of personnel management. There are also performance requirements such as maximising the time that the bridge is open and reducing congestion at busy times.

Occasionally, the CSBT may need to operate at a lower level for a period of time, due to particular circumstances. If there was a major incident or structural failure, such as the hanger failure discussed in Chapter 11, then the organisation may initially go into survival mode to simply keep the essential processes ticking over while it investigates what has happened. Then, as better understanding of the situation is gained and a plan is developed, the organisation will move back up the hierarchy.

There would also be value in the CSBT considering the two levels further up the hierarchy; fulfilment of potential and further a cause. At the fulfilment of potential level there is the introduction of reviews of purpose and performance, and strategic planning. This could be beneficial to the Trust but does not currently take place formally. Through the study carried out and documented in Chapter 7, the process of exploring organisational purpose was started with the interviewees. A means of carrying out a formal review of performance is required for the CSBT. This may be partially addressed through the implementation of an asset management system, particularly as the CSBT it is an asset intensive organisation. However, a better overall picture of performance would be gained if performance review was part of a top-level integrated management system. This operational level also highlights a need for a strategic plan to enable the organisation to act on the outcomes from a review of purpose and performance. The need for both an integrated management system and a strategic plan is discussed further in Chapter 9.

The highest level (further a cause) introduces the social, economic and environmental context with which the organisation interacts and the process of engaging in non-revenue generating activities. There is evidence of the CSBT engaging in non-revenue generating activities, particularly through the operation of the visitor centre and the associated engagement and outreach. In addition, the Trust is committed to ensuring that pedestrians have free and open access to the bridge. The Trust is a charity and as such operates differently to many asset management organisations. In addition, the Trust is required to provide for education and enjoyment through the (15 & 16 Geo. 6 & 1 Eliz. 2 1952, Elizabeth II 1980, Elizabeth II 1986). It could be beneficial for the CSBT to systematically consider the opportunities for non-revenue generating activities and formally review what it already does. Assessing this and then the impact on the environment within which the Trust exists will enable the organisation to prioritise the activities that will have significant positive impact.

6.4 Conclusions

Two novel frameworks have been developed and presented in this Chapter. The first for classifying approaches to asset management and the second for structuring understanding of organisational archetypes.

The simple asset management classification approach is generic could be of use generally to asset managers. It was developed to fill a gap as no simple classification tools were found in the literature review. It is interesting as it explicitly frames the distinction often drawn between hard and soft assets. It is a simplistic framework but has proved useful for understanding where the CSBT was and where it may aim to be. It could potentially have similar application in other organisations.

Within the field of asset management classification, however, there is the potential for development of a far more comprehensive approach that could be useful for both research communities and for asset managers in industry. This would better enable the organisation to make explicit choices about asset management and select the most appropriate approach.

The application of Maslow's hierarchy of human motivation to organisational processes has produced a series of organisational archetypes. This is a new application of Maslow's hierarchy and has resulted in a novel framework. These archetypes have been useful as a lens through which to view the CSBT. This can be used to better understand an organisation's current situation and can also be used to explore possible future scenarios to assess their potential implications on the organisational processes. Different archetypes may be more or less appropriate depending on the broader context at the time and there can be value in exploring other archetypes to determine whether they could offer benefit to the organisation. As this is a novel application of Maslow's framework, it could benefit from more applications to other asset management organisations to validate further.

7 Exploration of Purpose: Asset Management for the CSBT

7.1 Introduction

The CSBT board of Trustees raised the need for a systematic approach to the risk and performance management of the bridge. The belief was that this would then support the Trust in being better able to prioritise the risks it faces, select appropriate actions and allocate funding to address the risks and safeguard the future of the bridge.

To explore the problem space further, the researcher engaged in both informal and formal dialogue with the Trustees. Initially, the problem areas expressed by the stakeholders were risk, data, performance and asset management. This is evident in the following quotes taken from informal correspondence with several Trustees:

- "[…] the need for a systemic approach to the risk and performance management of the bridge."
- "I would like to have an Asset Management System that enables fast and easy to use access to all data on the bridge and the rest of our building portfolio."
- "From a Trustee perspective I guess I would feel reassured that we were capturing all our learning and that we were not missing something because a piece of useful but old data had been lost."
- "One of the starting points [...] was the recognition that the UK infrastructure [...] depends on ageing, and often neglected, assets and the idea was to use the bridge as a test house for the development of asset management systems to prolong their life economically."

Reflecting on these expressed needs of the stakeholders, they do not clearly convey what the actual problems facing the organisation are. The stakeholders have instead focused on what they believe the solution to be. Therefore, the actual problem situation and the purpose of an asset management system for the CSBT needs to be explored further, in order to better understand the stakeholders' requirements and expectations. The need for determining the purpose of an asset management system and exploration of stakeholder requirements also is a fundamental first step in implementation of the ISO 55000 Asset Management standard.

7.2 ISO 55000 Asset Management Standard

The ISO 55000 family of standards were published in January 2014 and are largely based on the Publicly Available Specification PAS 55 for asset management, which has been widely adopted internationally (Woodhouse 2014). This set of standards represents a holistic approach to asset management that is not limited to purely physical assets but also considers management of people, information, and finances (Woodhouse 2014). The ISO 55000 standards define asset management as the “co-ordinated activity of an organisation to realise value from assets” (International Standards Organisation 2014). Additionally, this standard recognises that asset management involves “the balancing of costs, opportunities and risks against the desired performance of assets, to achieve the organizational objectives” (International Standards Organisation 2014).

As the ISO 55000 series is the most recent standard for asset management and based on the extensively adopted PAS 55 predecessor, this standard may be considered as the state of the art. The ISO 55000 series has been taken as a starting point for exploration of the process of developing an asset management system for the CSBT.

The standard describes the elements of an asset management system and the relationship between them, including the strategic asset management plan, asset management policy, asset management objectives, asset management plans, performance evaluation and improvements, as shown in Figure 7.1. It also shows that outside of the asset management system but feeding directly into it are the stakeholder and organisation context, organisational plans and organisational objectives (International Standards Organisation 2014) as highlighted in Figure 7.2.

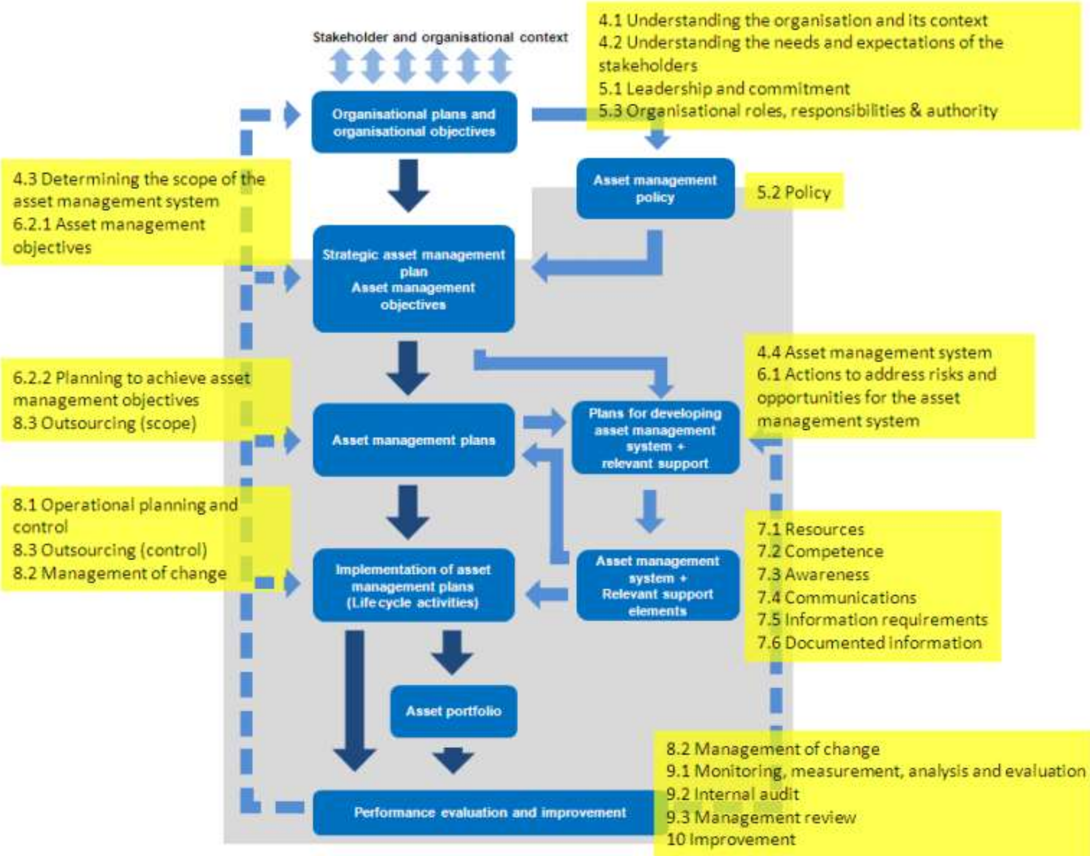

Figure 7.1 Relationship Between Key Elements of an Asset Management System (International Standards Organisation 2014)

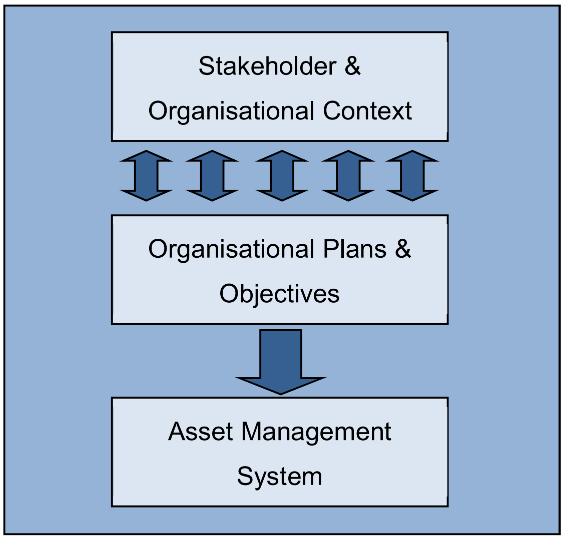

Figure 7.2: Prerequisites for an Asset Management System

This can be considered a top down approach to managing assets, in order to achieve organisational purpose. In the development of an asset management system for the CSBT, according to this standard, it is important to first understand what the purpose of the organisation is and the environment it operates within, along with identifying the stakeholders and considering their perspectives. The standard states that:

“When establishing or reviewing its asset management system, an organization should take into account its internal and external contexts. The external context includes the social, cultural, economic and physical environments, as well as regulatory, financial and other constraints. The internal context includes organizational culture and environment, as well as the mission, vision and values of the organization. Stakeholder inputs, concerns and expectations are also part of the context of the organization.” (International Standards Organisation 2014)

The standard gives some detail on what needs to be considered when trying to understand the organisation and its context. It also notes the importance of capturing stakeholders’ expectations and the importance of using that information in the asset management process. What is not included, understandably, is guidance on how to actually go about capturing this information and then how to present it in such a way that allows it to be used as an input to the asset management system design.

In the published literature on implementation of asset management, most material is related to IT applications (Gharaibeh, Darter and Uzarski 1999), modelling (Campos and Márquez 2011), decision support tools (Banyard and Bostock 1998), and lifecycle maintenance and condition monitoring (Malano, Chien and Turral 1999). There is, however, a move towards looking at organisational factors (Slootweg and Clemens 2007) and identifying what is required for success in asset intensive organisations (Murphy 2010).

7.3 Data Capture

In applying the guidance of the ISO 55000 standard, the first step before developing an asset management system was to understand the organisation and its context and the stakeholders’ needs and expectations. Many elements of the context could be determined from CSBT organisational documentation, including the Acts of Parliament, various reports, minute books, and documented procedures. What was not recorded however was the stakeholders' perspective on the organisational context and purpose.

A sample of internal stakeholders were selected to be interviewed, to investigate their needs and expectations and to capture information on the context and purpose of the organisation overall. A sample of Trustees (69%) were interviewed along with the Bridgemaster, who is effectively the managing director of the CSBT. An audio recording of all interviews was produced and then transcribed.

As the CSBT is a small organisation, it was considered practical to carry out an in depth study, capturing qualitative data. The views were captured through semi structured interviews. An inductive approach was taken to avoid constraints due to adopting a theoretical position (Saunders, Lewis and Thornhill 2008a). All respondents were allowed to answer freely to the same set of general questions, so that the data could then be analysed to identify themes.

The scope of the interview was intentionally designed to be broad. This was partly because access to the Trustees was not readily available and the intention was to collect as much data as possible as it may also be useful beyond the immediate study. By keeping the interview subject and questions broad, this enabled the interviewees to go into detail where they thought appropriate. The following questions were selected to guide the interviews:

- Do you feel that the CSBT's mission statement is adequate for the organisation?
- What is the organisational strategic plan/policy? (Can you comment on its appropriateness?)
- What would you consider to be the assets of the CSBT?
- What is your interpretation of an asset management system?
- Why do you feel that an asset management system is required?
- How do you see an asset management system fitting with other management systems?
- What should be considered in scope and out of scope?

- What are appropriate goals for an asset management system for the CSBT?
- What do you see as the CSBT's main challenges currently and in the future?

The transcripts of all of the interviews have been stored in the data repository Figshare under the project name "A systems approach to asset management for the Clifton Suspension Bridge Trust".

7.4 Analysis

7.4.1 Qualitative Data

A large amount of qualitative data was captured and required analysis. One strength of qualitative data is that it allows "illumination of the particulars of human experience in the context of a common phenomenon" (Ayres, Kavanaugh and Knafl 2003). Additionally, it allows development of theory closely related to the observed situation and therefore this theory may be more understandable and accessible for the people involved (Turner 1981). However, it can be difficult for the researcher to extract meaning due to the nature and quantity of the data. This needs to be handled carefully otherwise, at best, only an impressionistic view of meaning will be possible (Saunders et al. 2008a). Also, there is always a concern around bias due to the researcher deciding on which of the many interpretations to assign value (Wheeldon and Faubert 2009).

There is generally accepted to be a dearth of instruction in methods for qualitative data analysis (Collis and Hussey 2009). There does not exist an established and accepted praxis for the analysis of qualitative data in the same way as for quantitative data.

7.4.2 Coding

Due to the large quantity of data captured coupled with a desire to include as much of it as possible, an open coding approach was first taken. Each transcript was reviewed, and the raw data was analysed. Every concept or phrase that was felt to be significant in the context of the question asked or in relation to the purpose of the organisation was highlighted. These were then summarised for each question and for each respondent to capture the key concepts outlined in the interviewee's response. The coded data from all interviewees was then combined per question, such that all responses from all interviewees to question one were grouped together. The same was carried out for the remaining eight questions. Once combined, the data was then reviewed again and grouped into further themes.

Due to the quantity of data generated, the overall grouping of data by question has been maintained. However, it can be seen that there are themes that cut across several questions' responses. The themes have been summarised for each question and are presented in the following sections.

The analysis of the data from the interviews has been stored in the data repository Figshare under the project name "A systems approach to asset management for the Clifton Suspension Bridge Trust".

7.5 Presentation of Data

7.5.1 Mission Statement

The Trust's mission statement is explicitly documented and displayed throughout the offices and various workspaces. It is the main example of where the Trust's purpose has been captured and communicated to the staff and volunteers of the CSBT. The first question for the interviewees was whether they felt that the mission statement was adequate and appropriate for the organisation.

There was broad agreement from all interviewees that the mission statement was fit for purpose and captured the essence of the Trust. In terms of potential improvements, it was noted that some of the words, for example utility and perpetuity, may not have general appeal and could be seen as somewhat old fashioned. It was also noted that there needs to be an explicit reference to the Trust's purpose to provide learning and educational opportunities. There was also a comment that the purpose of providing a crossing point was not explicit enough and should be more explicit as this is how the Trust generates revenue.

The majority of the interviewees talked explicitly about the Trust's purpose. The consensus was that the Trust has a dual purpose. Firstly, they must keep the bridge well maintained and operational. Secondly, they must ensure that they provide for the enjoyment and education of visitors and the public. Although nobody openly gave more weight to either part of the purpose, most interviewees stated the maintenance, preservation and operation of the bridge first when talking about purpose.

The context of both the Trust and the mission statement was discussed. It was noted that a mission statement always needs to be considered in the current context. When circumstances change, it may need to be updated to remain meaningful. One example of this is that the bridge was originally designed before the dawn of motor vehicles but today around 3.5 million cars cross it annually. The purpose of the Trust needs to reflect the context of the bridge within Bristol and beyond. The connection to Brunel is important both technically and historically. The bridge is a cultural and historical icon for the city and a major tourist destination.

It was noted that the duties and responsibilities of the Trust and Trustees are set out in the Acts of Parliament. Two interviewees stated that the mission statement should be extracted from the Acts and we should be able to cross-reference back to that governing document.

Several Trustees specifically talked about what they felt the responsibilities of the Trust should be. In addition to preservation of the bridge, this included a proactive approach to interacting with the public to encourage their engagement with the bridge and to promote Brunel and his achievements.

The bridge is also a grade 1 listed structure and it was mentioned that the mission should reflect the requirements of this in relation to preservation. It was felt by one interviewee that regardless of the listed status the Trustees would never want to alter, change or replace any part of the bridge, beyond what was required for general maintenance.

One word from the mission statement that was singled out by several interviewees was ‘perpetuity’. It was noted that this is an interesting concept, to try to maintain something forever. While it is potentially possible to maintain in perpetuity, as long as replacement and long-term maintenance is carried out, continued income is necessary to enable this. It was also pointed out that the concept of perpetuity is “offensive in law”.

Another phrase that was singled out by one interviewee was “highest possible standards”. It does not specify what standards the mission statement is referring to or what “highest possible" means in the context of the Trust and bridge. This raised the question of whether this is constrained by or linked to resource. If the Trust had infinite resources would it be better maintained and if there was less money available what would the maximum achievable standard be.

Several interviewees discussed mission statements in general and what their purpose was for the Trust. The Trust's mission statement was created in the late 2000's as part of the activity around preparing for the Investors in People review. One interviewee felt that it was useful both externally to promote what the Trust is about and also internally to communicate to the employees what they should be doing and why. It was noted by one interviewee that the mission statement could be useful in situations such as the toll increase enquiry. In situations such as this, a simple statement about the Trust's purpose could be useful in helping to justify the need for the toll increase to the public.

There were also general comments about attitudes towards mission statements. There was some scepticism around mission statements and whether they are useful, engaging, or meaningful. There was a sense that they are somewhat old fashioned and that they can be created by committee and become unworkable.

7.5.2 Organisational Strategic Plan

The interviewees were asked about what the Trust's organisational strategic plan was and whether it was appropriate for the organisation and its aims.

None of the interviewees had any knowledge of a formally documented organisational strategic plan for the CSBT. There is nothing that captures the Trust's strategy and how it plans to meet the objectives of the mission statement. Several interviewees, however, feel that something akin to a strategic plan probably exists tacitly or within other documents. In fact, the tacit strategic plan could exist in the discourse that takes place at committee and full board meetings. It could also be captured in a combination of the Acts of Parliament, the papers and minutes of the Trustee meetings, the 5 year rolling maintenance plan and the annual risk assessment review.

There were comments on whether there should be a more explicit strategic plan for the organisation. Some interviewees felt that it could be beneficial in terms of capturing broad objectives for the next five to ten years and ensuring work is carried out to the highest possible standard. Such plans can be used to capture a common organisational purpose and the activities required to achieve it. Comments around what could be contained within such a plan included the necessity to charge enough money to operate, maintain, repair and renew the bridge with a reserve fund for unexpected catastrophic events, and the development of a heritage and learning centre.

Conversely, some interviewees were more sceptical about such a plan. One stated that the strategy was probably built in through the technical committee's activities. Another felt that the Trust was not unusual in not having a plan and that creating one would be for the sake of having a plan rather than it being useful.

There was reference again to the Trust's purpose, both to maintain in perpetuity and to develop the learning opportunities and visitor experience. Several interviewees then discussed how the purpose is linked to planning for the future. This included the visitor centre, how the requirement for one was included in the 1986 Act of Parliament and the Trust's commitment towards utilising it to engage more with a younger audience. One interviewee also mentioned the plan to replace the Clifton tollhouses which, although delayed, had been captured and agreed to. It was felt by a couple of interviewees that health and safety concerns will increasingly require attention and planning for this in the future will become necessary.

In responding to the question about an organisational strategic plan, five interviewees talked about finance and budgets. It was noted by one interviewee that there is much better control over spending and budgets now than there was in the past. The Trustees have a duty of care to protect charity funds and ensure that they are used appropriately. One interviewee explicitly stated that they felt the Trust needed to remain aware of its financial operations and that funds can only be raised through the Trust's own activities. These funds are essential to achieving the Trust's objectives. The reserve fund is seen as an important part of this so that if some unexpected event occurred there would be sufficient funds available to address it. Another Trustee stated that they felt the Trust was adequately funded, particularly in comparison to local authority managed infrastructure which is subject to budget cuts and spending constraints.

One interviewee talked about risk in relation to strategic planning. This interviewee felt that risk management and the risk appetite of the Trust going forward was an issue. They felt that it was difficult to find the right balance of risk due to the Trustees' duty of care and responsibility. The organisation is relatively conservative. In addition, when using consultants and external experts there is a risk of ending up with additional conservatism as they will also protect themselves from liability. This was also linked to the availability of new technology for investigation and analysis. If the Trust was advised by an expert to employ some new technique, it would be difficult for them to refuse but could ultimately become a drain on the Trust's resources.

The Trustee selection and induction processes were discussed by many of the interviewees. It was generally noted that there is no formal induction process for new Trustees. Generally, induction consists of lunch with the Chairman and possibly some other Trustees to find out a bit about the role. Then different Trustees had different approaches to getting familiar with the CSBT, including observation at committee and board meetings, asking questions, reading previous reports and papers and reading the Acts of Parliament. There were a couple of interviewees who felt that the induction process could be improved by being formally documented, making it quicker for new people to get up to speed. In addition, it could be useful for current Trustees to go through the process of documenting it. One interviewee talked about how important it is for the Trust to continue to select Trustees who are both appropriately qualified and who will maintain the high principles of the organisation.

7.5.3 CSBT's Assets

All interviewees were asked what they considered the assets of the CSBT to be. It was noted from literature that there are a range of definitions of the term asset and there was nothing that formally captured what the assets of the CSBT were considered to be. Only by identifying and understanding the range and type of assets owned by the Trust would it then be possible to develop an asset management system to suit.

All interviewees responded to this question with a range of opinions on what the Trust's assets were. They all talked about the physical assets of the Trust and these included the bridge structure, the land, all property including the visitor centre and maintenance yard, and the equipment. One interviewee felt that the bridge was the only asset and that everything else could be considered a liability. Several Trustees stated that the finances and investments of the Trust were also assets.

The Trust's documentation and records were regarded by several interviewees as assets. This included the historical records of the Trustees' meetings, books and other important documents. It was felt that these archives will have potentially significant educational value in future.

The history of the bridge, how it was built and its connections with Isambard Kingdom Brunel were considered to be assets of the Trust by several interviewees. One interviewee, however, felt that the heritage aspect is not an asset in itself but does define the nature and type of an asset such as the bridge.

All of the people involved with the Trust, including the staff, Trustees and volunteers could be considered an asset. This is because of the collective knowledge and experience that exists about maintaining, operating and managing the bridge, particularly as an historic structure. The nature of the bridge, its status in Bristol and the connection to Brunel also means that it is possible to build a very strong team as it is a desirable organisation to be involved with. The board of Trustees itself was also considered to be an asset as they have a wide range of complementary skills and experience, a combination that is seen as important.

In addition to the people involved, the relationships between different groups was also considered an asset by one interviewee. This includes the links to both Bristol City and North East Somerset Council and other related organisations and groups.

The organisation and management of the CSBT is seen as an asset by several interviewees. The independence of the Trust from local authority or other external influences, coupled with the fact that the organisation is essentially run by engineers rather than accountants, means that it is able to invest in maintenance and technical matters. One interviewee also thought that the process of running a Trust in itself could be considered an asset, however another interviewee felt that the organisation could not be considered as an asset.

The bridge is seen by many as an icon for Bristol, it is a significant tourist destination and it is used by many local companies in their advertising and marketing material. There is a sort of brand value and goodwill associated with it, but this is not something that can be easily exploited, and the Trust does not own intellectual property on the symbol of the bridge. Several interviewees considered this to be an intangible asset, although very difficult to value. One interviewee, however, felt that reputation is ancillary to the assets of the bridge as even having a bad reputation would not alter what the Trust was expected and required to do.

In addition to identifying the Trust’s assets, there were also comments from two of the interviewees related to the definition of assets. It was felt that the assets of the Trust are unusual compared to other organisations. The normal definition of assets as items that can be liquidated does not actually apply to the Trust. It was noted that asset may not be the best word to use for the CSBT.

One interviewee talked extensively about the people within the CSBT and how important teams were for the success of the organisation. Key points raised included that the Trust is a team that has been evolving and developing over many years and that the quality of the people in the Trust is key to ensure that everyone has their voice and can contribute. It was also stated that being a Trustee is a vocation, not a job. The interviewee also acknowledged that the Trustee selection process could be seen negatively due to the fact it is selective and not open.

It was felt that while the bridge needs constant care and attention, it does not actually cause many problems. The ancillary systems typically cause the issues and the Trust could view everything apart from the bridge itself as liabilities rather than assets. It was noted that the Trust is fortunate that it only has one bridge to look after, so there are no difficult decisions about which asset to prioritise. This enables the Trust to invest in more analysis work and take a proactive approach to management and maintenance.

7.5.4 Asset Management System

The interviewees were asked what their interpretation of an asset management system was. In general, it was noted that the asset management system should start from the overall purpose of the asset, so should be concerned with enabling the Trust to keep the bridge operational in perpetuity at the current rate and volume of use. One interviewee also felt that the asset management system should be a holistic system that includes all areas of the organisation. Another interviewee defined asset management as how you go about managing the asset and the asset management system as the documentation and formalisation of the asset management. Then, between the asset management and the asset management system there is the asset management plan that explains how the organisation plans to implement management of the asset.

There were a number of different definitions and descriptions of asset management systems given by the interviewees. One important feature is that they should document and explain what the organisation's assets are. It should capture the purpose of the assets and the role of the asset management system in enabling the assets to achieve their purpose. The asset management system should capture the long-term programme of work planned by the organisation to maintain the capability of the asset. It should show evidence that the organisation has thought about the asset from a risk perspective to understand safety, durability, reliability and that it has identified what needs to be done and prioritised based on how much the organisation is able and willing to pay. The asset management system should be a means of triggering the organisation to ask important questions at regular intervals such that critical issues do not get overlooked. The asset management system should then enable the organisation to make sound knowledge-based decisions. It was also noted that the asset management system will depend on the asset you are considering as different assets will have very different requirements.

A number of specific groups of requirements of an asset management system were also found from the interviewees responses. These are as follows:

- Asset Register
    - Location, Identification and Value

    - Condition and Performance
- Maintenance Planning, Replacement and Repair
- Prioritisation, Timescales and Scheduling
- Information and Data Management
- Processes

It was felt that there needs to be a full register of all assets and their constituent components and systems. There is a need to be able to uniquely identify all assets and components such that there can be repeatability in inspections and maintenance work. It is important to be able to easily find the assets and, as such, recording location is crucial. It also may be useful to record the estimated value of the assets.

In addition to enabling location and identification of the assets, the asset register can also capture the current and past condition and performance. This can include age, deterioration predictions against actual behaviour, performance, log of component history, condition rating and details on how condition is measured for that specific component. All of this information then helps the organisation to understand what the performance will be in future and make decisions on what works needs to be done to maintain and enable the assets to continue to fulfil their purpose.

Based on the asset condition and performance data, the asset management system should then enable the planning of maintenance, repair and replacement. The system should set out the approach to planning and the actual plans for the short, medium and long term. This should enable improved controlled over and confidence in the asset maintenance. The system should also capture a measure of effectiveness of the maintenance activities, which will feed into future planning.

Linked to planning of maintenance, repair and replacement is then the prioritisation and scheduling of work it in such a way that it is affordable for the organisation. It was noted that to minimise cost and disruption, consideration needs to be given to scheduling work in the same or similar locations at the same time. It was also noted that the Trust takes a long-term view as their objective is to maintain in perpetuity and, as such, the asset management system needs to reflect this.

The interviewees felt that the asset management system needs to ensure that asset data and information is captured, organised, maintained and regularly updated. Decision making should be recorded and, in future, the data captured should enable further decisions to be made. Data needs to be easily accessible and there needs to be resource allocated to manage this. It will be difficult due to the quantity, age and format of the information to capture it all in an accessible way. It was noted that it would potentially be a large document to cover all aspects of the bridge. There was also some discussion about whether a single management system was required or whether there could be one per asset.

The system also needs to be user friendly and allow engineering judgement to be captured alongside numerical data and analysis. The structure of the asset management system was felt to be important. It needs to be simple at the very top-level but with the ability to have many layers of detail below. This will enable the different users of the system to access the appropriate level of detail required. It was noted that although the Trust owns a lot of data, access to it is poor and that an asset management system needs to address this issue.

The asset management system should capture the processes used in order to manage its assets. These can include the way in which inspections are carried out, the flow of that information through the organisation and then the decision-making processes that follow. For the historical or cultural assets, the asset management processes will be quite different. The asset management system may also include some of the human resources processes such as training of staff and operational procedures which enable the Trust to go about delivering its aims.

One interviewee noted that the asset management system generally needs to take a process view of asset management. They also commented that both the assets and the asset management system are dynamic systems that will be constantly changing.

Another interviewee talked about the difficulties associated with running an asset management system. For such a system to be effective, it needs to be maintained and updated. This is not always easy, and it needs resource assigned to it.

7.5.5 Need for an Asset Management System

When asked why an asset management system was required there were two interviewees who were unconvinced that such a system was indeed required. Another interviewee felt that there was already a reasonable system in place. However, a further interviewee responded by stating that an asset management system was something that the Trust needed and that it was a "must have". They felt that such a system was required because the bridge is such an important and historic structure. In addition, the Trust owns far more assets now than in the past and this is likely to further increase as time goes on.

Many of the interviewees talked about issues around data and information as reasons why an asset management system was required. Both internal and external issues were discussed. Firstly, the data needs to be captured, organised, co-ordinated and made accessible internally. This should help ensure that nothing gets lost, lessons are learnt, work does not have to be duplicated, and future Trustees and staff can find the relevant data about what has happened to the assets over the years. This data will enable decision making and can form the input to future projects. There is a need for a single place where all documentation can be pulled together and for a reporting system to give a view on how the assets are performing. In addition, there is a need to enable external people to access information about the bridge for research, education or simply for interest. In both cases, there is a need to think carefully about the structure of the system so that it is possible to find information easily and quickly.

Several interviewees talked about the need to explicitly capture the asset management activities and processes. There is a need to have this written down so that everyone knows what is happening and it was felt that if an asset management system is implicit then it is unlikely to be very effective. It was noted that an asset management system for the Trust should be explicit and that it may need to capture a lot of implicit processes that currently take place.

It was also stated by a few interviewees that an asset management system could be beneficial as it would serve to remind the organisation about various issues that could otherwise be forgotten or overlooked. The system should prompt the organisation to ask the right questions at the right time.

It was noted that the Trust is responsible for managing the bridge appropriately and needs to be seen to be up to date in the way it goes about this. The aim is to keep the bridge operational in perpetuity and this will become increasingly difficult. All Trustees have collective responsibility, with the Bridgemaster and external experts having some responsibilities for maintenance and project work. An asset management system is needed to explicitly set out the roles and responsibilities.

There is also a desire internally to have confidence that the Trust is acting and prioritising appropriately and that its activities add value to the organisation and its assets. Two interviewees stated this as the reason for needing an asset management system. In addition, with a system in place, the Trust will be seen to be doing the right thing and managing its assets appropriately.

Although the Trust is able to operate differently to local authorities, one interviewee stated that the Trust still wants to have highly auditable processes and to ensure the best value for money is achieved. An asset management system could enable this and support the Trust to develop a coherent programme of work to maintain the longevity of the bridge, in line with the available budget. It was also noted that reactive maintenance is not appropriate, so this long term planned asset management is essential.

One interviewee stated that the assets have to be managed systemically and whatever approach is put in place needs to be flexible enough to cope with future change. It was pointed out by two interviewees that it is important that the asset management system is appropriate to both the assets themselves and to the organisation. While there are some fundamental principles that will apply everywhere, there needs to be an understanding as to how to implement for this specific case.

It was also felt that an asset management system is required to make the organisation more efficient, effective, purposeful and innovative in how it operates. This should apply to both ongoing maintenance and to project work.

One interviewee talked about the asset management system as a means of formalising the learning processes taking place in the organisation in order to carry out asset management. By capturing these and complementing them with theory from formal learning principles, it may improve and accelerate learning in future. The same interviewee also talked about the philosophy of asset management and questioned whether there was value in exploring the development in philosophy around asset management in the context of the management of the bridge.

Another interviewee discussed the fact that no brief or set of processes exist for the property committee. It could be beneficial if an asset management system resolved this. There are areas of decision making controlled by the technical committee with no input from the property committee where input from the property committee would be beneficial, for example landscape gardening.

7.5.6 Interface with Other Management Systems

The interviewees were asked about how they saw an asset management system fitting in with the Trust's other management systems. It was noted by one interviewee that the Trust has a simple management structure but that much of this is implicit, as a result of established working practices. There is no overall manual and a lot of the activities rely on the Bridgemaster to ensure that they are carried out. It was also noted that there is a lot of reactive recording of information and fewer proactive management systems. One reason for this could be because the Trust is not a profit-making organisation. It was noted by another interviewee that having such management systems can be a burden as someone needs to manage and maintain them.

It was felt that there was no need for any conflict between the asset management system and other management systems and that having more explicit systems could be beneficial. However, the interaction between the systems will depend on what the definition of assets and asset management systems are.

The link to the information and historical record management system is seen as important. This may be part of the asset management system, but it was noted that the historical records would need to be managed separately from the current records.

When answering this question there was a lot of discussion from the interviewees related to the Trust's organisational processes. The reporting structure, decision making processes, and roles and responsibilities are clear and are generally thought to work well. In addition to the Trust's general processes, the current Bridgemaster has also developed processes at an operational and bridge management level, but these rely on him to maintain. It was stated that the difficulty is often with the executive side of the organisation as the Trustees generally only meet every quarter. This means that they are more distant from the day-to-day running of the bridge and hence things can be forgotten. The asset management system needs to prevent the organisation from forgetting things about the bridge and the other assets.

It was felt that the engineering and maintenance reports and processes should all become part of the asset management system in future. The relationship between the asset management system and the health and safety file for the bridge was discussed at length by one interviewee. Because the bridge is old it does not have an overall health and safety file in the sense that newer bridges do. There are, however, health and safety files for individual systems and projects that have been carried out more recently, together with a large number of older drawings and documents. It was felt that a health and safety file for the overall bridge would be beneficial and it should be linked to the asset management system. The asset management system would be more about capturing what needed to be done, when it should be done and how. It would also set out the resources required to carry out the work.

One interviewee talked about how important prioritisation was to the Trust. They felt that the asset management system would capture the process of prioritisation, enabling that process to be reviewed as necessary. An output of the asset management system would also be that prioritisation of work. Another interviewee talked about the need for a reliable set of reporting and monitoring documents. This would enable the Trustees to easily interrogate and understand what needs to be done when and how much it is likely to cost. The asset management system would therefore be a simple management tool that supported decision making and audit, ensuring that things did not get forgotten.

Several interviewees talked about the finance and investment management. There was discussion over whether the finance and investments should be considered as assets of the Trust, and if they are then they should be included in the asset management system in some way. If not, there needs to be a strong link as the technical committee spend the majority of the money.

It was stated that all of the intangibles associated with the Trust such as the heritage value and visitor activity should be part of the asset management system. Another interviewee thought that the asset management system should be part of the overall holistic enterprise management system. Asset management would then be the dominant part of the overall management system as the Trust's purpose is to manage its assets in order to deliver a service.

It was noted by one interviewee that there are no standard asset management systems. There are standard principles which mean that you do not need to start from scratch but the application of them will vary depending on the organisation.

The Trust has no explicit HR management system although staff have clear instructions on what they are expected to do to meet the objectives and policies of the Trust. Two interviewees stated that the asset management system should be linked to an HR system that included issues such as resourcing and staff training.

One interviewee talked extensively about the safety management system, including operational safety as well as structural safety. They felt that there was a need for more formalised focus on the operational safety of the bridge, including the safety of staff, contractors, commuters and visitors. There was a feeling that the approach to operational safety tends to be reactive and that the Trust only looks at lagging indicators. The interviewee felt that the operational safety should be subject to the same rigorous scrutiny as the structural safety of the bridge. Such a holistic safety management system would need to interface with the asset management system.

7.5.7 Scope

The interviewees were asked what they thought should be considered in and out of the scope of an asset management system. One interviewee talked about the definition of scope in the context of an asset management system. They thought that scope should not be fixed and that different elements may move in and out of scope over a period of time. Linked to prioritisation, there is a need to adapt the scope to suit what is important at that time. The interviewee was concerned that by setting the scope of the system, people would assume that this is then a fixed boundary.

Only two things were explicitly stated to be out of scope. These were toll collection (as an activity) and financial information. However, another interviewee simply stated that there was “not a lot” that should be left out of such a system.

A wide range of things to be considered in scope were discussed by the interviewees. This included all of the tangible assets, so the bridge, abutments, land and approach roads, buildings, toll houses, maintenance yard, visitor centre and all ancillary systems such as lighting and CCTV. Intangible assets were also discussed, including the Trust’s staff. The data, documentation and drawings should be within scope. Training records, health and safety information, inspection and maintenance records and information about the safety for the general public should be included. Reference to the overall management and management structure should be within scope although the actual systems will be separate. Two interviewees stated that everything defined as an asset should be included and another stated that everything should be in scope. Another interviewee reflected that such a system should capture and define roles and responsibilities.

7.5.8 Goals

The interviewees were asked what they thought were appropriate goals for an asset management system for the CSBT. Three of the respondents linked the goals to the organisation’s purpose, as captured in the mission statement. It was noted that the mission statement captures the top-level purpose of the organisation and this should then be unpacked into a series of objectives and goals. There will be a hierarchy of goals and the asset management system should enable the organisation to identify what these should be. It was also noted by one interviewee that the semantics of what we mean by goals, objectives and purpose is important because we need to ensure that everyone has a shared common understanding.

A number of clear goals for the asset management system were identified. The system should enable the Trust to:

- Increase its understanding of the bridge and how it behaves over time
- Review the assets and their performance over different timescales
- Carry out effective scheduling of work

This should then allow the Trustees to carry out effective prioritisation to ensure focused maintenance, repair, renewal and other capital project works.

An asset management system should be a formalisation of what already happens at the Trust and should ensure that nothing gets missed, forgotten or overlooked. One interviewee noted that the system should be developed in accordance with an existing external standard or guideline.

The system will need to perform many functions. It should be a reporting tool, a cost control tool, a condition management tool, a planning tool, a performance management tool and a maintenance record. Having such a system in place would not only improve the organisation's management of its assets but also demonstrate externally that the Trust is managing appropriately.

Several interviewees stressed the importance of the system being easy to use, access and update. The system needs to accurately document the asset and enable the appropriate management of data both for the present and for the future. There is a need to protect both the digital and physical data. The system should enable a variety of people to find different types of data for different purposes. Users should require only minimal instruction before being able to access and use the data stored within. There is a challenge in achieving this due to the quantity of data that the Trust owns and also because it requires reasonable technical knowledge to sort, review and cross-reference it.

In addition to the data that already exists explicitly, the system should be capable of storing and prompting the capture of implicit knowledge. It was noted by one interviewee that the bridge is based on built up knowledge rather than written down knowledge.

However, they felt it would be beneficial to start to capture this, particularly with the impending retirement of staff and Trustees.

There is also a requirement that the system supports the Trust in its aim to inform and educate the public. The system should improve the public's access to the Trust's information.

7.5.9 Organisational Challenges

Finally, the interviewees were asked what they thought the main challenges for the Trust were, both currently and in future.

It was noted by one interviewee that it was a challenge for the Trust to balance maintaining the historical importance of the bridge with the desire to maintain it as an operational bridge. It was acknowledged that the bridge is seen to be owned by everyone and that the Trust has the difficult job of trying to do the best for as many people as possible. This is particularly challenging due to the changing operational requirements over the years. The bridge was designed to cope with pedestrians and horse and cart whereas today it is a key part of Bristol's transport network. In addition, continuing to meet current and future health and safety requirements was seen as a challenge by several interviewees. Maintaining the safety of the bridge for its users can be at odds with preserving its historical integrity.

Continuing to keep the bridge operational for as long as possible through maintenance and the management of technical challenges was stated by several interviewees. The key technical challenges were identified as the uncertainty around the long-term performance of the overall structure, corrosion, fatigue, the gorge geology, the condition of the anchors, and the sensitivity of the structure to high wind. In particular, there were several comments around the geological study into the condition of the rocks beneath the abutments. It was noted that this is a challenging issue to resolve due to the inherent impreciseness of geological studies and the fact that the Trustees were going to have to make a decision that could potentially cost a lot of money.

Linked to these technical challenges is the issue of effective and ongoing prioritisation of the technical work to try to avoid unexpected events or structural failures. The structural risk register and annual risk review process goes some way towards addressing this issue. However it is still felt by some stakeholders that there is the potential for something unexpected to happen with potentially serious consequences.

Another challenge highlighted by the interviewees was the Trust's ongoing business case and ability to maintain its income stream. It is difficult to account for factors outside the Trust's control such as changes in traffic volume. It is vital, however for the Trust to maintain its income stream. This is only possible through the collection of tolls but, as one interviewee pointed out, the cost of future maintenance is virtually limitless whereas the toll income is limited by how much people are prepared to pay. It is felt that the Trust would not be comfortable charging any more than the current £1 per crossing and that this is in conflict with the asset being available for all. Also, the Trust does not have the freedom to raise the tolls without seeking approval from the Government. This means that potentially a time could come when it could not fulfil its legal duty because the Government did not allow it to raise the toll. In addition to the ongoing running costs, there are also the reserves and it is unclear whether they would be sufficient in the case of a major incident. If they were not, then such an incident could be the catalyst for a change in the ownership of the Trust. If the Trust could no longer afford to maintain the bridge or if some major incident was to take place, then it is likely that the ownership would transition to the local authority or government. However, it was also noted by another interviewee that the independence that comes with the current ownership is essential to keep the bridge in its current state. Some form of government management would be subject to funding challenges and delays in carrying out maintenance.

Maintaining the knowledge and experience of the bridge staff and Trustees was identified as a challenge by one interviewee. This is particularly relevant with impending staff retiral and also because Trustees have to step down at the age of 70.

Selection of new Trustees is not an open process but is based on reputation and recommendation. It is felt that this is better because if it was an open process the mix of skills and interests may not be as suitable. Selection of Trustees is seen as important to maintain the variety and range of expertise, and to ensure that it is a stimulating board to sit on. However, this has an impact on the public's perception of the Trust as it does not stand up to modern standards of accountability. It was also noted that there is a need to build the brand value of the CSBT in the eyes of the public as the bridge will only continue to exist if people are willing to pay for it. The recent toll enquiry was very challenging and if public opinion was to go against the Trust then it would be very difficult to continue looking after the bridge.

Two interviewees talked about the need for alternative ways of thinking and talking about asset management. It was felt by one that the current language is unhelpful as it encourages people to think about traditional asset management of equipment and machinery. For the bridge it would be more useful to include the whole organisation and the broader asset base, including intangibles. Another noted that the vocabulary used means different things to different people and that effort has to be made to share definitions and to build clear understanding within the organisation.

There are general concerns about the challenges of setting up an asset management system for the Trust. One interviewee expressed concern that the system should be set up for and owned by the Trust, not anyone else. There is a difficult decision to be made about whether it should be a bespoke or proprietary system with advantages and disadvantages for both. It was noted that the Trust does not have the resilience to be an early adopter of new technology or systems. Succeeding in setting up a knowledge-based asset management system to deliver to the needs of the organisation across the range of assets was seen to be a significant challenge by another interviewee.

7.6 Discussion

A large breadth and depth of data was captured. The purpose was to gain better understanding on the internal stakeholders' views on organisational purpose and context and to clearly identify their requirements and expectations.

From the data captured, there appears to be a good understanding and agreement among the stakeholders of the Trust's purpose. However, most interviewees talked first about maintenance of the bridge and secondly about the cultural aspects of the Trust's purpose. It is generally felt that the mission statement reflects the purpose and is appropriate for the organisation. The mission statement could be updated to have more emphasis on the Trust's duty to educate and could consider the use of more modern wording.

From the data captured, it was clear that no explicit organisational strategic plan exists for the CSBT. However, many different sources of data exist that could feed into or form part of an implicit strategic plan. It was generally agreed that having such a plan would be beneficial as it would give a level of detail beneath the mission statement and capture the activities required to fulfil it. The recommendation for an organisational strategic plan for the CSBT was made to the technical committee, who agreed and asked the researcher to draft it with input from the staff and Trustees. Further detail on this is given in Chapter 9.

There were a range of views on what should be considered to be the assets of the Trust. This partly reflects a lack of a common definition for what assets are in the context of the bridge and for infrastructure in general. Overall, however, there was consensus that most elements of the organisation could be considered assets. This would include both physical tangible assets and intangibles. The assets of the Trust need to be explicitly captured in an asset management system.

The interpretations of an asset management system highlighted by the interviewees again pointed to a lack of an accepted definition for assets and asset management systems. A number of key features required in an asset management system were identified and these include:

- Asset Register
    - Location, Identification and Value
    - Condition and Performance
- Maintenance Planning, Replacement and Repair
- Prioritisation, Timescales and Scheduling
- Information and Data Management
- Asset Management Processes

When asked why an asset management system was needed for the CSBT, responses ranged from it not being necessary to it being something that was essential. The interviewees identified a number of issues that they hoped an asset management system would address. Data and information management was one of the key issues discussed at length. Explicitly capturing the asset management activities and ensuring that things were not accidently overlooked were also seen as drivers for an asset management system. The Trust wants more confidence that it is acting appropriately in looking after the organisation’s assets. It also wants to be seen externally as doing the right thing and managing the assets adequately. The general opinion is that an asset management system should enable the Trust to be more efficient, effective, purposeful and innovative in how it operates.

The relationship between an asset management system and other management systems is not clear. It was not apparent from the interviews whether many other explicit management systems exist in the CSBT. Specifically, it was stated that there should be strong links between the asset management system and the following other management systems:

- Human resource management system
- Safety management system
- Finance and investment management

It was also assumed by some interviewees that the data management system would either be part of the asset management system or very closely linked. This has fed in to the development of an integrated management system for the CSBT which is presented in Chapter 9.

The scope of an asset management system was considered to be broad and included all tangible assets, all intangible assets, operational processes, training records, structural and operational health and safety, and inspection and maintenance records. Links and references to the other management systems should also be within the scope of the asset management system. It was noted that the scope of an asset management system should be reviewed at various points to reflect what is currently important and not assumed to be fixed.

The goals of an asset management system should be linked to the purpose and mission statement of the organisation. Specifically, the following goals were identified:

- Increase the Trust's understanding of the bridge and how it behaves
- Enable the Trust to review the assets and their performance over different timescales
- Enable the Trust to carry out effective prioritisation and scheduling of works
- Formalise what already happens at the bridge and ensure that nothing gets forgotten or missed
- Be easy to use, access and update
- Accurately document the organisation's assets
- Enable appropriate management of the data for the present and future needs
- Support the Trust in its aim to inform and educate the public
- Act as a tool for the Trust with the following functions:
    - Reporting
    - Cost control
    - Condition management
    - Planning
    - Performance management
    - Maintenance record

The interviewees identified a number of challenges that the Trust faces, either now or in the future. A key area identified was the balance between the historical integrity of the structure and maintaining it as a safe operational part of Bristol's transport network. This is particularly challenging given the dramatic changes in the operational requirements since it was designed. There are a number of technical challenges to be addressed. These relate to the bridge's unique location, the fact that it is an old bridge designed before wrought iron's material properties were fully understood and before the development of sophisticated fatigue analysis methods. A lot of the original information about how the bridge was built and maintained in the early days has been lost and so there is uncertainty around parts of the structure, including the anchorages. Developing and implementing a data management system is required but is also seen as challenging in itself as there is no simple solution. Linked to this is the ability to capture and maintain the knowledge and experience of the staff, Trustees and volunteers for the future.

The continued income stream of the Trust is another challenge, and this is linked to the ongoing ownership of the bridge. For the Trust to continue to exist the public have to want to pay to use the bridge. If there were to be a shortfall in funding or a catastrophic event that the reserve fund could not cover then it is likely the bridge would need to be taken on by local or central government.

The only document capturing the Trust's aims, apart from the Acts of Parliament, is the mission statement. Everything else that has been surfaced during this study has been implicit, in other words it exists in the minds of the stakeholders. This study therefore, formally captures a lot of this data for the first time.

7.7 Conclusions

It has been recognized that there is a perceived need to implement an asset management system for the CSBT. The ISO 55000 series of standards for Asset Management, considered state of the art, have been selected as a starting point to explore the structure the asset management system and guide the development of the system.

This qualitative study has been carried out to elicit from internal stakeholders' views on organizational purpose and context along with their needs and expectations. This study yielded a large quantity of data which was then coded and structured. A report was produced for the CSBT (Appendix A), detailing the organizational purpose and context, from the internal stakeholder perspective and capturing the requirements of an asset management system. This report formed the input to an organisational strategic plan developed by the researcher. This information also provides the stakeholder and organisational context necessary as shown in Figures 7.1 and 7.2 for the development of an asset management system. The findings of this study have also shaped the development of an integrated management system for the CSBT.

This study has attempted to take the recommendations of the ISO 55000 standards and develop a method for implementation. There is currently little published material on implementation of asset management in an organisation from first principles, as it has generally been an evolutionary process. Where there is published material on implementation of asset management it is typically concerned with decision support, IT tools, maintenance planning etc. This study is an attempt to fill that gap.

8 Systems Models of the CSBT

8.1 Overview

A model is a simplification of reality. According to Selic (Selic 2003), there are five key characteristics of a model and these are:

- Abstraction – a simpler, reduced version of reality
- Understandability – reduces the intellectual effort required to understand the complexity
- Accuracy – must be a realistic representation of the features of interest
- Predictiveness – should enable correct prediction of important but not obvious system behaviour
- Inexpensive – cheaper to create and analyse the model than testing the actual system

It can be useful to build models of complex systems because it is difficult to comprehend these systems in their entirety. These models help us to better understand the systems that we are developing (or using) and can help us to answer certain questions (French 1995):

- Definitive questions – models address how something should be defined e.g. inputs, outputs, functions, resources
- Descriptive questions – models provide answers for potentially unknown situations such as climate change
- Normative questions – models provide answers on how we should think about a problem e.g. the model describes approaches for attacking problematic situations

The choice of model is important as the models developed affect our view of the world and each world view leads to a different kind of system (Senge 2006). Because models are simplifications, they cannot capture every detail and they are not accurate and complete representations of reality. Each model will have a certain perspective or world view and no single model is sufficient.

Models have been developed to capture snapshots of the CSBT organisation and to understand the processes taking place. Different models have been created in order to represent the system in alternative ways to determine whether they reveal useful insights. The researcher, situated within the organisation, has developed both a Hierarchical Process Model (HPM) and a process interaction model based on observations of the processes of the organisation.

These models bring together and structure a broad range of organisational elements crucial to asset management. They represent different world views, while externalising and formally capturing implicit processes and tacit knowledge inherent within the organisation.

These models provide a better understanding of where the organisation is and what the possible futures could be. This can then enable more holistic decision making, considering all elements likely to be impacted by the decisions, not just the assumed ones. Modelling can also enable identification, understanding and exploitation of different types of value flow through the system.

Models of the CSBT and of asset management in general can help to answer the following types of questions:

- Definitive questions: how elements of the CSBT system should be defined, what the inputs, outputs and value flows through the system are, what processes are taking place and how they contribute to overall system performance
- Descriptive questions: the ability of the CSBT organisation to cope with unknown situations such as future uncertainty, the resilience of the system to cope with unexpected disruptive events, the ability of the system to evolve to cope with a different world context in future
- Normative questions: how the CSBT organisation should think about approaching particular problem situations such as dealing with data management or what to do in the event of an unexpected component failure

The process of capturing the models and the information contained within them supports the development of the asset management system. While the standards explain the requirements of an asset management system and give some guidance, they do not help an organisation to actually implement asset management or suggest any methods that may be useful for capturing the current processes or identifying areas for improvement. By modelling the processes taking place within the organisation, it highlights how the asset is currently managed and the gaps, risks and uncertainties that need to be addressed. The process of developing the models also improves the understanding of the system in question.

While the models developed are specific for the CSBT, it may be possible to apply the same approach to other asset management organisations. It would be more complicated for larger organisations with many asset systems, but all of these model types are extensible, and the ones outlined within this Chapter could be used as blueprints.

Hierarchical process modelling has been used to explore the propagation of uncertainty and to identify how that impacts the achievement of overall organisational outcomes. This has been beneficial in identifying where data management can reduce uncertainty and to highlight where investing in data management will have the most positive impact.

Process interaction models have been constructed to capture the interconnectedness of organisational processes and to explore how asset management is carried out currently. This has captured both implicit and explicit processes enabling the CSBT to formalise processes that are currently carried out tacitly and to capture best practices. These models have provided the CSBT with alternative ways of looking at the system, highlighting interdependency between organisational elements which in turn helps in identification of unintended impacts of decision making.

8.2 Hierarchical Process Modelling

8.2.1 Background

Originally, the Hierarchical Process Modelling tool Perimeta was developed as part of the Condition Monitoring and Asset Management (CMAM) Project run by the University of Bristol. The aim of this work at Bristol was to develop tools for problem structuring and decision support to improve performance within engineering infrastructure systems (Baker-Langman 2003). There was a need to improve decision support for these domains as the systems often comprised of a complex mix of social, economic, environmental and safety factors (Davis and Hall 2003). Davis states that "the motivation behind the development of HPM as both a modelling approach and a PSM [Problem Structuring Method] has been the need to support decision making (purposeful intervention) whilst dealing with issues of risk and uncertainty" (Davis, MacDonald and White 2010).

The HPM is used to formally capture the process of decision making, which includes all of the sub questions that need to be answered in order to make the overall decision. There are three main steps to using the method:

1. Hierarchical process model used to capture and structure the overall process
2. Process attributes added (at each level)
3. Interval probability theory used to capture uncertainty

The process of argumentation begins with structuring the problem in the shape of a question to allow a number of potential solutions to be posed. These solutions can then be debated and weighed up against each other. The argumentation structure has four elements: process, issue, option and argument from which the model is built and structured, as shown in Figure 8.1. For each process, it is then possible to capture the perceived issues from the stakeholders and then the options for managing or responding to those issues. Arguments put forward both for and against these options can then be recorded (Marashi and Davis 2006). This is useful for group model building as it allows the detail of the discourse to be captured for further exploration and gives structure to the problem. There is the ability then to discuss and agree what performance means, evaluate the appropriate performance indicators and include these in the model. Subjective opinion and arguments are captured allowing all stakeholders to informally externalise their opinions.

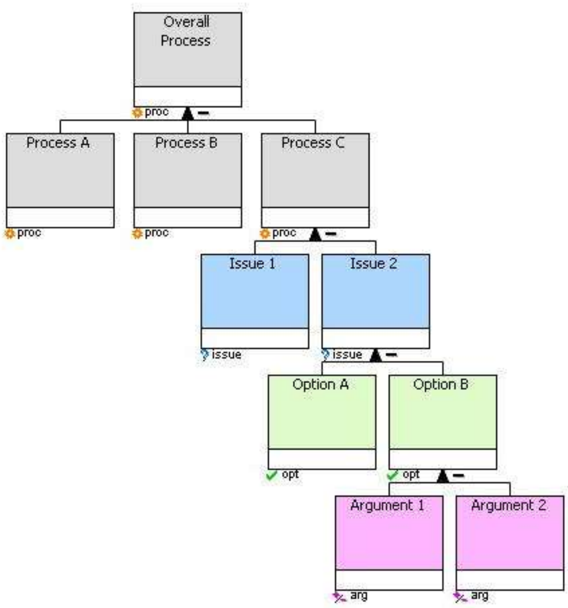

Figure 8.1: PeriMeta Process and Argumentation Structure

However, if a definitive answer with a high dependability is required then this method is not going to be suitable. The method will always be shaped and biased to some extent by the stakeholders involved in developing it, meaning that stakeholders who are not involved in the model building will not have their perspective included (Davis et al. 2010). Another issue with the methodology is the requirement for somebody to commit to build the initial model. This can require a considerable amount of time, effort and knowledge. If the model proves useful, then someone will be required to keep it up to date.

8.2.2 Applications of HPM for the CSBT

HPM has been used as a system modelling tool to try to structure the problem space from the perspective of the researcher. It was selected for its cognitive accessibility and because it has been used in other cases of infrastructure asset management (Baker-Langman 2003, Hall et al. 2004, Marashi and Davis 2007, Davis et al. 2010).

There is the potential to use this modelling method to explore the uncertainty within the sub-processes and run through different scenarios based on confidence in the processes. One of the benefits of hierarchical modelling is that it creates a snapshot of the process and sub processes, which can be used to facilitate discussion and debate. This can be useful amongst stakeholders to develop a common shared picture and understanding of what the process should look like and how it actually works (Hall et al. 2004).

A hierarchical process model was created for the CSBT, based on the researcher’s experience of working within the CSBT. It was also been shaped by input from the Bridgemaster, Trustees and consultant engineers. In creating this model, the bridge was treated as a process. It is proposed that anything with a lifecycle can be considered to be a process (Blockley 2010b). This enabled the understanding of system performance and uncertainty to be captured. The model therefore represents a version of how the artefact, organisation, stakeholders and operating procedures can be viewed to combine in achieving the overall purpose of the bridge. An extract of the top three levels of the initial CSBT model is shown in Figure 8.2.

An area that needed to be addressed was the representation of the duality of the CSBT’s purpose in the hierarchical process model. There was evidence available for the performance of the hard system i.e. the physical structure and the processes that allow provision of a safe crossing of the Avon Gorge. However, it was more difficult to represent the process of being an icon for Bristol and having historical and cultural value and the subsequent sub-processes. There was less available evidence to support this and evidence for this may be more difficult to capture.

Creating a model in this way required the researcher to start at the top-level process and to then unpack this into a series of sub-processes that contribute to the performance of the overall top-level process. The process of creating the model was insightful as it provided a logical structure for exploring and unpacking the organisational processes. The review with internal stakeholders helped to refine and agree the top-level processes and how they should be broken down into more detail. At this stage only the processes were captured, it was not used to capture issues, options or arguments. The intention of this was to focus on establishing a process model that was felt to adequately reflect the organisation. The issues, options and arguments could then be utilised as part of a group exercise with stakeholders.

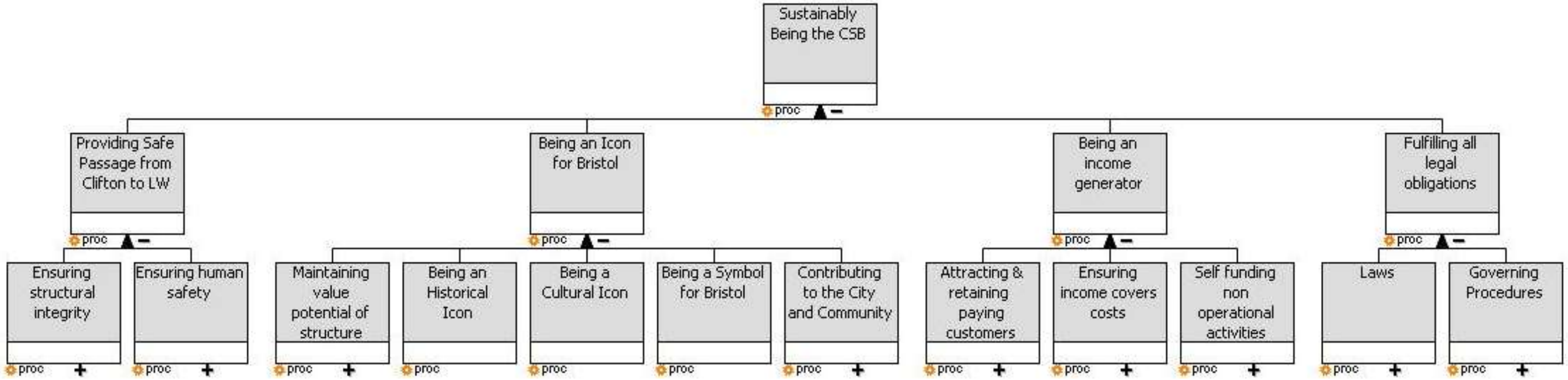

Figure 8.2: Initial CSBT HPM (Top Three Levels)

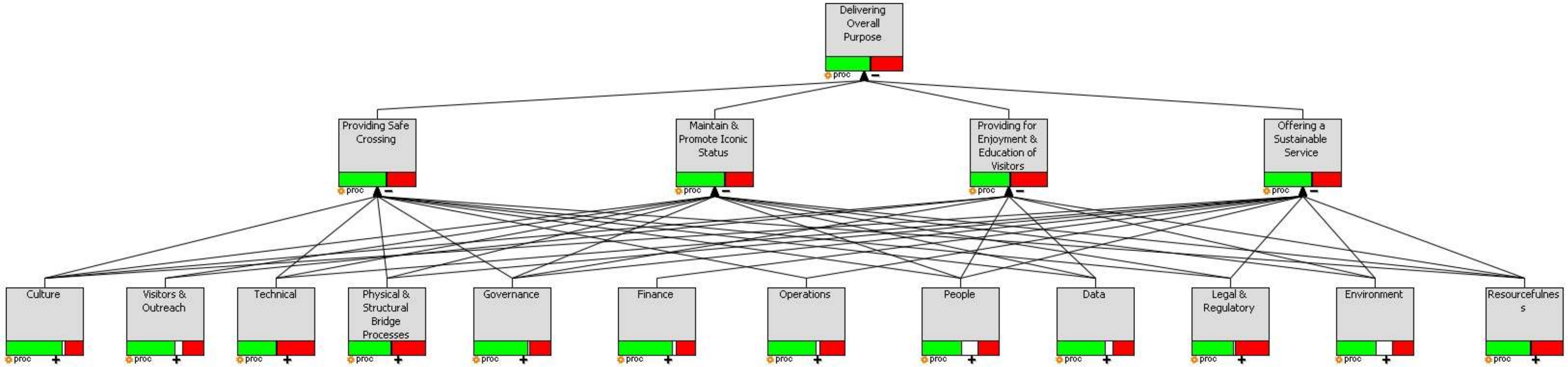

Figure 8.3: Later Version of CSBT HPM (Top Three Levels)

The next stage in utilising this model was to look in more detail at the processes. Each process was considered in turn to explore what evidence would be appropriate to demonstrate that it is performing as required. Figure 8.4 shows an example of this for the process of “Representing Value for Money” where in the description, the concept of value is explored along with some ideas of means of performance measurement.

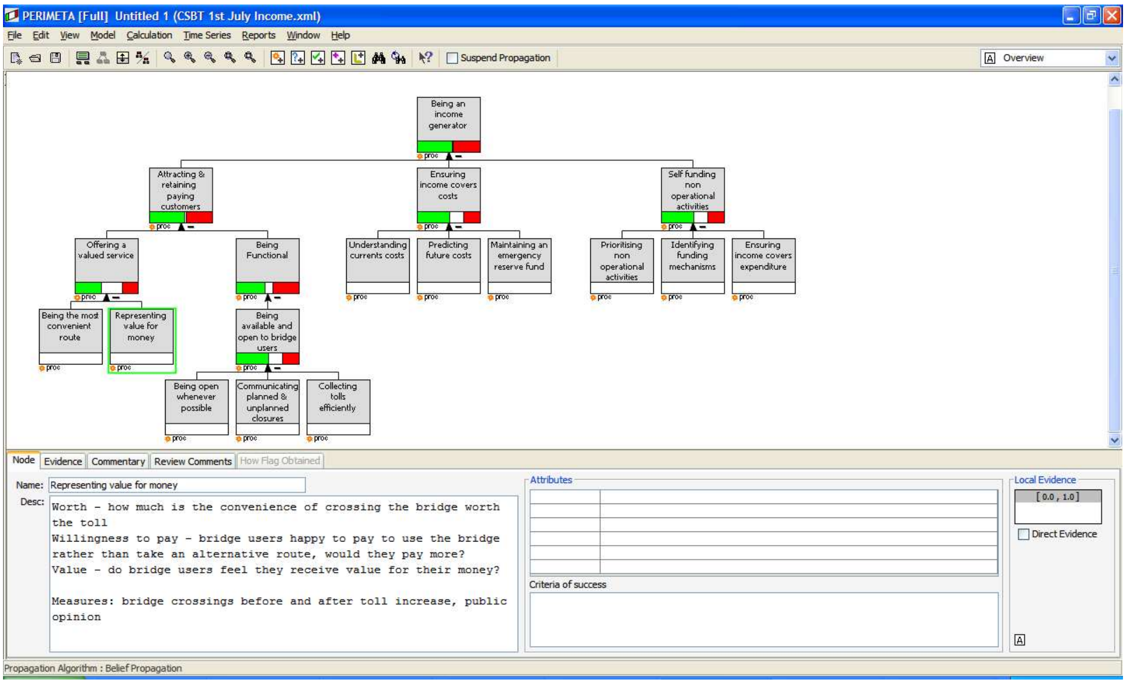

Figure 8.4: Extract from Perimeta

This approach to modelling the organisation was revisited at several points throughout the research. While it was useful for exploring the purpose and processes of the organisation, the researcher found it difficult to fully capture a meaningful overview of the organisation in this way. The model was therefore never expanded out to consider the issues, options and arguments. While stakeholder input was sought and incorporated, the model was never formally used in a group model building workshop.

The linear nature of unpacking processes from a top level downwards worked well to conceptually describe the organisation. However, when trying to identify the links between the processes and how evidence propagates through the model, it was found to be less useful. There are a lot of interfaces between the different processes and in reality, there is no linear path through. An example of this is when considering the load paths in the physical structure, there is no single route through the bridge from load input to load output. There are many loops and HPM does not well represent such relationships. Simplification of such loops takes away from the model's validity and representativeness. Attempts were made to recreate the model as the researcher became more familiar with the organisation and its processes as shown in Figure 8.3. However, so many links were identified between processes that it did not add any value in understanding or analysis.

Overall, the benefit to the bridge of developing such a model was a common shared understanding of the bridge and the processes that are required for the bridge to achieve its purposes. The process map also enables stakeholders to think through the processes and identify the evidence required to give certainty that processes perform as they are understood to perform. The model can also be used to highlight to the Trust any gaps in knowledge about the bridge. This will enable the Trust to decide what sub-processes have the greatest influence on the achievement of purpose and allow them to spend their limited resources accordingly. The application of such systems concepts could support the Trust in decision making regarding where the risks are and what is most worthwhile investing in for the continued preservation and operation of the bridge.

Initially and at a simplistic level, the HPM has been found to be a straightforward means of capturing the entire CSBT system, subsystems and the interactions between them. It enables both hard and soft elements, social and technical aspects of the system to be captured in the same format and on the same page. It supports a process view of the system, encouraging both the model builders and stakeholders to decompose the system in this way. Typically, in industry, this is often not the obvious way to explore or model an infrastructure system. It has also been a useful visual tool for communication with stakeholders and can be easily interpreted and understood.

The HPM was used to structure the problem space, explore process and purpose at the beginning of this project. As further detail emerged on the system throughout the project, it was found to be difficult to represent with accuracy and clarity the relationships between the processes. Other modelling approaches were then investigated. However, it could be useful to revisit the HPM approach in future work for the CSBT, particularly in light of improved access and availability of organisational and technical information.

8.3 CSBT Process Interaction Model

To address some of the difficulties in modelling the interconnected nature of the CSBT's organisational processes, a process interaction model was created. This is shown in Figure 8.5 and was useful for identifying where relationships exist between the different processes and where the feedback loops occur.

The difference between this model and the HPM model is that this model shows more clearly the interconnections between different processes. It can show the flow of uncertainty or information or decision making through the organisation and how it impacts on other processes. It does not, however, show the decomposition of top level processes into more detailed sub processes. A modelling approach that combines both hierarchical decomposition and also captures interactions and interdependencies between elements (in this case processes) was not found to exist. It could be beneficial to combine these approaches in future. However, the decision was made not to at this stage to ensure that the model was of a size and complexity that could be easily understood by and communicated to a range of stakeholders.

The model in Figure 8.5 shows a top-level view of the different elements of the CSBT organisation that interact to contribute to the achievement of the overall purpose. The CSBT requires its assets in order to achieve its overall purpose and as noted in Chapter 7, the organisation is largely set up around management of these assets, so the model can be considered to reflect the asset management of the CSBT. It shows the processes (identified in black) taking place in order to meet the requirements (identified in purple) of the stakeholders (identified in red) and achieve the overall purpose (identified in green). Also shown are some of the decision points in the processes (identified in orange). The blue arrows show the connections between the different elements of the model. Visually, this looks like a complicated model, but the aim was to try to capture everything in one diagram.

For example, it can be seen that the Trustees, as stakeholders, set the requirement that the organisation should fulfil its purpose. This then inputs to both the strategic management of the organisation and the prioritisation of work. The strategic management and strategic choices are a feedback loop. The strategic management includes the processes that are taking place at the very highest level of the organisation. Strategic management is distinct from (but closely related to) strategic choice. Strategic management is where an organisation creates and shapes its vision and operational strategy. The strategic management feeds information into the strategic choices that are made in order to implement that strategic vision. The strategic choices will also need to be made with information regarding the financial landscape of the organisation. Equally, the outcome of the strategic choices will provide information that inputs to further strategic management activities. These strategic choices decide how work will be prioritised, how normal operations will carry on, what visitor services will take place and they will also set out how the financial processes will work. The strategic choices enable the organisation to achieve its three overall purposes of providing a safe and convenient crossing, maintaining in perpetuity, and providing enjoyment and education for visitors and hence there is a direct link to these. Information about whether all three of these overall purposes are being achieved will be used in performance management. The performance management information is then used in the strategic management process. There are clearly many paths that can be taken through the model as shown in Figure 8.5.

This representation of the model was found to be useful as it takes a holistic view of what is happening and why. It does not just show processes but also requirements, decision points and outcomes. Any element can be connected to any other element leading to multiple loops and interactions. This was reviewed with some internal stakeholders to refine the model and ensure that it reflected a common view of the organisation. It is likely that every time this approach is used a different model will be created and this will depend on the people involved in the model building. The real benefit of this approach is that when created as a group activity, the model can be very quickly built and can simply describe what is happening in an organisation. The feedback loops that are identified and those that are missing can then inform future work. An example of this is that a need for performance management was identified in the CSBT model. This would capture how well the CSBT is achieving its overall purpose and feeds the information back into the strategic management process. It was noted, however, that this currently does not take place.

The model created represents the organisation’s activity at a very top level. The CSBT needs to manage its assets, both tangible and intangible in order to achieve its overall purposes. All of the elements of the organisation contribute to this as can be seen in Figure 8.5. As discussed, the CSBT’s purpose is entirely focused on the management of its assets to deliver its purpose, so all of its organisational processes are contributing to asset management. This model, therefore, can be considered as a representation of asset management within the organisation.

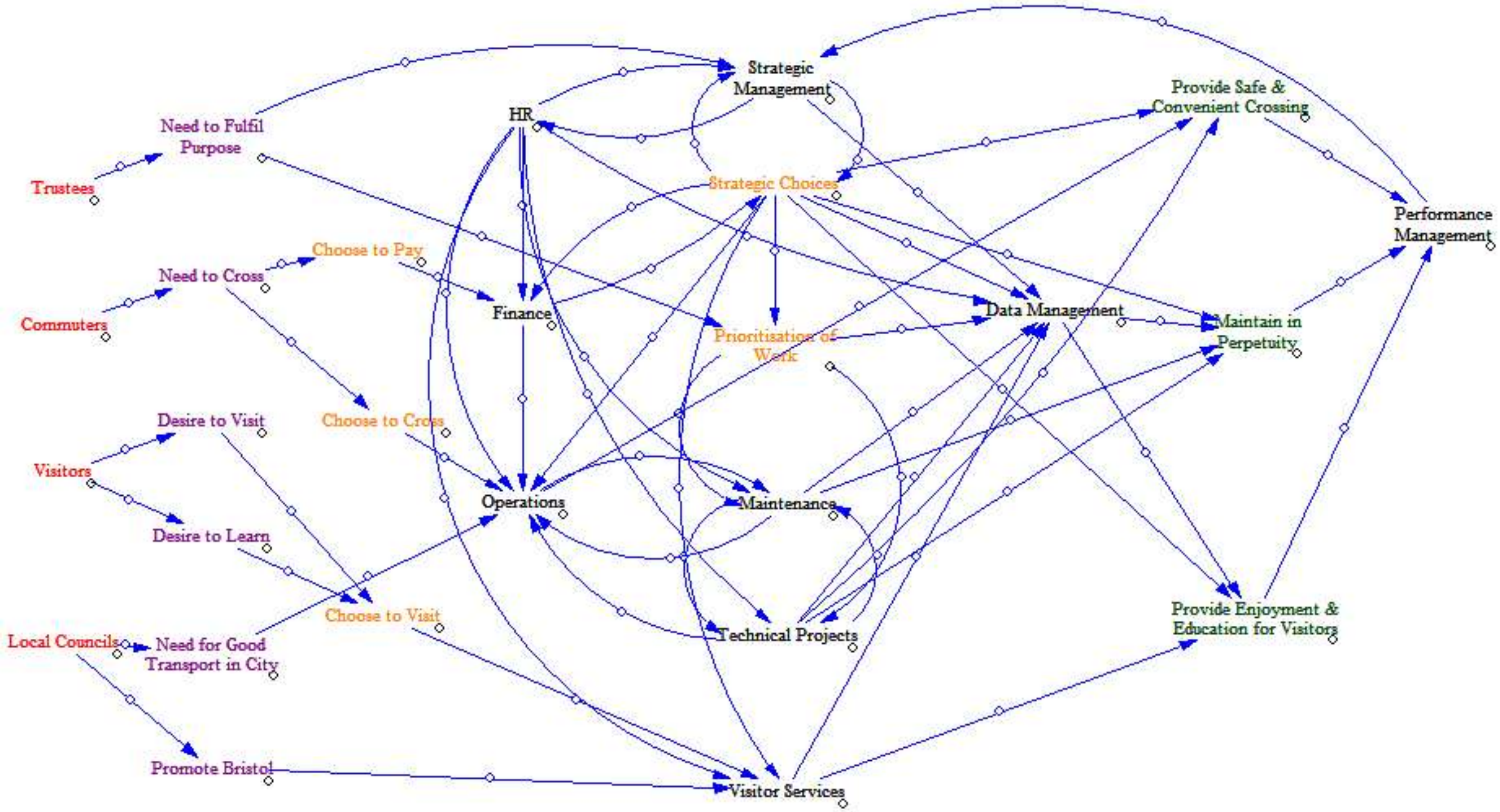

Figure 8.5: CSBT Process Interaction Model

8.4 Generic Process Interaction Model for Asset Management

Drawing on the learning gained from the CSBT, together with the ISO 55000 asset management standards and the literature review outlined in Chapter 3, an attempt was made to create a more generic version of the process interaction model, that more explicitly considered asset management activities. There are many more elements to such a model than were identified for the CSBT. It was found that when considering any one area, such as the stakeholders' expectations and requirements, many interdependencies with other elements would emerge, for example world context and environment, organisational purpose, values and ethics, and performance. The resulting map of generic elements of asset management, presented in Figure 8.6, shows a messy complicated picture, particularly as it only considers the high-level detail.

However, as in the case of the CSBT, the process of collaboratively creating and reviewing such a model in the context of a particular organisation can be extremely powerful in developing a deep understanding of how the organisation works. It can also reveal gaps in either processes or the connections between processes.

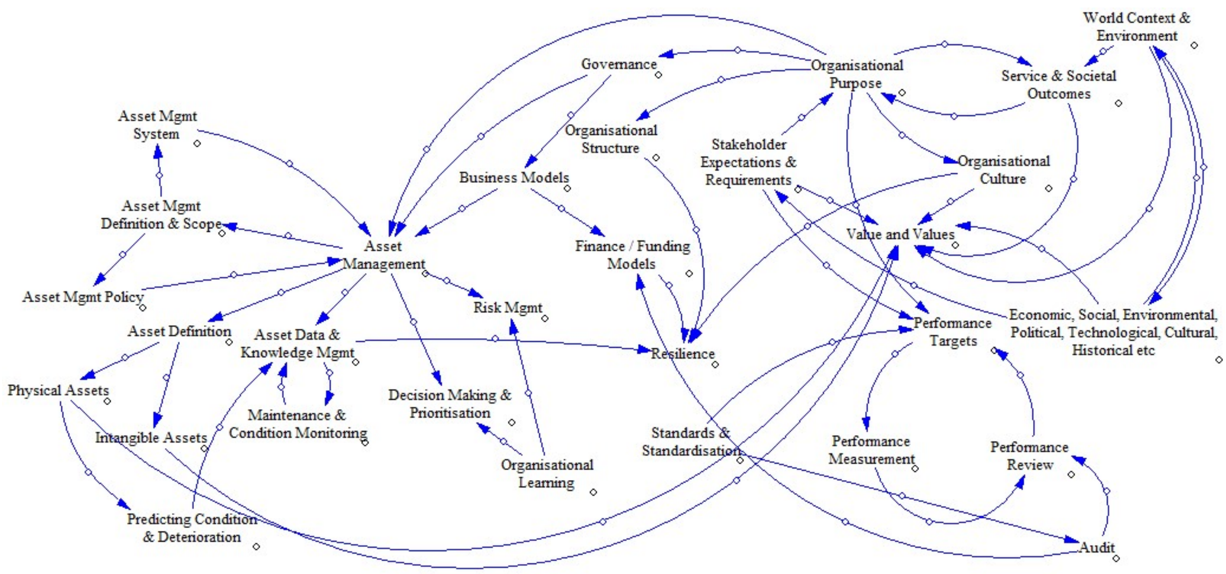

Figure 8.6: Generic Process Interaction Model for Asset Management

The overall model can then be used as the basis for more detailed analysis. This can include identification and exploration of sub-sections of the overall model or analysis of the value flow throughout the model. Table 8.1 shows an extract from analysis of the different elements within the model. This could then be tailored for specific organisations to capture their inputs and outputs and identify the sources of information or other currency that flows between each element.

Table 8.1: Example of Inputs and Outputs for Generic Asset Management Model

Element Name	Element Type	Description	Inputs From	Outputs To
Organisational Purpose	Self-defined constraint, requirement, expectation	Definition of why the organisation exists, how it fits into its environment, and how it aims to continue to exist in the future	World Context & Environment: sets the wider scene in terms of what is important and why.	Service & Societal Outcomes: the service that the organisation delivers and outcomes that result from it, defined by organisational purpose.
			Stakeholder Expectations & Requirements: a major input to the definition of organisational purpose. Both internal & external stakeholders views should be included.	Organisational Culture: the purpose will shape the organisational culture to some extent. Some purposes will drive certain cultures be developed.
			-	Performance Targets: once the organisation has established what it intends to do it needs to measure whether it is succeeding in achieving this.
			-	Governance: the will help to define what governance is appropriate for the organisation.
			-	Asset Management: the organisational purpose reflects the world context and stakeholder requirements, will input to defining the top-level asset management system, policy & processes.
			-	Organisational Structure: the purpose will shape the organisational structure necessary to achieve it.

Thinking this through for an organisation such as the CSBT, where both the asset and organisation are relatively small and simple, is possible. However, due to the potential complexity of this type of generic model, when used on a larger organisation or to a greater level of detail than considered here, the number of processes and interconnections could easily become overwhelming. Choosing the appropriate level of abstraction for the model is important. In addition, the generic model in Figure 8.6 is not particularly cognitively accessible as presented. In order to make such a generic type of model more useful, attempts were made to restructure the same information.

It was found that the elements identified could be grouped into one of the following general categories:

- Context: essentially the world within which the system under study exists, can include political, environmental, social, technological, legal, economic and historical factors together with possible futures
- Purpose: why the system exists and how it fits into this context or world, how the system intends to generate value and how it plans to ensure continuity in the future
- Processes: all of the things that the system does, starting at a high level such as governance, through to various types of management processes, down to the specific activity such as operational, technical etc.
- Issues: all of the blockers and problems that can prevent the system achieving its purpose, typically caused by uncertainty in the system or in the greater world context
- Capital: the resources that the system either has or can access, the five capitals identified by Forum for the Future (Forum for the Future) have been used (natural, human, social, manufactured and financial) together with resilience capital
- Controls: tools or structures in place that help to ensure the system is doing what it planned to do and that it is complying with all legislation or regulation

These categories could then be arranged as shown in Figure 8.7. The context is the top-level world environment and within this sits a system or multiple systems. Each system has a purpose and then a series of processes, issues, capitals and controls that interact to either enable or restrict the organisation in achieving its purpose. This model is useful for exploring different systems explicitly and identifying the organisational elements present. However, care must be taken as this is a simplification. The systems would in reality be interacting with one another other and these interactions are important in understanding the overall system of systems behaviour.

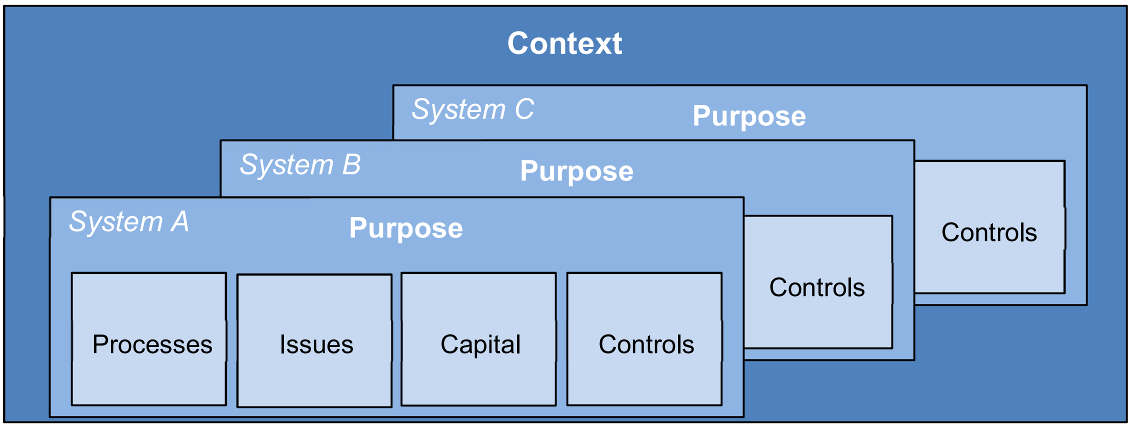

Figure 8.7: Generic Structure of Organisational Elements for Asset Management

The typical elements considered within each grouping are outlined in Figure 8.8 and are described in more detail in Table 8.2. In the application of this to other organisations, clearly some additional elements may be identified and some of those captured in Figure 8.8 and Table 8.2 will not be applicable. However, this approach provides a more structured way to identify the elements within the organisation that can then help with further modelling to explore the interactions between them.

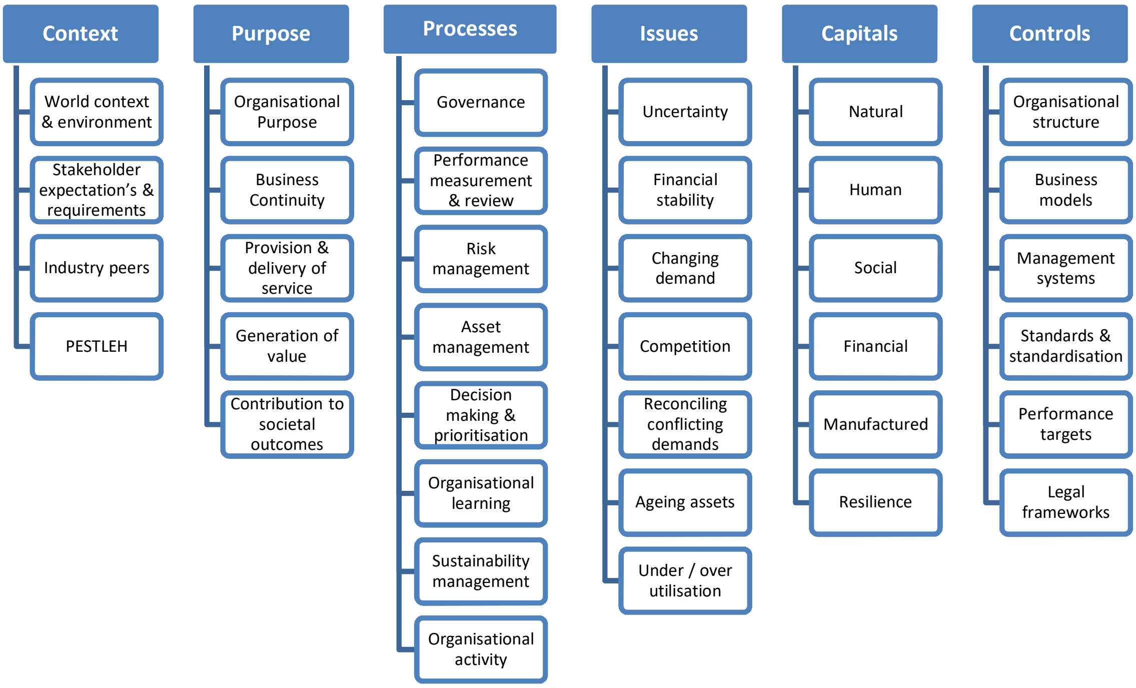

Figure 8.8: General Categorisation of Organisational Elements for Generic Asset Management Model

Table 8.2: Organisational Elements for Generic Asset Management Model

Category	Element	Description
Context	World context & environment	Background, system definition & boundary, key features of the world within which the organisation exists
	Stakeholder expectations & requirements	Stakeholder analysis and requirements capture
	Industry peers, Porter's Five Forces	Porter's five forces analysis: suppliers, competitors, new entrants, buyers or substitutes
	Political, Environmental, Social, Technological, Legal, Economic & Historical	PESTLEH analysis and key factors identified
Purpose	Organisational purpose	Key reason that the organisation exists e.g. mission
	Business continuity	Plan for how the organisation will ensure its continued operation and achievement of purpose in the event of potential threats
	Provision & delivery of service	Description of intended service to be provided and method of delivery

	Generation of value (profit)	Transformation of something into something else that is deemed to be of value, exchange of value, provision of value to a customer in exchange for something of value back
	Contribution to societal outcomes	Understanding of how value generation & provision of service contribute to wider societal outcomes
Processes	Governance	Governance policy, description of processes, enactment of processes, audit & review
	Performance measurement & review	Measures of performance, understanding of what the measures say about the performance of the organisation and identification of how the performance measures demonstrate that the overall purpose is being achieved
	Risk management	Risk management policy, description of processes, enactment of processes, audit & review
	Asset management	Asset management policy, description of processes, enactment of processes, audit & review
	Decision making & prioritisation	Decision making and prioritisation policy, description of processes, enactment of processes, audit & review
	Organisational learning	Understanding of whether formal or informal organisational learning take place, how is it utilised and whether it is adequate
	Sustainability management	Sustainability management policy, description of processes, enactment of processes, audit & review
	Organisational activity e.g. operational, technical etc.	Bridge management processes, operational processes, technical processes, administrative processes, financial processes etc
Issues	Uncertainty	Identification of the sources of aleatory & epistemic uncertainty, and the impact of the uncertainty. Processes by which uncertainty is managed. Consideration given to how the organisation can be sure that all sources of uncertainty have been considered.
	Financial stability	Security in the financial sustainability of the organisation, financial planning, forecasting issues, identification of what types of issues could occur / are occurring and how can they be managed / mitigated
	Changing demand	Knowledge about whether there is too much demand or not enough or constantly changing demand, information about the trends, consideration of the potential impacts
	Competition	Identification of competitors or competitive services, what the impacts are and how this can be managed or mitigated
	Reconciling conflicting demands / stakeholder requirements	Conflicting demands on an organisation or conflicting stakeholder requirements, identification and approaches for resolution or management
	Ageing assets	Identification of the potential or actual issues caused by the ageing of the assets, evaluation of potential scenarios and approaches to management of the issues

	Under / over utilisation	Understanding of under or over utilisation of the assets or service, identification of potential impacts and management approaches
Capitals	Natural Capital	Environmental or ecological capital, natural resources & processes needed by organisation in order to deliver their outcomes
	Human Capital	Health, knowledge, skills, intellectual outputs, motivation, capacity for relationships, joy, passion etc.
	Social Capital	Value added to activities & economic outputs of an organisation by human relationships, partnerships & co-operation. Networks, communication channels, families, communities, businesses, trade unions, schools, voluntary organisations as well as social norms, values & Trust.
	Financial Capital	Assets that exist in currency, can be owned, traded, including shares, bonds & banknotes, reflects the productive power of the other types of capital.
	Manufactured Capital	Material goods & infrastructure owned, leased or controlled by organisation that contribute to delivery of outcome but do not become part of that outcome. Buildings, infrastructure & technologies.
	Resilience	The ability to cope with unexpected disruption and recover to some minimum level of service within the required time
Controls	Organisational structure	Blueprint or map of how organisation is structured, how work is divided & allocated and how individuals fit within this (static model)
	Business models	Dynamic abstract representation of how the organisation works including structure, operations, finance, relationships with external organisations.
	Management system e.g. asset management system	Framework of policies, processes and procedures that ensure the organization can fulfil the tasks required to achieve its objectives. There may be a suite of management systems or one overriding system that captures many different elements.
	Standards & standardisation	Mandatory (& optional) requirements that must be met, standard approaches to activities, means of ensuring safety, efficiency & effectiveness & sharing best practice
	Performance targets	Performance targets that the organisation needs to meet and identification of how these will demonstrate achievement of required performance.

This framework has emerged as a potentially useful means of exploring organisations and structuring the elements that make them up. It was largely developed to address organisations where asset management is the major activity. However, the elements identified are generic themselves and so this approach could potentially be used to explore any organisation. No similar model has been found in the literature. This model was created to bring together and structure all of the organisational elements found at the CSBT and as such is useful as it is based on a deep understanding of the entire organisation. In order to test this framework, it has been used to structure a study into organisational sustainability for the CSBT.

8.5 Conclusions

Models can allow systems to be looked at in different ways and through different lenses. They can highlight patterns or behaviour not otherwise noticed from simply observing the system. Throughout the project, systems modelling approaches such as hierarchical process modelling and process interaction model generation have been used to try to frame the problem space. Both the hierarchical process model and the process interaction model could be used to address the descriptive questions given in section 8.1. Both approaches to modelling should enable the organisation to review its ability to cope with future uncertainty and its resilience to cope with unexpected disruptive events. The models highlight the processes and organisational elements and relate them to how the Trust achieves its purpose. It is then possible to use these models for scenario planning to understand the impact of various events or failures in processes. This was not done but would be a useful application of these models for the CSBT in future.

The generic asset management model was developed for categorising and exploring a set of organisational elements including context, purpose, processes, controls and capitals. These elements are all connected. They interact and contribute to the overall achievement of the organisation's purpose. The model is useful in structuring a process of exploration of how different elements of the organisation are interconnected and what value flows occur between them. It is a systematic approach for thinking through all aspects that may contribute to an organisation's performance. It also enables identification and capture of implicit knowledge.

The model was developed because nothing that existed sufficiently captured all of the organisational elements present or reflected all of the processes taking place in the CSBT. The value of the model may be to show the interconnectedness of various elements in achieving asset management and in turn realising the organisational purpose. This model addresses the definitive questions set out in section 8.1 relating to how elements of the CSBT organisation should be defined, what the inputs, outputs and value flows through the system are and what processes are taking place.

It is believed that this framework can be generalised and could act as a template for other asset intensive organisations to enable them to think through their approach to managing their assets and highlight areas for further work. This model could be used by an organisation that was looking to create or update their strategy as it requires the user to think through the context and purpose of the system (or organisation). The overall model also provides a blueprint that an organisation could use as a checklist to ensure that they have considered all organisational elements that are relevant to them and, if necessary, explicitly capture tacit elements. The framework was used to structure a sustainability study of the CSBT, and this is discussed in Chapter 10.

9 Organisational Interventions

9.1 Overview

A number of interventions were made at an organisational level throughout this research. As previously stated, the Trust had identified a need for an asset management system. The new ISO 55000 family of standards were taken as a starting point for exploring the process of developing an asset management system for the CSBT. This led to the work presented in Chapter 7 to capture the stakeholder and organisational context. The outcomes of this exploratory study together with the guidance set down in the asset management standards highlighted the need for an organisational strategic plan.

From the systems modelling carried out in Chapter 8 to understand and structure the Trust's processes, it was noted that an integrated management system could be beneficial for the Trust. The systems modelling demonstrated how many processes were taking place and the number of organisational elements that had to be considered when thinking about asset management at the CSBT. An asset management system would not be sufficient to encompass all of these and this in turn would not be sufficient to enable the CSBT to holistically manage its assets. An integrated management system, however, would be able to include asset management but also extend to include data management, financial management, sustainability, health and safety, and visitor services. This would also aim to address some of the concerns highlighted in Chapter 7, that there are no explicit management systems in place at the Trust.

Work on data management was then carried out as part of the overall integrated management system. This was as a direct result of the original project brief and the data management problems revealed through the experience of working at the CSBT.

9.2 Development of the Organisational Strategic Plan

The new ISO 55000 family of standards were published in January 2014 and are largely based on the Publicly Available Specification PAS 55 for asset management, which was widely adopted internationally (Woodhouse 2014). As the ISO 55000 series is the most recent standard, it may be considered as the state of the art. The ISO 55000 series has been taken as a starting point for exploration of the process of developing an asset management system for the CSBT.

This new standard presents a holistic approach to asset management that is not limited to purely physical assets but considers management of people, information, finances etc (Woodhouse 2014). The ISO 55000 standards define asset management as the "co-ordinated activity of an organisation to realise value from assets" (International Standards Organisation 2014).

The standard describes the elements of an asset management system and the relationships between them. The standard shows stakeholder and organisational context feeding into the asset management system at the top level. This framework is shown in Figure 9.1 (repeated from Figure 7.1).

The first section of the ISO standards specifies the requirements for identifying and understanding the organisational context, and the needs and expectations of the stakeholders. In order to document this, the CSBT needs to identify and understand its internal and external context. The external context is essentially the world within which it exists and operates. The internal context includes the policies, systems, processes, structures, values and culture existing within the organisation. It then needs to capture the stakeholder requirements and expectations. The CSBT first needed to identify its stakeholder groups and then consider each in turn to understand their specific requirements. The combination of organisational context and stakeholder requirements then enables the CSBT to review and refine its overall purpose and mission statement. The purpose should fit with the stakeholder requirements i.e. it should be delivering something that meets a need, and it should also be appropriate for both the world in which the organisation is operating and how it operates. To address this, the study as detailed in Chapter 7 was carried out.

As shown in Figure 9.1, the stakeholder and organisational context has a two-way relationship with the organisational plans and objectives. These plans and objectives then feed into both the strategic asset management plan and the asset management policy. The organisational plan is the documented information that specifies the programmes necessary to achieve the organisational objectives. The organisational purpose, objectives and plans shall also be captured within the organisational strategic plan.

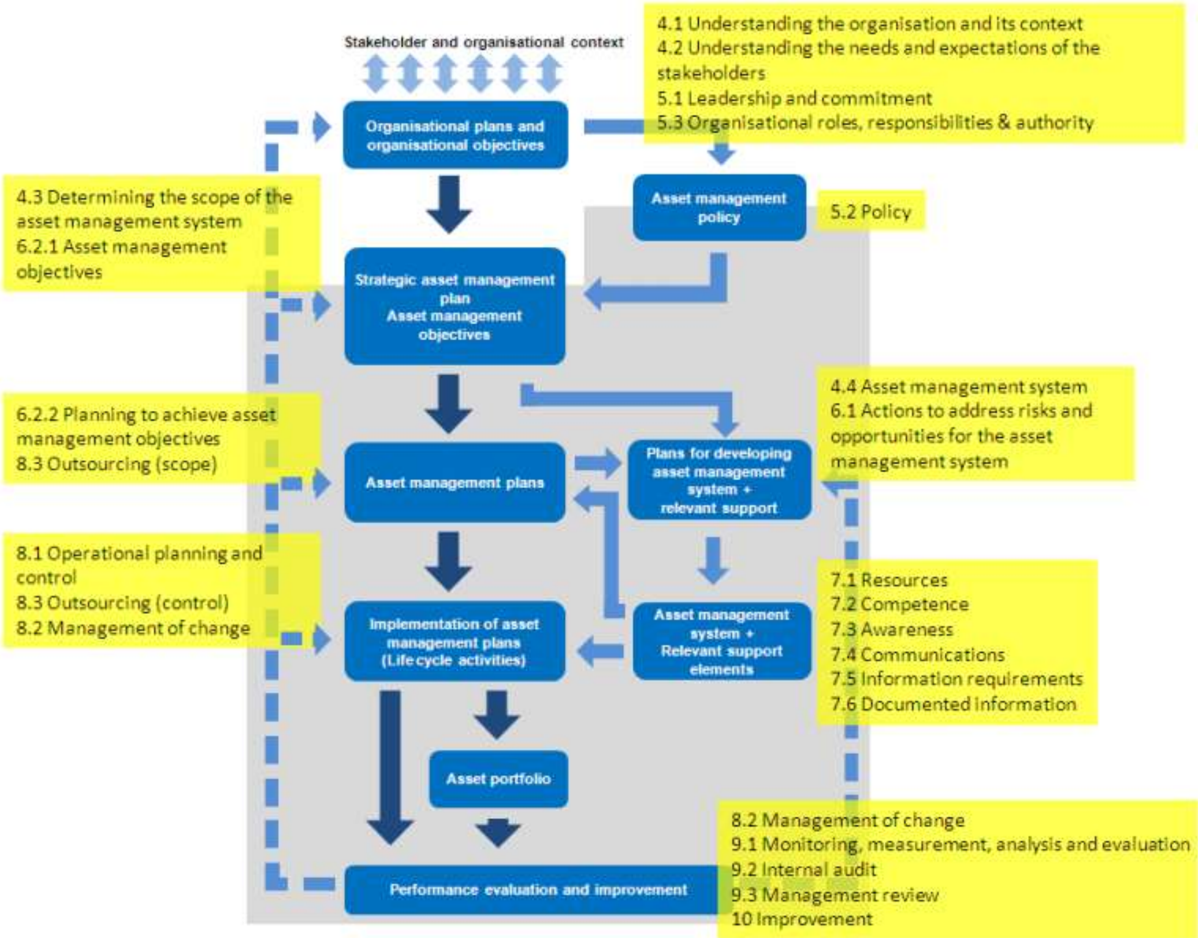

Figure 9.1: ISO 55001 Elements of an asset management system (International Standards Organisation 2014)

In order to develop any specific management system (e.g. asset management system, data management system, environmental management system etc.), the organisation needs to first have a clear understanding of how the overall organisation works and what its purpose is. This should be captured in the organisational strategic plan. This then enables the organisation to integrate its organisational planning activities such that it includes finance, human resources etc as well as asset management.

The ISO 55000 series of standards for asset management require that such an organisational strategic plan is in place before an asset management system is developed. There are also guidelines (Institution of Civil Engineers 2013, The Institute of Asset Management 2012) that suggest for asset management to be successful and effective, there needs to be good line of sight between the people doing the day to day asset management tasks and the overall purpose of the organisation.

The CSBT did not have an organisational strategic plan that explicitly captured its objectives. There exists the mission statement, the Acts of Parliament, various reports produced for the Charity Commission and the supporting documents produced during the application for toll increase. However, there is no single document that brings all of these together in an accessible format for all staff, Trustees and volunteers.

It was proposed that as part of the ongoing work into development of an asset management system, in line with the ISO 55000 asset management standard, that such an organisational strategic plan should be created for the Trust. The technical committee agreed and reported this upward to the Trust board. The researcher was asked to draft such a document in collaboration with the Bridgemaster, Visitor Services manager and other staff as appropriate.

The structure of the organisational strategic plan was created in line with the purpose of the document as defined in the ISO 55000 standards. It was also developed in tandem with the integrated management system and so reflected the structure of this system.

The document captured the Trust's mission statement and expanded this out to include the organisation's purpose, vision and values. The purpose and vision was largely influenced by the data captured from the stakeholders in Chapter 7.

It was felt important that the Trust's values were captured. The values aim to define how the organisation and individuals within conduct themselves to ensure a positive experience for all of the users of the Clifton Suspension Bridge. It was also felt that these values should be chosen by the staff to reflect how they felt about working at the CSBT and what was important to them. A total of eight values were developed by the researcher, Bridgemaster and visitor services manager. These were then circulated to all members of staff as a survey. Each member of staff then had the opportunity to respond anonymously as to whether they strongly agreed, agreed, felt neutral, disagreed or strongly agreed about the applicability of each of the proposed values for the CSBT. There was space for any suggestions for alternative values and also for any general comments. The survey was given to 22 of the 23 members of staff, the researcher did not complete the survey. There were 19 respondents so a response rate of 86%. There were no suggestions for alternative values. From the eight values suggested, four were clearly ranked most highly. These were as follows:

- Pride: We take pride in the Clifton Suspension Bridge and its history, heritage and environs. We strive to share this with visitors, commuters and bridge users. We demonstrate our pride through our work and performance.
- Excellence: We always aim to do our duties to the best of our ability, demonstrating excellence in everything that we do.
- Responsibility: We always take responsibility for our actions and ensure that our colleagues and volunteers can rely on us. We understand that our actions impact others around us.
- Customer Focus: The satisfaction and safety of our customers is central to everything that we do. We aim to deliver a high quality service and ensure that everyone who uses the bridge has a positive, enjoyable and informative experience.

It was noted that teamwork was scored the lowest of all of the values suggested.

- Teamwork: At the Clifton Suspension Bridge we work together as one team and support each other in achieving the Trust’s goals.

Appendix B shows the feedback given to the CSBT staff regarding the results of the survey.

It had been observed by the researcher that there were some implicit divisions within the organisation. There was a natural divide between office staff who worked regular hours and the toll attendants. This is likely due to different working patterns and locations and the fact that communication was more difficult as a result. There was also a divide between the staff and the Trustees. The Trustees only typically visited the bridge offices twice per quarter, once for the committee meetings and then once for the board meeting. There was very little interaction between the Trustees and most of the members of staff and no way for the staff to find out more about the Trustees. Finally, there was a division between the permanent paid staff and the volunteers. Again, this was likely due to different working hours and locations. In addition, they were managed by the visitor services team and as such had less contact with the rest of the bridge team.

While these subtle divisions existed, it was felt important that a small organisation should work closely together to achieve the overall aims of the Trust. The researcher proposed that as teamwork had been scored the lowest and that these implicit divisions had been observed, it could be beneficial to include teamwork as a value. This would need to be acknowledged as something that the Trust needed to improve on and there would need to be a plan in place to do so. This was discussed with the Bridgemaster and it was agreed to include it as one of the CSBT's values.

The organisational strategic plan then captured information about the organisation including the assets, management, organisational structure and roles, and capabilities and competences. A strategic evaluation of the organisation was then outlined including an overview of the stakeholders and the key strengths, weaknesses, opportunities and threats. In line with the structure of the overall integrated management system, the top level objectives of the organisation are captured within the key areas of organisation, asset management, visitor services and public engagement, knowledge and data, environment, health and safety, finance, and people. Organisational objectives are established at a strategic level and set the context and direction for the organisation's activities.

The organisational strategic plan was reviewed by the Bridgemaster, Visitor Services manager and approved by the Trust. A copy is included in Appendix C.

9.3 Integrated Management System

As discussed in Chapter 8, the CSBT is a small organisation, whose processes are largely focused around management of its assets. As highlighted in Chapter 7, there are no explicit management systems in place at the Trust for any aspect of its operations. There was, however, general consensus that creating and documenting management systems and processes would be beneficial for the CSBT in ensuring it was managing effectively and appropriately. This would also help the organisation to capture much of the knowledge that was tacitly held in individual's heads. There was also the view from several of the interviewees that any management system should be holistic and take a system view of the CSBT.

It was felt that a top-level management system would be beneficial for the CSBT. This would then incorporate asset management and data management but also extend to include the other areas of management such as finance, people, health and safety and visitors' services.

The ISO 55000 series of standards follow the general ISO management system structure. This structure was used to guide the development of the overall management system structure. The top-level structure is shown in Figure 9.2. It can be seen that there is a central top-level organisational part that will contain all of the elements central to how the CSBT operates. There are then six different branches, one each for the following:

- Asset management
- Visitor services, Public Engagement and Customer Service
- Data and Knowledge Management
- Environment, Health and Safety
- Finance
- People

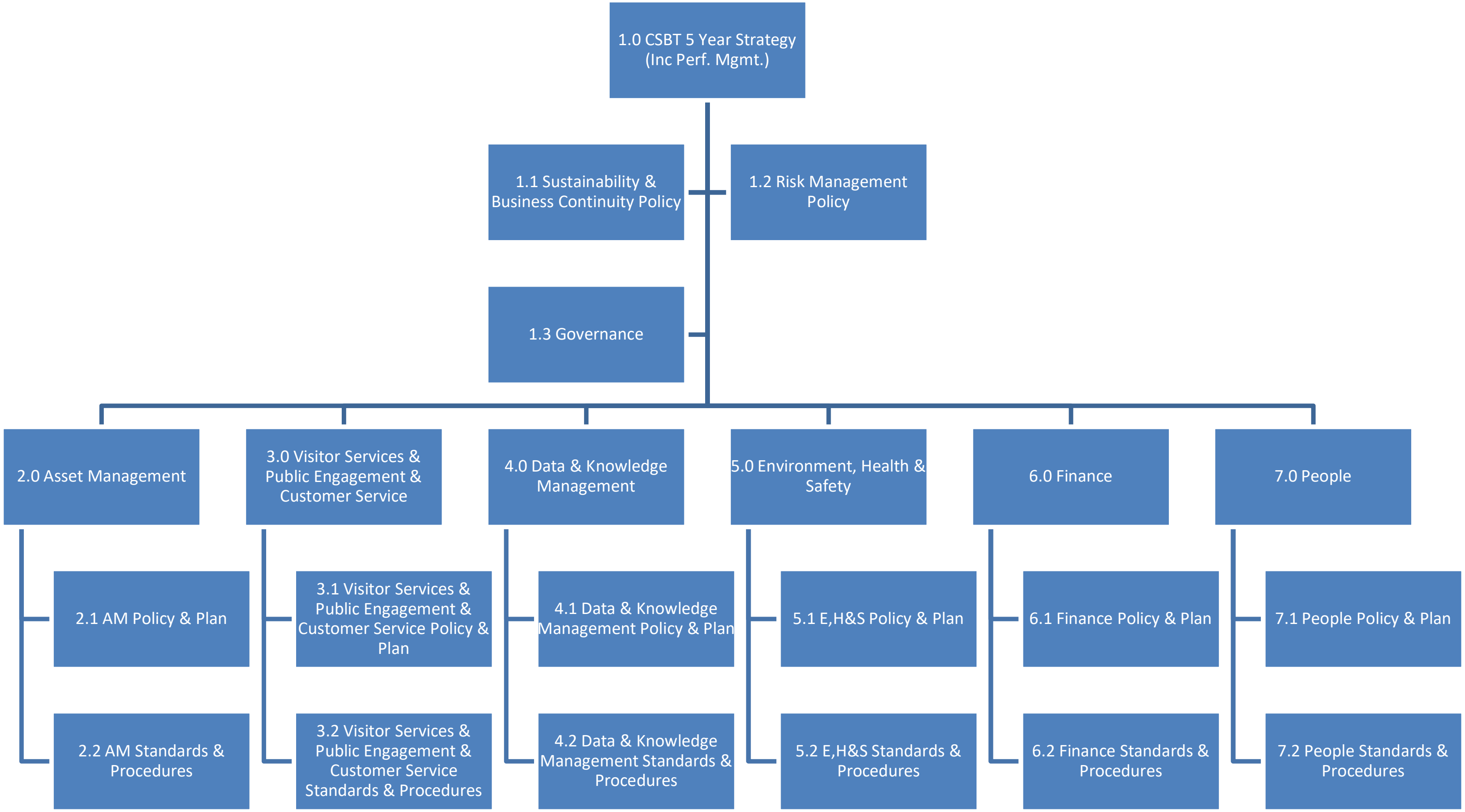

Figure 9.2: CSBT Integrated Management System Structure (Top Level)

Each of these branches will have an overarching policy and plan and then supporting standards and procedures. The documentation structure and description is shown in Figure 9.3.

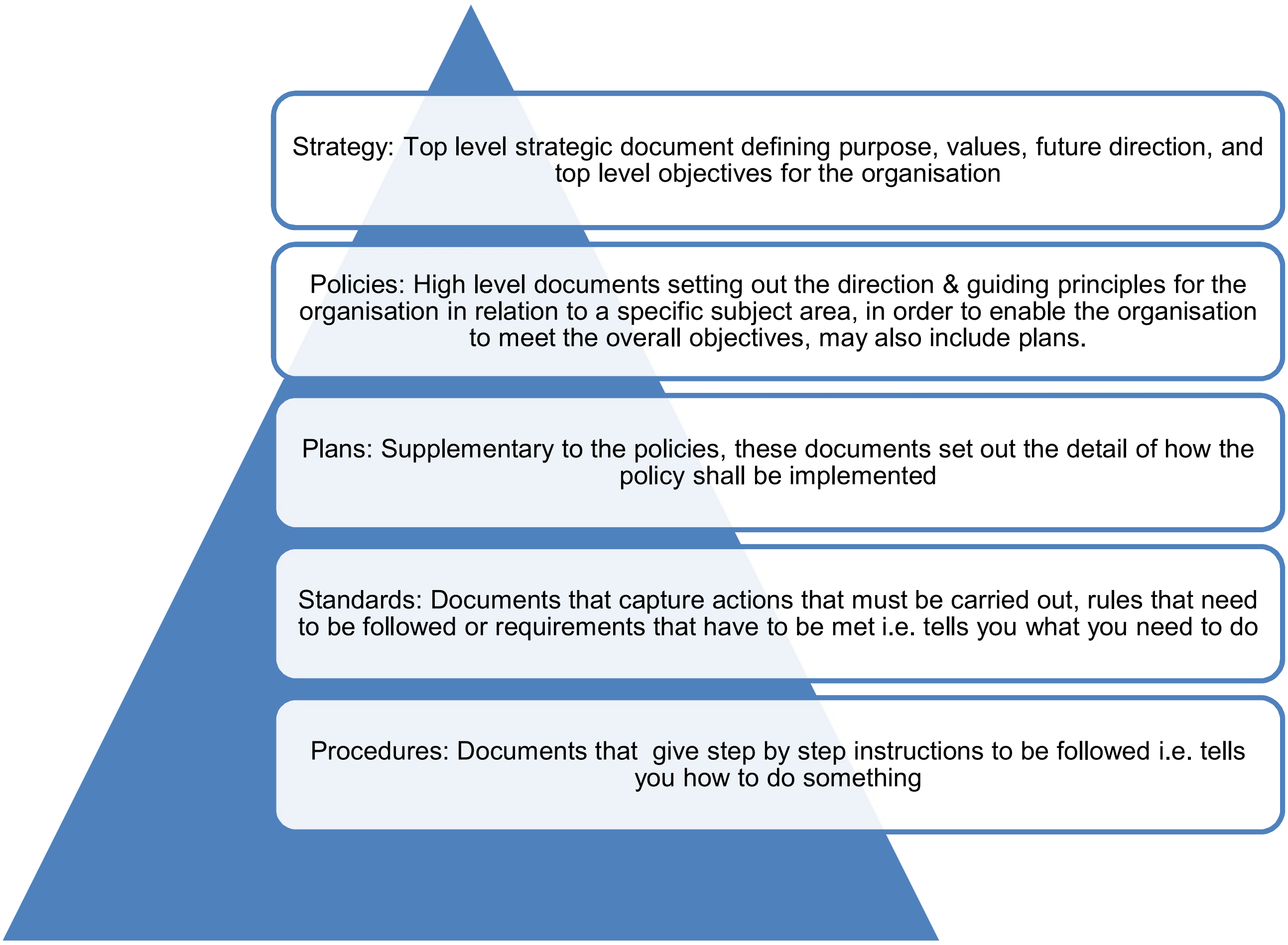

Figure 9.3: CSBT Integrated Management System Documentation Structure

It was proposed that this standard framework should be adopted for each of the individual branches to help both creators and users of these systems. While the specific content would vary, the top-level structure and naming convention would remain the same. It should also help identification of interdependencies, links and duplication between the systems. As the structure follows the ISO approach to management systems (International Standards Organisation 2014) it may be considered best practice and would support accreditation if that became a priority for the organisation.

The integrated management system structure was reviewed with the Bridgemaster and technical committee and it was agreed that it should be implemented. A file management structure was created to reflect the structure of the management system and a document register was set up to capture what documents existed and which ones had to be created. The register also gave every document a reference number, recorded the version, the owner, the review interval and date of next review, together with the current status. To test the proposed structure, the existing policies and procedures were added to the document register and included in the file management. It was discovered during this process that many of these documents were in need of updating and review and that some of them were only available in printed format. This provided the opportunity to standardise the format and templates used while checking the content was still relevant and accurate.

By the time the researcher left the organisation, the basic structure was in place and populated with a large number of documents. The Bridgemaster and other bridge staff planned to finish populating the system and start using it. A networked laptop had been procured for the maintenance chargehand so that he could start the process of digitally recording the maintenance work. This would then feed into the overall management system. In addition, there were plans in place to procure PCs for the two toll houses so that they could also access and create data digitally, reducing the paperwork and burden on other staff logging their reports.

9.4 Data Management System

Data and archive management is a concern for the Trust as they own a large quantity of data in various locations and have a limited index. The organisation has identified the need for a data management system, partially because data is one of the major assets of the CSBT but also because there is currently poor management and utilisation of existing data. From the work presented in Chapter 7, data management is clearly a concern for many stakeholders within the organisation.

Like many organisations managing infrastructure assets, the CSBT has a large and growing amount of data. It stores much of this data physically although more recently produced information is increasingly being stored digitally. The data available on the financing, design, planning, building, maintenance and management of the bridge dates from the early 1800s to the present day. In many cases, this data has the dual purpose of being both historically and functionally important.

From talking to stakeholders and exploring samples of the data, a number of issues with the data management have been captured. These have been arranged loosely into groups for clarity as shown in Figure 9.4. It was clear that any proposal for improvement of the data management process needed to consider these issues.

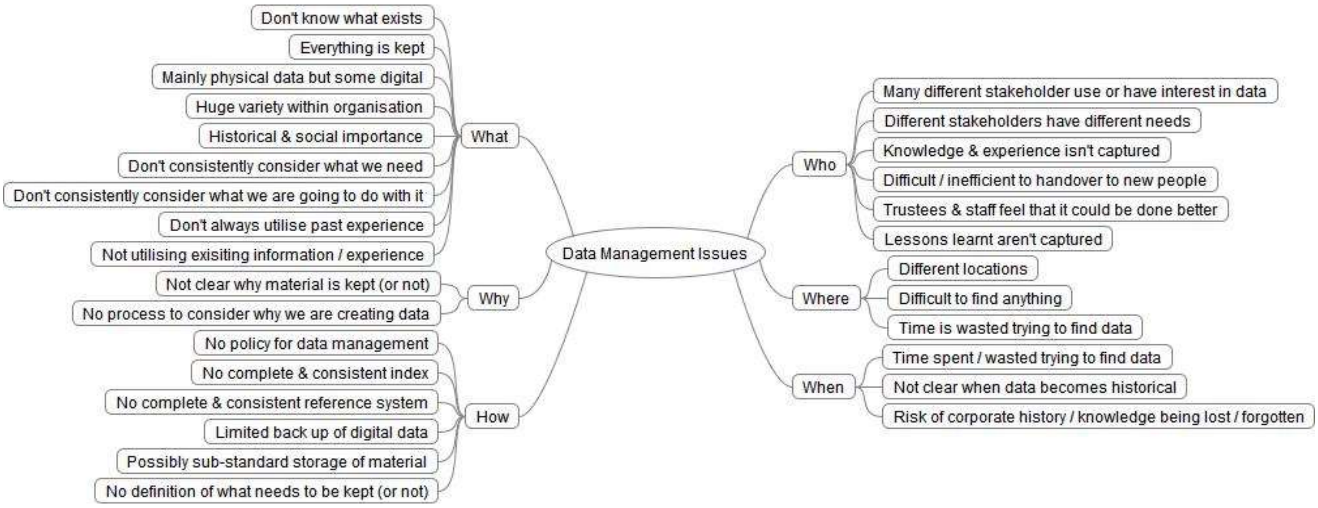

Figure 9.4: Data Management Issues at the CSBT

In addition to considering the issues captured in Figure 9.4, the data management process would need to be clear about and continually review its own purpose. The scope of such a system should be well defined.

The topic of data management was explored at various points throughout the period of research. Initially the general type, quantity and storage of physical data was reviewed. For the purpose of this study, all data was considered to be within the scope of a data management system. No division was made between technical and historical, as there would be items that would fall into both categories. At various points, the archives would have to be consulted to try to find technical data on a particular topic. Sometimes this would be successful for example finding information on structural testing carried out on the bridge in the 1950s in relation to the hanger fatigue issues (described further in Chapter 11). In other cases, even staff or Trustees were sure that data did exist, it was impossible to find.

Generally, most importance was placed on being able to interrogate the data to find information for technical purposes. However, as reflected in the opinions of the stakeholders in Chapter 7, there is also a desire to make as much of the data accessible to the public as possible.

Various approaches were considered for data storage and access, from engineering led 3D models which data could be embedded within to complete digitisation and coding of all documentation. However, it was felt that implementation of any data management system should be carried out in line with the overall integrated management system structure. A more detailed structure for the data and knowledge management branch of the management system was developed, based on reference to the appropriate standards (Collections Trust 2011, ISO. 2001a, ISO. 2001b). This is shown in Figure 9.5.

Initially a data management policy was drafted by the researcher and reviewed with the visitor services manager, prior to issue. The policy was developed in line with the SPECTRUM 4.0 Collection Management standard (Collections Trust 2011) and (ISO. 2001a, ISO. 2001b). The purpose of the policy was to document the CSBT's approach to data management, the persons responsible for enactment of both the policy and the processes contained within it. This would then provide clarity for the organisation, allow data to be processed more effectively and enable more value to be gained from the data. A copy of the policy is included in Appendix C.

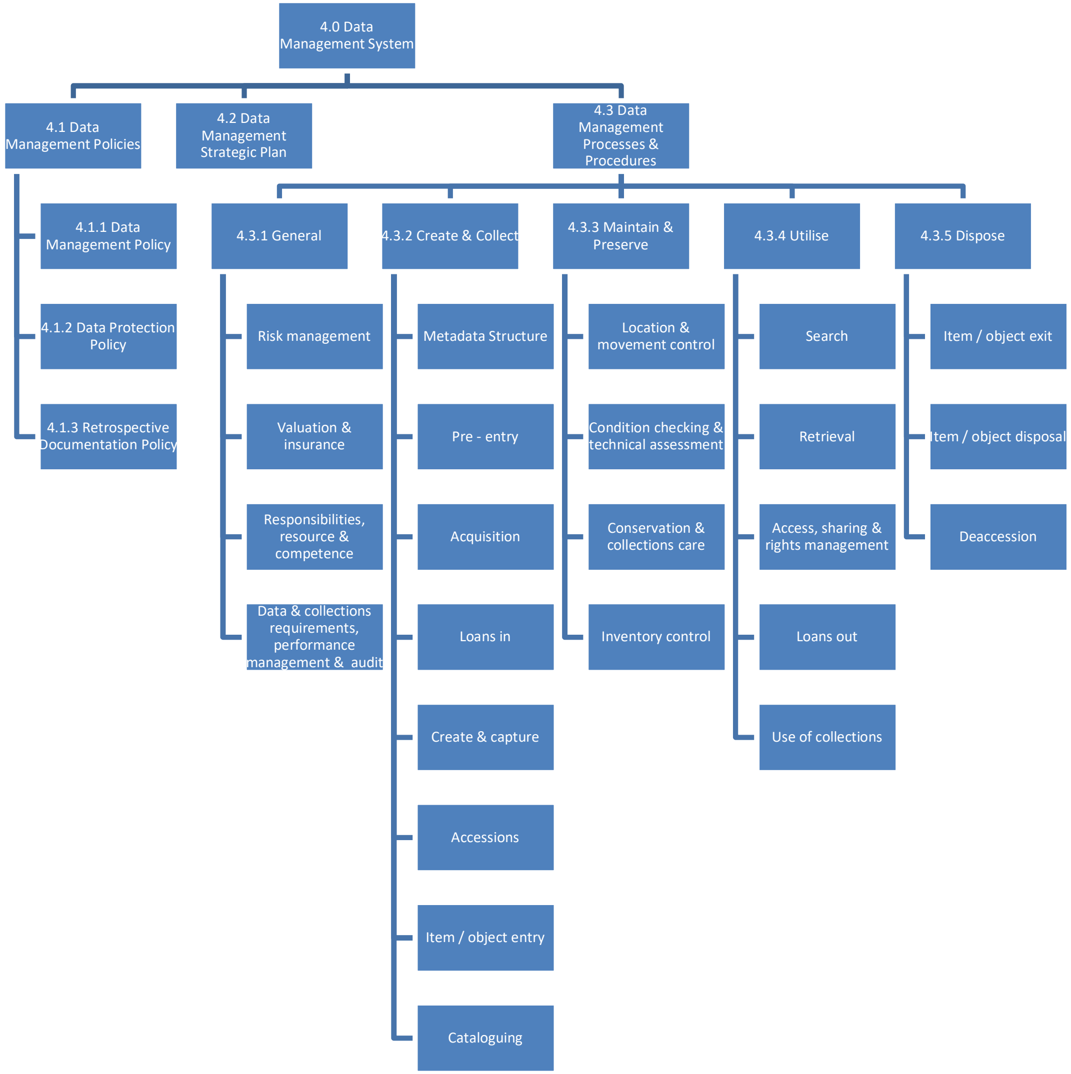

Figure 9.5: Data and Knowledge Management System

There were some fears amongst the Trustees about disposal of any data. However, the policy was not intended to force the organisation to dispose of data. Indeed, much of the CSBTs data was recognised as potentially being useful in future, either from a technical perspective or for historical or cultural interest. Instead, the policy was intended to encourage a conscious approach to choosing what data to keep. Justification could be made to keep material that falls outside the scope or requirements of this policy. Following the processes of this policy, however, should ensure that data is recorded and stored appropriately and that it can be found again in future.

The data management policy covers documents, drawings and other paper based or digital material. It was decided that objects should be covered by a separate Collections Policy, controlled by the Visitor Centre Manager as most objects were under the care of the visitor centre.

For the purposes of this policy, data management was defined to include the following:

- Data creation, acquisition, processing, use and disposal
- Data type and format
- Date storage and preservation
- Data ownership, protection, security, access, sharing and dissemination

The data management policy specifies the data covered by the policy and defines what criteria the data must have (e.g. provenance, author, date created etc.) in order to be accessioned into the data management system. The policy sets out a categorisation framework to be applied to sort the data by age, importance and potential future use. Once categorised, the data shall then be retained for a period dependent on that category. The data shall also be stored in a location and under conditions appropriate to that category.

Access to data, movement of it and disposal (where appropriate) are also set out in the document. Statements on the CSBT's position on data security, protection and ownership are captured, along with how collaborative projects are managed, from a data perspective. The top level requirements of a data management database are also specified. Roles and responsibilities for the various data management processes are allocated. Finally, references to other related documents are given, both external standards and internal reference documents.

The policy also calls for a review of the current conditions and storage of all data, with an emphasis on that material stored at the Crown Records facility. It is felt that there is a risk of deterioration in condition and loss of some material in future if not assessed and addressed in the near term.

The researcher reviewed all of the archive material stored on site, at the Crown Records archive facility and at the Brunel Institute. A detailed list of all of this material has been created which was a significant step forward from the previous situation. Notes on the condition and perceived usefulness of this data has also been recorded.

In addition to the data management policy, the researcher developed a brief for a more focused project on data management and archiving. It was recognised that while the researcher could carry out the requirements capture and review the existing data, a qualified archivist would be more suitable to developing the detailed implementation plan for data management at the bridge.

The purpose of the data management project was to improve the CSBT's ability to find, access, utilise, preserve and share its data to deliver the following benefits:

- Demonstrate appropriate management and governance
- Provide deeper understanding of elements of the organisation (technical or otherwise)
- Maintain and preserve the history of the bridge and organisation using the documentary resource.
- Help solve technical issues as they arise, and to support inspection and maintenance planning by making the historic records accessible and searchable.
- Prevent duplication of work by making the knowledge from earlier work accessible and searchable
- Provide evidence to underpin proposals to upgrade and change the bridge, for example the toll house project and the corrosion protection strategy.
- Generate greater engagement with the public through controlled access to historic records.

- Support research and education in partnership with the Brunel Institute and the University of Bristol Special Collection.

The project shall also put in place strategies to ensure the continuation of the data management processes introduced after the project is complete, and the management of more recent electronic communications and files. The aim is to have one overarching system and approach to management of all data, complying with the relevant standards where appropriate. The project shall also be an important starting point for the development of an electronic management system for bridge maintenance.

9.5 Conclusions

While the work presented in this Chapter did not address fully the need for an asset management system or data management system, it put in place much of the underpinning structure that would then enable such systems to be developed and implemented.

The work in this Chapter built upon knowledge gained from the systems modelling presented in Chapter 8. The systems models built highlighted the number of processes taking place at the CSBT and the interconnectivity of them. These processes collectively contribute to the CSBT achieving its purpose. This led to the conclusion that an asset management system would not be sufficient and that an integrated management system would be more appropriate. It also became clear how important a shared understanding of the context and purpose is for an organisation. Particularly in the hierarchical process model, the top level of the CSBT model captured the purpose of the organisation and all processes were linked back to achievement of these purposes. This led to the development of the CSBT organisational strategic plan.

An overarching structure for an integrated management system was developed and applied to the CSBT. This structure followed the standard ISO management system structure (International Standards Organisation 2014, ISO. 2018). In line with the ISO 55000 family of standards, the top level structure of the asset management branch of this system was developed (International Standards Organisation 2014). In line with SPECTRUM 4.0 Collections Management standard and ISO 15489 Information and Documentation – Records Management (ISO. 2001a, ISO. 2001b, Collections Trust

2011) the data and knowledge management branch structure was also defined. Based on data captured from the study carried out with the internal stakeholders (as presented in Chapter 7) and a small-scale survey carried out with staff, an organisational strategic plan was developed for the Trust.

10 Sustainability Assessment of the Clifton Suspension Bridge Trust

10.1 Overview

The purpose of this study was to carry out a sustainability assessment of the CSBT organisation. This assessment was carried out in response to some of the challenges identified through the work reported in Chapter 7 and also because of the general agreement that the Trust's mission was to maintain the bridge in perpetuity. In order to look after something in perpetuity, the organisation needs to be aware of its interaction with and impact on the surrounding environment. It was felt appropriate that the Trust review how sustainable the organisation is at present. This study was intended to help the organisation to identify potential risks and opportunities, both current and future, relating to sustainability. Based on these, recommendations would be made for options to improve its sustainability.

10.2 Sustainability

Sustainability originates in ecology and is concerned with being able to uphold or maintain supplies of natural resources for the future as well as the present. Sustainable development brings together the ideas of preserving or enhancing natural resources with economic or societal progress. Today it spans many fields with numerous definitions (Dobson 1996), theoretical concepts (Jabareen 2004) and frameworks for assessment. Sustainability has become one of the fastest growing system properties mentioned in scientific work and on the Internet (De Weck, Roos and Magee 2011).

This multiplicity of definitions and theoretical constructs is problematic in practice. Stakeholders may have radically different mental models of sustainability and sustainable development and the lack of a common, definitive language exacerbates this.

For the purposes of this research, the definition of sustainability from the United Nations Report of the World Commission on Environment and Development shall be used. Sustainable development is that which "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission 1987). This remains one of the most widely quoted definitions to date.

There has been reluctance within industry to fully embrace sustainability, with a belief that it will incur additional cost with little benefit (P. Braithwaite 2007). However, a report by the World Business Council on the business case for sustainable development stated that "there is a strong and compelling case to be made for pursuing a mission of sustainable development" (World Business Council for Sustainable Development 2002). The benefits to an organisation adopting sustainability principles includes increased competitiveness, improved resilience, more agility, clarity and unification of purpose, higher likelihood of attracting and retaining customers and staff and a more comfortable relationship with financial organisations and regulators (World Business Council for Sustainable Development 2002).

Sustainable development in civil engineering and infrastructure management requires engineers to look beyond the traditional elements of their profession and consider how the needs of all present end users can be met. They must also recognise the potential impacts on the natural environment and future generations and consider both benefit and mitigation (Fenner et al. 2006). Sustainable infrastructure has been defined as "infrastructure in harmony with the continuation of economic and environmental sustainability" (United Nations 2006).

There is general agreement amongst engineers that sustainability assessment systems are helpful in analysis and evaluation of systems in order to score their sustainability performance (Amiril et al. 2014). In the UK there are various assessment approaches, including toolkits developed by private organisations and universities (e.g. Halstar (Pearce, Murry and Broyd 2012), SILENT (Yigitcanlar and Dur 2010) and SPeAR (P. Braithwaite 2007)).

10.3 Evaluating Organisational Sustainability

The purpose of sustainable development is to enable organisational or societal progress that does not come at the cost of the environment, or prevent current or future generations from meeting their specific needs (Brundtland Commission 1987). The purpose of sustainability assessment tools is to support the assessment, management and delivery of sustainable systems (Pearce et al. 2012). Arguably, these tools are likely to have the most impact if they are implemented at the early concept design stage and developed alongside the system as it is designed. However, these tools can still be usefully applied to existing systems, such as the CSBT (an example of ageing Victorian infrastructure) to evaluate the organisation and identify whether it is operating sustainably or whether there is a need for change. The output of such a sustainability assessment may identify risks not otherwise identified.

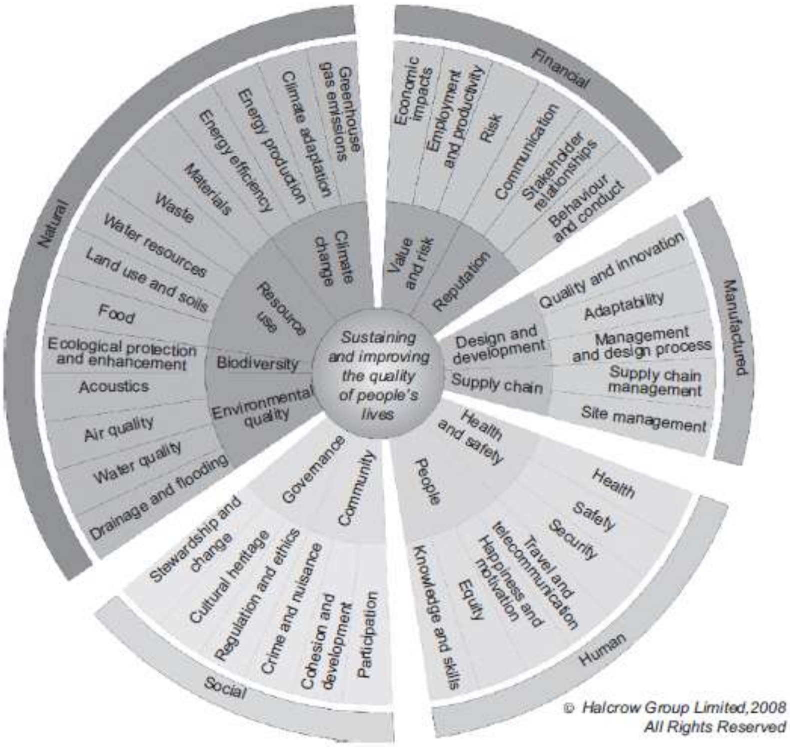

Figure 10.1: Halstar Sustainability Wheel

(Pearce et al. 2012)

For the CSBT, the intention is to use the Halstar model to explore a broad range of elements of organisational sustainability. Halstar was selected as it is based on a systems thinking approach and is very comprehensive when compared with other techniques (Hojjati et al. 2017). The Halstar model enables the researcher to capture multiple stakeholder perspectives across the system lifecycle. For this initial assessment, the stakeholders considered are primarily internal to the organisation (although some external views have been captured). Also, the system is in the “maintain and operate” phase of its lifecycle which it has been in for 150 years and intends to remain within, in perpetuity. There are no plans for change of use or disposal. Most of the likely changes in future will come about as a response to the environment. The analysis has attempted to capture this to an extent, but essentially provides a snapshot of the current situation.

10.4 CSBT Organisational Elements

Before using the Halstar framework to carry out the sustainability assessment, the generic structure of organisational elements model developed in Chapter 8 (see Figure 10.2, a repeat of Figure 8.7) was first applied to the CSBT. This framework has emerged as a potentially useful means of exploring asset management within organisations, enabling classification of organisational elements. This model was applied in order to enable the researcher to formally explore and capture information about the organisational elements at the CSBT. This would be particularly valuable if the person carrying out the sustainability assessment was not familiar with the organisation. This could also be useful as a tool to get stakeholder consensus on the organisation overall. Once this model has been applied, the system within which the sustainability assessment should be carried out should be clearly defined and understood.

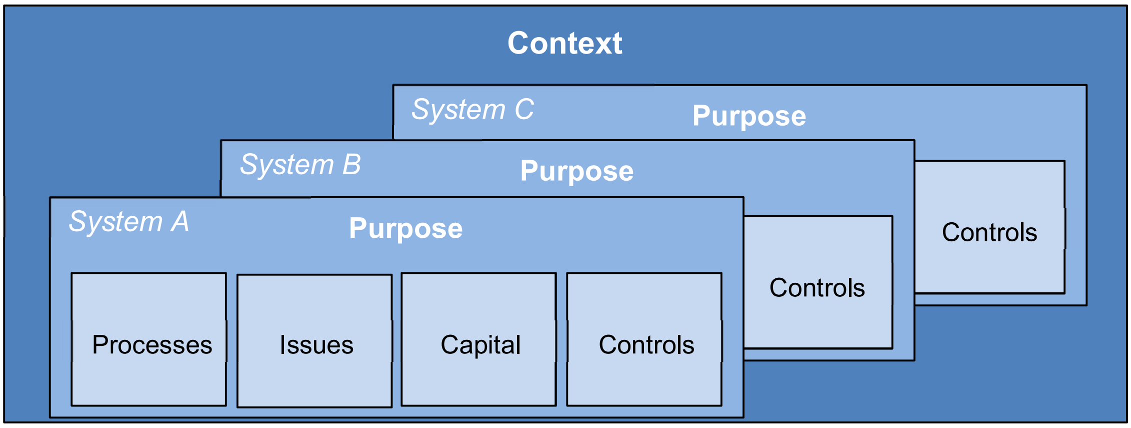

Figure 10.2: Generic Structure of Organisational Elements for Asset Management

The context is essentially the world within which the system under study exists. This can include political, environmental, social, technological, legal, economic and historical factors together with possible futures. The purpose then describes why the system exists and how it fits into this context or world. There are likely many systems within a given context (only one is shown for clarity). The purpose should include how the system intends to generate value and how it plans to ensure continuity in the future. There are then four main elements within the system that affect whether it achieves this purpose.

Processes are all of the things that the system does, starting at a high level such as governance, through various types of management processes down to the specific activity such as operational, technical etc. Controls are tools or structures in place that help to ensure the system is doing what it planned to do and that it is complying with all legislation or regulation. Capital represents the resources that the system either has or accesses. For this study the five capitals identified by Forum for the Future Five Capitals Model (Forum for the Future) have been used (natural, human, social, manufactured and financial) together with an additional one, resilience capital. Finally, issues cover all of the blockers and problems that can prevent the system achieving its purpose. Typically, these issues are caused by uncertainty in the system or in the greater world context.

The following sections explore these elements and identifies how they apply to the CSBT.

10.4.1 Context

As outlined in Chapter 4, the organisation has the duty of preserving the Clifton Suspension Bridge in perpetuity. As stated in section 4.6, the physical bridge is a hard system sitting within the soft system of the organisation, the CSBT. The CSBT delivers the service of enabling people to cross the Avon Gorge, while acting as a historical and cultural icon for the city and sitting in a visually and environmentally prominent position. The organisation forms part of two further city wide systems; the transport network and the historical and cultural identity. The CSBT has a broad range of stakeholder groups. These are presented and discussed in section 4.7.

The competitors of the CSBT, in terms of providing a crossing point for the Avon Gorge, are the other crossing points along the river. The next adjacent ones are the Cumberland Basin flyover and the Avonmouth Bridge. The Avonmouth Bridge is a motorway bridge and a 14 mile round trip from the CSB. The Cumberland Basin is a busy road interchange, close to the city centre.

The competitors in terms of historical and cultural landmarks are less clear cut. The SS Great Britain, another legacy of I.K. Brunel, resides in the floating harbour, one of the other main tourist attractions in the city. However, it is a fee-paying attraction and not something people use for utility, so unlikely to be a direct competitor. The hot air balloons are probably one of the other most commonly used symbols for Bristol apart from the bridge. This is due to the history of balloon making in the city and the annual balloon fiesta. It is difficult to identify anything else which would fulfil the role that the bridge plays culturally and historically.

10.4.2 Purpose

As outlined in Chapter 4, the Trust's mission statement is:

"It shall be the mission of the bridge Trust to preserve the Clifton Suspension Bridge in perpetuity, to the highest possible standards, for the utility of the public, and to provide information and facilities for the enjoyment of visitors to the bridge."

The Trust considers itself to be responsible for both the physical upkeep of the bridge and also for enabling and supporting a softer aspect of the bridge's purpose, that of social and historical importance. The CSBT is governed by several Acts of Parliament, the primary one dating from 1952 outlining the duties of the Trustees in managing and operating the bridge.

Beyond the specific duties of maintenance and operation of the bridge, the purpose is really about providing a safe and efficient crossing service, providing value for money for the paying customers. That crossing service then has broader societal outcomes such as connecting communities. Provision for visitors to the bridge then feeds into the purpose of the bridge being an icon and focal point for the city. Then at an even broader level this contributes to wellbeing and happiness.

Sustainability of the organisation and its operations has not explicitly been given a lot of consideration so far. There is no sustainability policy and environmental drivers are not always at the forefront of decision making. However, from the mission statement above, it can be seen that sustainability of the bridge and the organisation is required, in perpetuity.

10.4.3 Processes

The main processes that the CSBT perform can be grouped into one of the following:

- Governance – board level processes, strategic development of direction, goals, purpose, making decisions on the "what" and "why" of the organisation
- General management – day to day management of operations and organisation of resources, how the organisation achieves the "what"
- Risk management

- Asset management
- Organisational learning and data management
- Organisational activity – operational, financial, administrational, technical, maintenance, visitor services etc
- Performance measurement and review

In reality these are less well defined than a simple list suggests. Some are explicitly documented while others are more implicit ways of working. Some processes are duplicated between the operational side of the organisation and the visitor services. In principle each process has a role in helping the organisation achieve its overall purpose.

At present there are no specifically sustainable processes or sustainability management. However, each process will have the potential to have an impact on the sustainability of the organisation.

10.4.4 Controls

Overall, the CSBT has several forms of controls in place to ensure that it is doing what it planned to do and that it is complying with applicable legislation and regulation. These are:

- Standards and codes of practice – (voluntarily) comply with requirements of the Design Manual for Roads and Bridges, require suppliers are ISO 9001 accredited
- Legislation – comply with Charity Commission requirements, Health and Safety at work etc.
- Performance targets – achievement of sufficient revenue, crossing availability, crossing speed
- Governance structure – organisation of the board of Trustees and committees within
- Organisational structure – organisation and division of tasks amongst staff
- Business model – tolling structure, maintenance of reserve fund, self sufficiency of visitor centre
- Audit – formal financial audit, informal benchmark against other bridge operators

10.4.5 Issues

The issues that the CSBT faces are typically related to uncertainty. There is uncertainty over how the changing demand will affect the CSBT, with a noticeable increase in people using public transport, walking or cycling. Means of securing financial stability and alternative business models if tolling is no longer sufficient could become a major issue. The asset is old and there are elements of the structure that are still not well understood today. Examples of this are the ongoing geotechnical investigations and aerodynamic assessments, both a result of the bridge being designed and built in a time before these were understood.

Other issues are a result of competing and conflicting demands. Because of the dual nature of the bridge's purpose, there will always be a tension between providing a service (i.e. the bridge) and a maintaining a historically and culturally significant icon for the city.

10.4.6 Capitals

The Five Capitals model states that for an organisation to be sustainable it needs to maintain or even replenish these stocks of value rather than constantly deplete them (Forum for the Future). It expands an organisation's notion of value beyond purely economic to consider the environmental and social aspects, often referred to as the three pillars (United Nations 2005) or the triple bottom line (Elkington 1997). However, it goes further to include human capital and manufactured capital. Together the five capitals give a well rounded basis from which to assess the sustainability of an organisation. Table 10.1 gives a brief description of each.

Table 10.1: Description of Five Capitals

(Forum for the Future)

Capital	**Description**
Natural	Environmental or ecological capital, natural resources and processes that the organisation interacts with order to deliver their outcomes
Human	The capital of the individual includes their health, knowledge, skills, outputs, motivation and relationships.
Social	Internal to the organisations this includes the culture, values, Trust and communication. External to the organisation this can include society in general and specific structures such as government, legal systems etc.
Financial	Financial assets owned by the organisation that can be traded e.g. shares, bonds and currency.
Manufactured	The physical elements used by the organisation that contribute to it delivering its outcome, but that are not specifically part of the outcome.

Resilience capital has been included as the sixth capital. It was felt that resilience was a source of value or capital for an organisation or system and that it was not adequately captured within any of the other five capitals.

Resilience and sustainability are often found together in literature. Similarly to sustainability it has roots in ecology and has no single accepted definition. For the purposes this study the definition used shall be the “ability of an organisation to anticipate, prepare for, and respond to incremental change and sudden disruptions in order to survive and prosper” (British Standards Institution 2014).

Resilience may be seen as a sort of meta-capital that sits above the other five. It requires necessary and sufficient reserves of the other five capitals and also the ability to release and utilise them, as and when required. In order to effectively draw on these other capitals, the system needs to have clarity of purpose and a vision of the desired future state. Agency or the ability and authority to make these decisions is also required. A sense of value means that there is a clear cohesive view on the how the purpose of the organisation translates into value at a societal level. Awareness is also vital, including a sense of the past and the future, the situation and context, values, ethics and culture, wants and needs and strengths and weaknesses.

10.5 Measurement Criteria

For sustainability assessment of the CSBT, the Halstar framework was used to explore a broad range of elements of the organisation. The Halstar framework breaks each capital into sub categories and then elements. Resilience capital has been broken down to the same level of detail.

Initially, relevant data was entered into the framework. It was primarily qualitative in nature. Each element was then considered in turn and classified according to the definitions in Table 10.2. This enabled a visual representation of areas of good performance and quickly highlighted risks and areas for improvement.

Table 10.2: Assessment Criteria

Colour	Meaning	Key
Dark red	Unaware or not considered the (potential) issues and not managing	
Red	Partially unaware or not considered the (potential) issues and not managing	
Amber	Aware of (potential) issues but not managing	
Yellow	Aware of (potential) issues but only partially managing / plan in place to partially manage	
Green	Aware of (potential) issues and proactively managing or plan in place to manage	
Grey	Considered (potential) issue and found N/A	

10.6 CSBT

The assessment of the CSBT sustainability has been carried out primarily from an internal perspective. A lot of the data comes from an interview with the Bridgemaster (overall manager) using the Halstar framework to explore the different dimensions of sustainability. The remaining data comes from the knowledge and experience of the author, who works within the organisation.

The top level results are shown in Table 10.3 and discussed in more detail in the following sections.

Table 10.3: Sustainability Assessment of Clifton Suspension Bridge Trust

Capital Type	Sub Category	Element	
Resilient	Purpose	1.1	Clarity of purpose
		1.2	Vision
	Agency	1.3	Sense of value
		1.4	Awareness
		1.5	Agency
	Resources	1.6	Resources
		1.7	Resourcefulness
Natural	Environmental quality	2.1	Acoustics
		2.2	Air quality
		2.3	Water quality
		2.4	Drainage and flooding
	Biodiversity	2.5	Ecological protection and enhancement
	Resource use	2.6	Materials
		2.7	Waste
		2.8	Water resources
		2.9	Land use and soils
		2.10	Food
	Climate change	2.11	Greenhouse gas emissions
		2.12	Climate adaptation
		2.13	Energy production
		2.14	Energy efficiency
Human	People	3.1	Travel and telecommunication
		3.2	Happiness and motivation
		3.3	Equity
		3.4	Knowledge and skills
	Health and Safety	3.5	Health
		3.6	Safety
		3.7	Security
Social	Governance	4.1	Stewardship and change
		4.2	Cultural heritage
		4.3	Regulation and ethics
	Community	4.4	Crime and nuisance
		4.5	Cohesion and development
		4.6	Participation

Financial	Value and risk	5.1	Economic impacts
		5.2	Employment and productivity
		5.3	Risk
	Reputation	5.4	Communication
		5.5	Stakeholder relationships
		5.6	Behaviour and conduct
Manufactured	Design and development	6.1	Quality and innovation
		6.2	Adaptability
		6.3	Management and design process
	Supply chain	6.4	Supply chain management
		6.5	Site management
	Operations	6.6	Operational infrastructure

10.6.1 Resilience Capital

In general, the CSBT appears to score well on most aspects of resilience capital. There is implicit agreement on the purpose, vision, sense of awareness and agency of the organisation. While the mission statement is documented, there may be value in explicit capture of the other elements. This will useful for people new to the organisation and having this type of information captured may provide the prompt for intentional review of it in future. The sense of value is less well defined, specifically how the value delivered by the CSBT can be quantified and how it contributes to wider societal outcomes. A better understanding of this may help in ensuring the organisational purpose remains relevant and also in developing a truly sustainable approach to governance and management, accounting for all types of capital. Finally, the CSBT is less mature in resources and resourcefulness. This is not because they lack them, but because they do not currently think about their resources as a contributor to their resilient capital. The concept of resilience has not been explored and there is no explicit statement on what it means for the Trust.

10.6.2 Natural Capital

The CSBT generally has a well considered proactive approach to environmental issues and a low impact on natural capital. This is partly due to its location above the Avon Gorge (designated a site of Special Scientific Interest) which means that great care has to be taken to contain materials used on the bridge and dispose of them appropriately. Again, it may be beneficial to explicitly document the Trust's position on these elements as it would provide a guide for all staff as well as contractors.

One area where improvement is possible is in awareness, selection and control of materials. The CSBT relies on their suppliers to ensure that they are using appropriate materials, where they could potentially take a more proactive approach to identifying the most sustainable and least hazardous options. Also, there are occasions where stock control has meant disposal of unused material due to the shelf life.

There is also potential to better understand the provenance of the food products procured by the Trust for its own consumption and for sale in the visitor centre.

The main area of concern identified is climate adaptation. There has been little thought given to the impacts of long-term climate change on the organisation and what the CSBT could do to mitigate this. Climate change may not be a significant risk directly to the bridge, but it could have indirect effects that will in turn have an impact. In light of the uncertainty surrounding this, it would appear to be an area for further consideration.

10.6.3 Human Capital

Two potential issues were identified under human capital. These are the somewhat irregular approach to annual staff reviews and knowledge capture and data management. There is an aspiration to carry out annual reviews with all staff, but they do not always take place. This means that the CSBT is missing the opportunity to formally work with people on an individual level to ensure that they are satisfied and progressing within their role. This could have an impact on motivation and also may limit identification of training needs.

Data management and knowledge capture are recognised as areas that need improvement and work is underway on developing an approach for managing the written information that belongs to the CSBT. The way forward for capturing and utilising individuals' tacit knowledge and experience is not so well understood however. There was also recognition that more information about the organisation could be shared with new starts into the organisation to enable them to understand the purpose of the organisation.

10.6.4 Social Capital

In terms of social capital, the CSBT scores well. Most elements have been considered even if they have not necessarily been recognised as contributing to organisational sustainability. The only issue that was noted was regarding communication. As a charity, the CSBT is not obliged to publish as much information as other organisations. The CSBT take the view that the less they publish, the less likely they are to be misrepresented. There are also some varying opinions on how well communication works both internally and externally. It may be useful to document the communications policy and publish it so that everyone is clear on what information is available and how they can expect to receive it.

10.6.5 Financial Capital

The issue identified related to financial capital was around understanding the economic impacts of the organisation. It is recognised that the organisation creates and possesses value that is not easily measurable in financial terms, this is not well defined or documented. Consideration has not been given to the financial value of the other types of capital and how they contribute to the organisation's performance.

Again, there is the issue of communication, as the CSBT only publish the financial accounts as required by the Charity Commission. The intention is to protect the organisation, but it results in what may be perceived as a lack of transparency.

10.6.6 Manufactured Capital

The CSBT owns a range of manufactured capital that enables it to achieve its outcomes. In general, the organisation is innovative in the solutions it implements and tries to utilise new technologies when appropriate. The organisation is not itself accredited to a quality standard, but it does require that all suppliers and contractors are accredited to ISO 9001.

The issue identified was with adaptability. Many of the systems are bespoke due to the uniqueness of the bridge, its location and historical importance. The bridge itself has been adapted to meet the demands of current users. However, there is a limit to how much the CSBT could adapt to future conditions. For example, if cars were to get significantly heavier in future or if car use was to decline substantially, this would significantly impact the Trust's ability to continue to fulfil its duty. It is not clear that the Trust has adequately thought through possible future scenarios, documented possible courses of action or considered how the notion of resilience may help them.

10.7 Recommendations and Opportunities

From the sustainability assessment carried out, the issues identified have been highlighted and are summarised in Table 10.4. Alongside each issue is a statement on recommended action and the opportunity for additional value that action would result in. In each case there would be some benefit to the organisation aside from simply improving its sustainability rating e.g. time saving, cost saving, positive impact to reputation. It is recognised that some of these are not straightforward to implement but by seeing the potential additional side benefits, it might be more attractive to the CSBT to address them.

Table 10.4: Summary of Assessment and Identification of Opportunities

Element	**Identified Issue**	**Recommendations and Opportunities**
Sense of value	Value delivered by the CSBT not well defined or quantified, neither is how it contributes to wider societal outcomes	Better understanding of value and contribution may help ensure continued relevance of organisational purpose and develop a sustainable approach to governance and management
Resources	Lack of recognition of extent of resources that the CSBT has, also means that gaps are not identified	Exploring the full range of resources may identify alternative sources of value for the CSBT Potentially also identify any gaps that could result in risks
Resourcefulness	Do not currently think about their resources as a contributor to their resilient capital	Understanding the notion of resilience and the strengths of the organisation to be resourceful will enable the CSBT to plan for different future scenarios and cope with uncertainty
Materials	Reliant on suppliers for selection of appropriate materials Over ordering and poor stock control can result in waste of unused material	Taking a more proactive approach to identifying the most sustainable and least hazardous material options may have health and safety benefits and will also mean the CSBT is a better informed customer Better control of stock and shelf life will reduce environmental impact of waste and cost or purchase and disposal

Food	It is not known if food products procured are from sustainable sources	Opportunity to select products on best overall value rather than just best price Can benefit brand and reputation if CSBT can say it only uses sustainably produced products
Climate adaptation	Limited consideration of impacts of long term climate change on the organisation and what CSBT could do to mitigate	Identifying and understanding potential impacts of climate change and mitigations will enable organisation to plan strategically and identify risks that may have otherwise not been considered
Happiness and motivation	Irregular approach to annual staff reviews Potential for better induction information for new starters	Regular staff reviews may improve staff motivation and engagement and also provide an opportunity for the CSBT to receive feedback. May also improve identification of training needs. An improved induction process will speed up the process of learning about the CSBT and becoming familiar with the role and the culture. The quicker this happens, the sooner that person is performing to their full value potential.
Knowledge and skills	No consistent knowledge capture and data management processes in place, what happens is ad-hoc	Improvement of data management and development of a policy is in progress There is a wealth of tacit knowledge and experience that would be beneficial if captured and shared, reduces need to start everything "from scratch", saving time and money
Economic impacts	Lack of understanding and accounting of economic impact of non-financial capitals	Opportunity to quantify the organisation's other sources of value. This may enable a more holistic approach to decision making where the benefits of decisions based on multiple criteria can be better understood. May also identify alternative revenue streams that could support long term financial stability.
Communication	Varying opinions on how well communication works internally and externally	A documented communications policy would ensure consistency and clarity and manage expectations with regard to what information is available and how it is communicated. This could save time, aid interactions with the public and improve reputation

Adaptability	Perceived limit to adaptability of CSB and CSBT and supporting systems. There are certain limiting factors, but potential future scenarios have not been fully explored to understand impact and mitigation	By considering some potential future scenarios, the CSBT can judge whether their resourcefulness is sufficient i.e. do they have the necessary resilient capital. They will be able to identify gaps or weaknesses and address these. By practicing this process of learning how to deal with such issues, when something does happen they should be more effective at managing it.

10.8 Conclusions

This study has used the generic structure of organisational elements model developed in Chapter 8 and shown in Figure 10.2 to structure a sustainability assessment of the Clifton Suspension Bridge Trust. The assessment itself was carried out using an adapted version of the Halstar framework, including the additional resilient capital. The assessment was carried out primarily from an internal perspective, although taking into account some external viewpoints. The assessment captures a snapshot in time. The assessment highlighted specific issues as well as demonstrating many areas of proactive management. The issues identified have been considered further and recommended actions, with potential benefits and opportunities, have been highlighted. This should enable the CSBT to see a broader business benefit to some of the actions, beyond simply improving the sustainability rating.

It would be both useful and interesting as a next step to formally include a broader range of stakeholder views, particularly in light of the insights from the stakeholder analysis. It would also be beneficial to apply the framework over various time horizons to build on today's snapshot and look in more detail at the medium to long term.

11 Technical Projects

11.1 Overview

In addition to the organisational interventions presented in Chapter 9, there were also examples of applying systems thinking to technical problems. The purpose of this, in both cases, was to understand whether these issues can be looked at in a different way and if so, what the outcome and potential benefit could be.

A study was carried out looking at how the structural interactions between the different bridge components could be used to improve the risk assessment and management process. A design structures matrix approach was applied to the grouping of bridge components into subsystems.

The Trust had expressed a desire to fatigue test the spare bridge hangers after the unexpected failure of one of the hangers. The study involved taking a systematic approach to the hangers overall, looking at the historical information available, the state of the art in wrought iron testing and material properties, information regarding previous hanger failures and the work that was carried out to investigate the cause of the recent failure. In addition, the purpose of testing the hangers was explored to determine what the uncertainties were and what the expected outcomes were.

11.2 Design Structure Matrix Application for Risk Management at the CSBT

11.2.1 Risk Management at the CSBT

The Trust is concerned with its ability to classify and prioritise risks, particularly related to the physical assets it owns. Robust risk management should enable the CSBT to deploy funds appropriately to mitigate risks and protect the long term performance of the bridge (van der Velde et al. 2012). In recent years, the Trust has been more proactive and structured in its approach to risk management. The consulting engineers, Flint and Neill, were asked to carry out a comprehensive structural risk assessment in 2010. This was based upon previous studies, including a risk assessment undertaken in 1999 and the present condition of the bridge (Flint and Neill 2010). The current condition is well understood and documented as the bridge is subject to annual inspections, together with specialist monitoring and regular examination by bridge staff.

This risk assessment then formed the basis of the ongoing risk management process. The risk assessment is reviewed annually at a dedicated meeting of the technical committee and consulting engineers and it is then updated as necessary when priorities change, or work is completed. The risk review includes the following sections (Flint and Neill 2010):

- Assessment of Individual Bridge Parts
- Events Leading to the Failure of Structural Sections
- Events Leading to Damage / Injury to Staff
- Preparation for and Reaction to Events.

Individual bridge parts are assessed, by means of a risk register that details each component with its location and description. The register records information regarding accessibility, visibility, vulnerability to environmental degradation, whether it is possible to remove it for inspection and any known defects. The component is given a "Preliminary Allocation of Risk Rating" in the range 1 to 5. This number is based on a qualitative assessment of the risk.

A question the Trust is keen to answer is whether there are gaps in the risk assessment due to unforeseen hazards. For example, in 2009 a wrought iron hanger failed in fatigue (Flint and Neill 2010). Looking back previous risk assessments prior to this event, it had been the common consensus that the hangers were not susceptible to fatigue failure. Therefore, this failure was unexpected and unforeseen. Another potential source of uncertainty could come from the interaction between the risks. Risk registers, including the CSBT's, typically list each risk individually and do not consider that they may be linked.

The application of Design Structure Matrix (DSM) in the assessment of risk may provide a useful insight into the links between different risks and how they are coupled.

11.2.2 Design Structure Matrices

Design Structure Matrices are used to model a system, representing the constituent elements and the interactions that occur between them. It is a network modelling tool that can be useful in representing the architecture or structure of the system (Eppinger and Browning 2012). Don Steward's theory in the 1960's was that problems could potentially be solved by a decomposition of the system into a square matrix, where the number of rows and columns is defined by the number of system elements. The matrix is then populated to show the relationships between system elements (Austin et al. 2000).

According to Eppinger (Eppinger and Browning 2012), there are three major types or applications of DSM, i.e. Product, Organisation and Process. There are also Multiple Domain Matrices (MDM) which combine more than one type of DSM and allow relationships between elements from different domains to be considered (Maurer and Lindemann 2007). The advantages of working with DSMs are that they display "the relationships between components of a system in a compact, visual, and analytically advantageous format" (Browning 2001).

DSM's have not been applied extensively within infrastructure or risk management, with references limited to research carried out at Loughborough University and the VTT Technical Research Centre in Finland (AUSTIN et al. 1999, Newton et al. 2007).

There are operations such as clustering, sequencing, partitioning and tearing which can be performed on the matrix to reorder the activities and reduce the size of iterations in order to optimise the process.

In applying DSM there are five main stages (Eppinger and Browning 2012):

1. Decompose: reduce the system to its elements
2. Identify: identify the relationships between the elements
3. Analyse: identify patterns and behaviour in the system by rearranging the elements and relationships
4. Display: demonstrate useful or interesting information revealed by the DSM system representation
5. Improve: provide better understanding and improvement of the system through insights gained from DSM representation of the system

For stage 3, once the DSM has been created, there are then operations which can be performed in order to identify patterns and behaviour in the system. This involves rearranging or partitioning the matrix. There are two common methods used and these are clustering and sequencing. Clustering is more commonly applied to product or organisation DSM models as the interaction marks are typically symmetrical around the diagonal. Clustering involves reordering the matrix to group the elements together which helps to identify sub systems or modules within the product or organisation. Sequencing is more common in process DSMs where there is a directional or time based structure to the model. Sequencing is concerned with rearranging the activities in the DSM such that they occur in the optimal order and identifying loops or iterations in the process.

11.2.3 Application to the Clifton Suspension Bridge

The CSB has many individual components that are arranged into bridge part groups. For example, the cross girder (under footpath) group includes the following components:

- Top chord (parapet to longitudinal girder)
- Bottom chord (parapet to longitudinal girder)
- Lattice members 27/28 to 24/25
- Lattice members 23/24 to 16/17
- Lattice chord connection

In the risk assessment, each of the individual components and specific risks are considered in turn. However, each is considered individually and there is nowhere within the risk register to record interactions between individual components and between different bridge parts.

The researcher proposed that when assessing the risk, it may be useful to look at the load path through the components and the interactions between the different groups. For example, live loading is input to the bridge deck from traffic. The deck is supported physically by both the longitudinal girders and cross girders so there is a direct connection and load path between these three groups.

To evaluate this, the major bridge part groups were mapped onto a DSM as shown in Figure 11.1. These groups are similar to those used in the risk assessment but simplified for ease of manual manipulation and understanding of the DSM. Figure 11.1 shows the initial DSM for the CSB, which was created manually in a spreadsheet. In this case the marks in the rows show the inputs to that row e.g. for the cross girders in row *D*, there are load inputs from *A* (pedestrian barriers), *B* (lattice parapet girders), *C* (bridge deck) and *E* (longitudinal girders). The marks in the columns indicate where the loads are output to. For the chains in column *G*, there are load outputs to *E*, *F*, *H*, *I* and *L*. The inputs are the component groups from which the load comes and also the component group immediately before that one. The outputs are the component group where the load goes and also the component group immediately after that one. For example, cross girders output load to the bridge deck and longitudinal girder as they are attached to both of these. However, through the longitudinal girder, they are also transferring load to the hangers.

The system boundary is considered to be the structure of the bridge from the Leigh Woods abutment and anchorage to the Clifton abutment and anchorage including everything in between.

The elements were arranged and labelled *A* to *M* in the order that the loads are understood to be transferred through the structure. This means that load enters the structure at the top left hand side and works its way out through the bottom right hand side. Any entry below the diagonal shows an element that is dependent on an input of load from an element before it in the matrix. A mark above the diagonal suggests an element that expects a load input from another element, before that element has been reached in the load path (Austin, Baldwin, Li, Waskett, 2000). This may of course be due to parallel load paths or an incomplete understanding of the structure.

		Pedestrian Barriers	Lattice Parapet Girders	Bridge Deck	Cross Girders	Longitudinal Girders	Hangers	Chains	Saddles	Towers	Clifton Abutment & Wing Walls	Leigh Woods Abutment & Wing Walls	Anchorages	Articulated Span
		A	B	C	D	E	F	G	H	I	J	K	L	M
Pedestrian Barriers	A													
Lattice Parapet Girders	B	0		0										
Bridge Deck	C	0	0		0	0								
Cross Girders	D	0	0	0		0								
Longitudinal Girders	E			0	0		0	0						
Hangers	F			0	0	0		0						
Chains	G					0	0		0				0	
Saddles	H						0	0		0			0	
Towers	I							0	0		0	0		
Clifton Abutment & Wing Walls	J								0	0				
Leigh Woods Abutment & Wing Walls	K								0	0				
Anchorages	L							0	0					
Articulated Span	M													

Figure 11.1: Initial DSM for the CSB

An empty row in the DSM shows that the element does not depend on a preceding element and can therefore be moved to the start (top). An empty column shows that the element does not feed into a following element and can therefore be moved to the end (far right) (Gebala, Eppinger, 1991). In this case, where an element has both an empty row and column, it has been sorted according to row and moved to the start.

The DSM was then reordered to try to maximise the number of marks close to or below the diagonal. As element *M* had an empty row this was moved to the start. Figure 11.2 shows the CSBT DSM with all marks either below the diagonal or in the next square above it. From Figure 11.2 it can be seen that there is potential to cluster elements together.

		Articulated Span	Pedestrian Barriers	Lattice Parapet Girders	Bridge Deck	Cross Girders	Longitudinal Girders	Hangers	Chains	Anchorages	Saddles	Towers	Clifton Abutment & Wing Walls	Leigh Woods Abutment & Wing Walls
		M	A	B	C	D	E	F	G	L	H	I	J	K
Articulated Span	M													
Pedestrian Barriers	A													
Lattice Parapet Girders	B		0		0									
Bridge Deck	C		0	0		0	0							
Cross Girders	D		0	0	0		0							
Longitudinal Girders	E				0	0		0	0					
Hangers	F				0	0	0		0					
Chains	G						0	0		0	0			
Anchorages	L								0		0			
Saddles	H							0	0	0		0		
Towers	I								0		0		0	0
Clifton Abutment & Wing Walls	J										0	0		
Leigh Woods Abutment & Wing Walls	K										0	0		

Figure 11.2: Iteration of the CSB DSM

Clustering is a form of partitioning analysis. The aim is to group the elements together by reordering the rows and columns in order to form modules with common interactions. Objective functions can be used to carry out clustering by trading off between minimising the number of interactions outside clusters and minimising the size of clusters.

Using the form of the DSM given in Figure 11.2, different clusters were formed around the elements and the objective function was calculated as a measure of how effective the clustering was, see Figures 11.3 and 11.4. The lower the objective function is, the fewer the number of interactions outside of the cluster and also the smaller the size of the clusters. It can be seen that Figure 11.4 gives the lower Objective Function and therefore, offers a reasonable identification and grouping of clusters.

Number of marks outside clusters = 3 Size of clusters = 4, 4, 4, 4 **Objective function = 940**		Articulated Span	Pedestrian Barriers	Lattice Parapet Girders	Bridge Deck	Cross Girders	Longitudinal Girders	Hangers	Chains	Anchorages	Saddles	Towers	Clifton Abutment & Wing Walls	Leigh Woods Abutment & Wing Walls
		M	A	B	C	D	E	F	G	L	H	I	J	K
Articulated Span	M													
Pedestrian Barriers	A													
Lattice Parapet Girders	B		o		o									
Bridge Deck	C		o	o		o	o							
Cross Girders	D		o	o	o		o							
Longitudinal Girders	E				o	o		o	o					
Hangers	F				o	o	o		o					
Chains	G						o	o		o	o			
Anchorages	L								o		o			
Saddles	H							o	o	o		o		
Towers	I								o		o		o	o
Clifton Abutment & Wing Walls	J										o	o		
Leigh Woods Abutment & Wing Walls	K										o	o		

Figure 11.3: Clustering Arrangement 1

Number of marks outside clusters = 1 Size of clusters = 4, 4, 5, 4 **Objective function = 830**		Articulated Span	Pedestrian Barriers	Lattice Parapet Girders	Bridge Deck	Cross Girders	Longitudinal Girders	Hangers	Chains	Anchorages	Saddles	Towers	Clifton Abutment & Wing Walls	Leigh Woods Abutment & Wing Walls
		M	A	B	C	D	E	F	G	L	H	I	J	K
Articulated Span	M													
Pedestrian Barriers	A													
Lattice Parapet Girders	B		o		o									
Bridge Deck	C		o	o		o	o							
Cross Girders	D		o	o	o		o							
Longitudinal Girders	E				o	o		o	o					
Hangers	F				o	o	o		o					
Chains	G						o	o		o	o			
Anchorages	L								o		o			
Saddles	H							o	o	o		o		
Towers	I								o		o		o	o
Clifton Abutment & Wing Walls	J										o	o		
Leigh Woods Abutment & Wing Walls	K										o	o		

Figure 11.4: Clustering Arrangement 2

The first thing that is clear from Figure 11.4 is that the articulated span remains outside of any cluster as it has no dependency on any other element in the DSM. Looking at the four clusters identified, from the top of the matrix down, they can be named the Pedestrian

Barrier Subsystem, the Deck Support Subsystem, the Suspension Subsystem and the Foundation Subsystem. This fits with typical breakdowns of bridge structures into subsystems (Blockley 2010a).

11.2.4 Summary

There is clearly a great deal of interaction and overlap between the clusters with many elements belonging to two clusters. However, it may be useful to consider these subsystems of bridge parts when carrying out risk assessments. If each component is assessed in isolation during the risk assessment, there is no way of formally capturing the impact of these risks on the other components that share the load path. When assessing the immediate impact of the risk to the particular component, this may not sufficiently evaluate the risk to the overall structure.

Using the DSM in this way to highlight interactions between elements and to identify sub-systems within the bridge structure can aid the risk identification and risk analysis process. It is envisaged that this bottom up approach would be useful in conjunction with other top down techniques such as fault tree and event tree analysis. Fault tree and event tree analysis determines the probability of identified events happening (Ahmed, Kayis and Amornsawadwatana 2007). This DSM approach could help in understanding the impact of that event on other parts of the bridge structure.

This is a simplified application of the methodology to an artificially restricted top-level model of the physical bridge system. However, it would suggest that there may be benefit in investigating this further and expanding the DSM to include a greater level of granularity. The interconnections considered here are only the load path between component groups, but it may be useful to apply this methodology to the organisation and its processes to evaluate the overall system risk more holistically.

11.3 Hanger Fatigue

The Clifton Suspension Bridge has 162 hangers which connect the suspension chains to the bridge deck. The hangers and most of other original metallic bridge components were manufactured from wrought iron, as they date from before cast iron was industrially available. The hangers are connected to the suspension chains with a single pin and to the bridge deck (through the longitudinal girder), thus in a pinned-pinned condition free to rotate at either or both ends. In reality, for the particularly long hangers they have enough flexibility between the two joints that they rarely rotate but instead deflect along their length.

On the 4th of April 2009, a member of the public reported that a hanger on the Leigh Woods North side of the bridge was broken. The bridge was immediately closed to vehicles and pedestrians while supports were put in place. A temporary hanger was then manufactured and fitted. The broken hanger was examined by Bodycote Testing Ltd to determine the cause of failure. The testing and inspection of the broken hanger found that the hanger failure was due to fatigue cracking, initiating from surface and sub-surface cracks in the material (Flint and Neill 2009). It was also determined that to cause fatigue loading within the hanger, one or both of the joints at either end of the hanger must have seized.

Magnetic particle inspection (MPI) of the remaining hangers commenced to determine their condition. The short hangers in the middle third of the bridge were fully inspected using MPI and the long hangers were inspected at the top and bottom, believed to be the critical locations. The MPI found cracks and indications in the hangers but only those that met all of the following criteria were generally considered significant enough to warrant further investigation:

- Cracks/indications near the top or bottom of the hanger as this was where fatigue cracking was most likely to occur
- Cracks/indications running horizontally and perpendicular to the bridge axis
- Cracks/indications greater than 10 mm in length

The defects meeting these criteria were removed by gentle grinding to a maximum depth of 3 mm. If the defect was still present after grinding, then the hanger was replaced. This was the case for five hangers. A further three hangers were found to have severe longitudinal laminations in the bottle screws and were replaced. Another hanger had been permanently deformed in the past and was also replaced. This was thought to be caused by overloading in compression during previous hanger removal procedures.

11.3.1 Hanger Testing

The fatigue failure of the hanger was an example of an undetected and unexpected sudden failure. It was disruptive and resulted in the bridge being closed while initial measures were taken to understand the failure and protect the rest of the structure. Further partial bridge closures were then required during the testing and removal of the hangers.

The Trust and consulting engineers expressed a desire to test the hangers that had been removed and replaced, to gain a better understanding of the fatigue performance. The researcher was tasked with carrying out such a study to provide the Trust with the necessary evidence to make a decision on whether further work was required to safeguard the hangers against future fatigue failures.

Fatigue testing could help to ensure no further unexpected hanger failures by providing empirical data on how long it takes for a representative specimen to fail after the pin becomes seized. This information could then be used to ensure that the inspection interval for pin rotation is sufficient to identify pin seizure before the minimum time to failure. It may also provide a better understanding of crack growth which will in turn support the selection of appropriate inspection methods and intervals to ensure that fatigue cracks are identified before they reach critical crack length.

11.3.2 Background Study

The researcher took a systemic approach to this study, exploring the system boundary of the problem, and the hangers' purpose and performance overall before considering testing. Initially to try to gain as comprehensive an understanding of the problem as possible, the researcher carried out a thorough review of the Trust's information on the hangers and other wrought iron components. A literature review was also carried out more generally looking into the history of wrought iron, its manufacturing processes, material properties and strength and the current state of the art in testing.

In addition, the purpose of testing the hangers was explored to try to determine what the uncertainties were and what the expected outcomes were.

As the fatigue strength of a material is dependent on both stress (S) and number of cycles (N), the results of fatigue testing are typically displayed as Wöhler Curves or S-N curves.

To ensure statistical significance of the testing and resulting curves, a reasonable number of specimens need to be tested, for example five at each specific stress level to create a data point on the curve. The fatigue limit is the highest stress amplitude for which failure does not occur even after a high number of load cycles and would be seen as a horizontal asymptote on the S-N curve.

In order to establish and make use of these S-N curves, there needs to be some understanding of the conditions the structure is exposed to. Typical stress levels need to be understood together with the nature of the loading, for example is it fully reversed or tension-tension, is it constant amplitude or variable amplitude. If the conditions are not well understood, there is likely to be significant uncertainty in the test results and difficulty in interpreting them for the structure.

For the CSBT, it was found that there was uncertainty regarding both the stress (amplitude and spectra) and number of cycles. The live load is a combination of traffic and weather loading. Both are obviously variable, and the nature of traffic loading has changed significantly over the life of the bridge. The effect of wind loading on the bridge is variable in terms of both magnitude and direction.

The bending effect of the worst case traffic load on a hanger with a seized pin has been calculated but this does not include the effects of wind. Additionally, the assumption of complete pin seizure may not be the most realistic case. It is possible that hanger rotation could instead be restricted due to friction in the joint.

The load spectrum or load time history gives the number of cycles at different amplitudes over the life of the structure. For the bridge, this is unknown as there is no record of the frequency or magnitude of traffic or wind loading. In addition, this load spectrum is only relevant to hanger fatigue if one of the pins is restricted or seized. It is believed that the hangers were all checked in the past by Howard Humphreys to ensure free rotation. However, there is no way to tell whether some of the hanger pins were seized prior to this and had therefore already been subjected to some fatigue loading before being freed.

Understanding how number of cycles relates to the life of the bridge is also uncertain. It is likely that only large vehicles, heavy traffic loads or high winds from particular directions are going to actually have an effect on the structure. The traffic loading is random and not currently recorded. Some weather data exists along with the structural response, but this is incomplete and only available for recent years. Therefore, work would be required to understand a conversion from the number of cycles until failure into time until failure.

Cullimore, referring to the Clifton Suspension Bridge, states that “consideration has been given to the possibility of finding the rate of propagation of a fatigue crack, once started, to enable an estimation of the survival of a cracked component to be made. Because of the uncertainty of obtaining consistent results with wrought iron, and the necessity of making measurements on the bridge to discover the number of loadings causing damage which the component is likely to suffer, this has been deferred” (Cullimore 1972). It is evident that the issue has been considered at least once in the past and not resolved.

In addition to stress and number of cycles, it is also important to consider corrosion. Corrosion may affect the residual fatigue life of a component as it reduces ductility. This can result in considerable variability in residual fatigue life if severe corrosion has taken place, in other words another source of uncertainty.

Generally, it was found that there were too many sources of uncertainty for meaningful testing to be carried out using the remaining bridge hangers. While testing could have been conducted and the fatigue life after hanger seizure found, this would not necessarily be helpful for understanding the remaining life on the existing hangers. Without accurate records, there is no way to know if they had been seized in the past and how long for. In addition, no comprehensive data sets exist that combine all live loading and give an accurate representation of what the likely fatigue load and cycles would be.

The background, literature and archive review and recommendations were all captured in a report that was produced for the technical committee, see Appendix E.

11.3.3 Inspection and Recommendations

Since the hanger failure, the Trust have reviewed and updated the hanger inspection and maintenance programme. The researcher reviewed this with the benefit of the knowledge form the background report produced. The aim is that the new inspection routine is sufficient to identify any damage or defects in the critical areas of the hangers before failure or loss of load path occurs. The researcher found that in addition to the regular visual inspections for defects and damage, it may be necessary to carry out detailed inspection of the short hanger joints to ensure freedom of rotation more frequently than is currently being carried out. The short hangers are considered to be from hanger 0 to hanger 16 which equates to 66 hangers. At the present rate of 4 per year, it would take 17 years to complete one cycle of inspection. This frequency may therefore have to be adjusted depending on the degree of wear found in the bearings during the early inspections.

As stated, the fatigue testing of the hanger material will not be of any additional benefit over the inspection regime, particularly in light of the significant uncertainties over the conditions the bridge is subject to. In future, if some of the uncertainties are resolved or better understood or if there is a specific requirement for further information then testing may prove useful.

In order to carry out fatigue testing on the hanger material in future, the uncertainty in the fatigue stress and number of cycles needs to be addressed. This could be achieved by strain gauges applied to the structure to gather the required data for worst case and typical loading. Development of an approach to determine the residual fatigue load in the hangers and the relationship between load cycles and life of the structure is also required. There are emerging technologies which may be of benefit, such as neutron diffractometry which is capable of measuring the strain deep within a crystalline material. This can then give the internal and residual material stresses which affect properties such as fatigue resistance, fracture toughness and strength.

While the uncertainty around the fatigue life of the wrought iron hangers has not been resolved, measures are now in place to prevent a similar failure in future. Testing would offer more evidence to the Trust for future maintenance and decision making however, the testing that would have taken place in the scope of this project would not necessarily have addressed the key questions. The recommendation to postpone testing until there is more loading data available protects the Trust's resources. Otherwise, the limited material may have been depleted by testing and funding used up.

The researcher came to these conclusions through taking a systemic view on the role of the hangers within the greater system, through reviewing available literature and hence understanding the difficulties involved with such a testing campaign and by exploring the purpose of such testing to the Trust. The Bridgemaster reviewed and accepted the recommendations and presented them to the technical committee.

11.4 Conclusions

The purpose of this Chapter is to illustrate that by approaching problems in a different way, interesting outcomes can be achieved. The risk management process at the CSBT was not updated to take into account the subsystems identified, partly because the study carried out was only to identify feasibility. A more detailed analysis would need to be performed, looking closely at the many different interdependencies and load paths through the structure.

The outcomes from the hanger study, however, did influence the way that the organisation proceeded with hanger testing. The objective was not to stop testing but to ensure that any testing carried out provided the answers to the questions that were being asked. It was found that due to the uncertainty in how the system was behaving, there was no way to define the testing parameters or validate if the test data provided reliable answers. Hence, in the short term the best course of action was continued maintenance and inspection. Over the longer term, a set of recommendations was made on what needed to be done to enable those tests to be carried out successfully.

12 Discussion and Conclusions

12.1 Introduction

The purpose of this thesis was to address the four research questions through a series of different studies. The studies were carried out by the researcher while based in the CSBT organisation for a period of four years. In this Chapter, each question shall be revisited, and the outcomes reviewed. The impact for the CSBT shall be discussed along with the academic novelty. The suitability of the research questions shall be considered and the contribution of the work to addressing the identified gaps in the literature shall be reviewed.

12.2 Reviewing Question 1

The first question to be answered was:

What is asset management, particularly in the context of infrastructure provision?

This research question was addressed through the literature review presented in Chapter 3 and also within the asset management classification approaches outlined in Chapter 6.

It was shown that there are many definitions of both asset and asset management with no general agreement on semantics. Not only is there no agreement on the definition of asset, there are also different approaches to classifying the type of asset including hard and soft, tangible and intangible. Similarly, there are no accepted definitions of asset management. Within standards and guidance documents aimed at industry there is more synergy between the definitions. Amongst the research orientated publications however, there is a very broad range of definitions and each tends to lean towards the specific research area concerned. Reviewing the research priorities in asset management revealed a large and diverse community. The disadvantages of this is the scope creep and lack of clear focus within the body of knowledge. In addition, this acts as a barrier to industry implementing novel developments. From this review a working definition of asset was proposed:

An asset is any element managed by an organisation that has potential or actual value to a stakeholder, either directly or through its contribution to the overall purpose.

Similarly, a working definition of asset management was proposed:

Asset management is the holistic and systemic approach to the sustainable continued achievement of organisational purpose and delivery of outcomes to stakeholders. This is realised through the coordinated and multidisciplinary management of all assets over their lifecycle.

Finally, a grouping of research priorities into fourteen broad areas which can then be further organised into three themes of societal, organisational and technological was proposed. This is shown in Table 12.1.

Table 12.1 Research Priorities in Asset Management

AM Theme	AM General Research Priority Areas
Societal	Sustainability, resilience and robustness
	Governance, strategy and leadership
	Cultural and historical asset value
Organisational	Performance service level monitoring and measurement
	Asset management issues, approaches and standards
	Asset and bridge management systems
	Systems approaches to asset management
	Risk and uncertainty management
	Organisational knowledge and asset data
Technological	Maintenance, replacement, rehabilitation, repair and inspection
	Condition monitoring, deterioration prediction and modelling
	Portfolio management and economic considerations
	Lifecycle analysis and management
	Decision making and prioritisation

The identification of AM research priority areas and the grouping of these into three themes was driven by the lack of an overarching definition or classification for asset management within academic research. The research priority areas were drawn from two sources (Schraven et al. 2013, Frangopol et al. 2012) reviewing the range of publications in the field, together with the researchers own literature review. The themes of Societal, Organisational and Technological was applied from Moon's work (Moon et al. 2009). The researcher's proposed identification and grouping of research priorities is an advancement over each of the individual approaches considered (Frangopol et al. 2012, Schraven et al. 2013, Moon et al. 2009) as it is more comprehensive and up to date. Bringing together three different views on research priorities (as shown in Table 3.3) provides a more complete overview. As this review has been carried out more recently and reflects the increase in focus on societal topics within asset management, in particular resilience, sustainability, governance and strategic leadership, it is more current and potentially more useful than the other sources cited.

The proposed standard definitions and identification of groupings in research priorities is beneficial to the CSBT and is more generally useful in filling a gap in current work. There would be benefit in testing out the definitions proposed in a range of contexts and for different organisations to test validity. There would also be benefit in further work on development of asset management themes within the overall body of knowledge to make the proposal useful for both research and industrial applications.

In Chapter 6, a simple framework for classification of asset management approaches within organisations was presented. This split the organisational approach to asset management into four broad groups depending on whether asset management was implemented functionally or cross organisationally and whether it concerned only physical assets or included all things of value. It is likely that organisations sit somewhere on a spectrum rather than completely in one of the four quadrants. This classification is generic and potentially of use to other infrastructure asset management organisations. As such it shall enable organisations to better understand their own approach to asset management in the context of the other approaches available. This should enable the organisation to make an explicit choice and select the most appropriate approach. For the CSBT is was evident that it had a functional hard approach but that the value of moving towards an organisational soft approach was recognised.

Drawing on Maslow's hierarchy of human motivation and applying it to organisational processes has produced a series of organisational archetypes. These can be used as a lens to view organisations through to understand how they are operating and what is important to them. Different archetypes may be more or less useful depending on the broader context at the time and there can be value in exploring other archetypes to determine whether they could offer benefit to the organisation. This is a novel application of Maslow's framework and could benefit from more applications to other asset management organisations to validate further. This was usefully applied to the CSBT context to identify the archetype where the organisation most typically operated and to identify the potential benefits of moving up the scale.

Both the classification framework of asset management approaches and the organisational archetype models were useful for the CSBT. They could also both be applied to other organisations in order to develop further and validate. Then the ideas may be generalisable to a wide range of infrastructure asset management organisations.

12.3 Reviewing Question 2

The second research question was:

Why does the CSBT want an asset management system?

Chapter 2 gave an overview of the CSBT case study, identifying the problem space and highlighting the original motivations for this research. The problem areas identified were risk management, data management, and asset management. The overall goal for the CSBT from this research was to define requirements and then implement an appropriate asset management system to support the Trust in effective and economical decision making. Alongside that, strategies for managing and organising the vast quantities of data and archive material also needed to be explored. During initial discussions with the stakeholders, different perceptions of what was meant by asset management and what was required for the organisation emerged.

Chapter 7 outlined an in-depth study carried out with the internal stakeholders to explore in more detail why the CSBT wanted an asset management system. From the interviews carried out and the data captured, there was agreement among the stakeholders that the organisation's mission statement accurately reflected the Trust's purpose. This means that the CSBT exists to maintain the bridge in perpetuity and to provide for the enjoyment and education of visitors to the bridge.

Generally, there was consensus that most elements of the CSBT organisation could be considered as assets as they had a value to the organisation. This includes both physical tangible assets and intangibles. An asset management system is therefore required to capture and manage these.

When asked explicitly why an asset management system was needed, the interviewees' responses ranged from it not being necessary to it being something that was essential. A number of issues were identified that the stakeholders hoped an asset management system would address. Data and information management was one of the key issues discussed at length. Explicitly capturing the asset management activities and ensuring that things were not accidently overlooked were also seen as drivers for an asset management system. The Trust needs more confidence that it is acting appropriately in looking after the organisation's assets in order to achieve its overall purpose. It also wants to be seen by the public as managing the assets adequately. They believe that having a formal asset management system in place will help make sure that the assets are managed well and that they are seen to be acting responsibility by external stakeholders. The general opinion is that an asset management system should enable the Trust to be more efficient, effective, purposeful and innovative in how it operates.

Through this study there was general consensus that the Trust's mission statement was appropriate and reflected the overall purpose of the organisation. The need for an asset management system was referenced back to the need to continue delivering the organisational purpose as outlined in the mission statement. There was extensive discussion over what could or should be considered as the assets of the organisation. This was important as it influences why the organisation wants an asset management system. Then a number of key reasons for asset management were identified. What seemed apparent however was that the Trust do not currently know how well they actually are managing the assets or how well they could be managing them.

For the CSBT's internal stakeholders this study provided the opportunity to consider and reflect on the reasons for requesting implementation of an asset management system in relation to the organisation's purpose. This is not something that had formally been done before and the report produced for the trust as a result of the study provided an overview of all the different perspectives for the Trustees and Bridgemaster to consider.

The novelty in this study is in the explicit process of exploring purpose, problem structuring and system boundary. For many established organisations, there may already be documented purpose, mission and strategy. However, these are concepts that can be temporal and need review and re-confirmation (or updating) periodically. In addition, the approach taken complements the ISO 5500x Asset Management standards, demonstrating a means of reviewing and capturing key inputs to the asset management system.

Although this was an extensive piece of work, the resulting value was significant. The outcome was a clear understanding of the issues and challenges facing the organisation together with consensus on the overall vision and aims of the Trust. This led to the following work being aimed at addressing the actual issues rather than simply implementing pre-conceived solutions. This approach could be further developed and refined such that organisations could use it when implementing an asset management system. The ISO management system standards specify the requirements of the systems but do not provide guidance to help an organisation implement such standards. This approach would be beneficial in helping the organisation to meet the requirements set out in the ISO 5500x Asset Management standards.

12.4 Reviewing Question 3

Research question 3 was as follows:

Is asset management adequate to meet the needs of the CSBT and if so what are the key features and requirements of such a system?

The third research question about whether asset management is adequate to meet the needs of the CSBT is explored in Chapter 7. The study presented in Chapter 7 explored what the stakeholders perceive as the key requirements of an asset management system. The interviewees identified a number of key features and these include:

- Asset Register
    - Location, Identification and Value
    - Condition and Performance
- Maintenance Planning, Replacement and Repair
- Prioritisation, Timescales and Scheduling

- Information and Data Management
- Asset Management Processes

These elements identified could all be addressed within a typical asset management system. There was nothing identified here that would require a different approach. These also align well with some of the key research priorities identified in Chapter 3.

The interviewees were asked about the other management systems that existed at the CSBT and what the relationship between an asset management system and other management systems should be. It was not apparent from the interviews whether many other explicit management systems exist in the CSBT. Specifically, it was stated that there should be strong links between the asset management system and the following other management systems:

- Human resource management system
- Safety management system
- Finance and investment management

During this study the interviewees were also asked to identify the challenges that the Trust faces, either now or in the future. The aim of this was to identify whether an asset management system could address these challenges or whether the actual problems faced require a different solution.

A key area identified was the balance between the historical integrity of the structure and maintaining it as a safe operational part of Bristol's transport network, especially given the dramatic changes in operational requirements. There are a number of technical challenges to be addressed relating to the bridge's unique location, age, and material properties. Much of the details of how the bridge was originally built and then maintained in the early days has been lost over the years. As a result, there is uncertainty around the condition and performance of parts of the structure.

Development and implementation of a data management system is urgently required but it was also considered as a challenging issue in itself, as there is no simple solution. Linked to this is the requirement for some mechanism to enable the CSBT to maintain the continuity of knowledge and experience of the staff, Trustees and volunteers for the future.

The final challenge identified was related to the continued income stream and ongoing ownership of the Trust. The public need to see the value in continuing to pay for the service of crossing the bridge in order for the Trust to continue existing. Either a shortfall in funding or a catastrophic event requiring more than the reserve fund to rectify, could result in the bridge being taken on by the local or central government.

The requirements for a means of balancing the historical and operational aspects of the bridge could be addressed through an asset management system that took into account the organisation's holistic purpose. This could then incorporate both the need to maintain the structure with the requirement to protect the historical importance of the bridge. There are elements of data management that would naturally be addressed by an asset management system, especially asset related condition data. However, given the extent of data owned by the Trust and that much of it is historically or culturally important as well as of technical importance, it was felt that a distinct data management system would be required. Finally, considering the ongoing business model of the CSBT and its ability to continue to be self-sustaining, this suggested the need for more than just an asset management system. A financial management system could monitor the situation and provide data useful for decision making. This issue could also be addressed directly in an organisational strategy to ensure that it is addressed and could be captured in the top-level organisational risk register.

The impact for the CSBT was to formally capture the organisational purpose and stakeholders' requirements in relation to asset management, data management and other general issues identified. This study also explored the stakeholders' perceptions on the meaning of the term "assets". This is the first time such a study had been carried out and the first time that such in depth conversations about the organisation had taken place. It was also clear from the full range of information captured, that an asset management system and data management system were not going to be sufficient to address all of the challenges that the CSBT were facing or enable it to continue to achieve its overall purpose.

The novelty in the study carried out was in the demonstration of an approach to exploring and capturing organisational purpose and stakeholder requirements. No such qualitative study has been found in the academic literature or industrial case studies related to asset management. In the implementation of an asset management system within an organisation, there is little emphasis on how to go about capturing stakeholder requirements and organisational purpose. It is often assumed that this is already known. The study carried out starts from the position of questioning whether an asset management system is even required and looks to explore the actual issues and challenges facing the organisation. The choice to carry out a qualitative study, through semi-structured interviews, was intentional to build up as rich an understanding as possible from the interviewees.

As this was an in-depth qualitative study, it produced a large volume of data to analyse. It may not always be practicable to carry out in depth studies of this kind for large organisations. However, it demonstrates an approach to addressing and exploring implementation of the approach outlined in the ISO 5500x asset management standards. The approach could be refined through application and test in other organisations and use of qualitative data analysis software may reduce the workload in processing the data.

12.5 Reviewing Question 4

The final research question was:

How does a systems thinking approach to asset management help meet the needs of the CSBT?

The final question is concerned with identification of the benefits of a systems thinking approach to asset management for the CSBT. This is addressed through several studies that use systems thinking approaches. Systems approaches have been used to structure the overall problem space, to implement interventions in how the organisation operates and to address particular technical challenges.

In Chapter 8 it is demonstrated that models can be useful for enabling systems to be examined and understood from different perspectives. They can be created as part of a group model building exercise to form consensus amongst stakeholders. They can also be used to construct idealised states illustrating where the system or organisation would like to be in future. Further work on this area would be worthwhile and could draw on Checkland's Soft Systems Methodology (Checkland 1999). A future state system model for the CSBT could be generated with the key stakeholders and the strategic plan then updated to reflect the objectives and actions required to achieve this. This would increase the industrial impact of the work carried out to date. The application of soft systems methodology in this context would contribute to the academic body of knowledge as there does not appear to be such an application in infrastructure asset management. More typically, Soft Systems Methodology has been applied in project management (Winter 2006), education (Patel 1995) and information systems development (Rose 2002). Mingers and Taylor present a findings from a survey into applications of Soft Systems Methodology (Mingers and Taylor 1992).

Chapters 9, 10 and 11 present some interventions, assessments and studies that were carried out at the CSBT. These all relate back to asset management and achievement of organisational purpose but explore different specific issues. The intention was to take a systems thinking approach to each of these, seeking to understand the broader context in each case. The purpose of resolving each issue, and how that would contribute to the achievement of the overall organisational purpose and objectives was considered. In some cases, this has involved broadening the scope to consider the soft systems within which the hard systems exist (Blockley and Godfrey 2000). The overall aim was that by demonstrating how taking different approaches could be beneficial, it would help the organisation to address the issues it was facing. This could also act as an exemplar to demonstrate how a different way of thinking could be beneficial in infrastructure asset management more generally.

An organisational strategic plan and integrated management system were developed in response to the original need for an asset management system. While it may have been easier to simply focus on asset management from a maintenance management perspective (in other words address a smaller subset of the overall problem), this would not have fully addressed the issues highlighted by the CSBT in Chapter 7, nor would this have represented a holistic approach. The researcher has enabled the organisation to make decisions relating to how its management systems should be structured. However, the specifics of data and asset management have been left to be developed by experts in future. As part of developing the organisational strategic plan, the CSBT staff were involved in selecting what the values of the organisation should be. In response to the need for a data management system, this was incorporated into the integrated management system. A data management policy was developed, and a comprehensive schedule of all archived material was created. After reviewing data management standards, meetings with various providers of data management and archival solutions, and consultation with an external archivist it was clear that further work would require the CSBT to employ an expert. The work on developing an organisational strategic plan and an integrated management system has therefore served to explore and structure the problem space, providing the CSBT with the data to make further decisions.

The impact of this for the CSBT is that for the first time they have a documented organisational strategy that captures purpose, shared values, the nature and scope of the organisation's assets and the strategic objectives that are being worked towards. The intention is that this document is formally reviewed annually, and it will evolve and adapt to suit the needs of the organisation at that point in time. Equally, for the first time, the CSBT now has an integrated management system in place. This incorporates the need for asset management and data management but has also highlighted other elements of the management system that should be incorporated such as finance, people, visitors' services and environment, health and safety. The structure of the asset management and data management branches of the integrated management system have been identified and the trust now has a better understanding of what they require.

Based on the identified purpose of the CSBT to preserve in perpetuity, a sustainability assessment of the organisation was carried out. This was in response to the researchers' findings, largely from Chapter 7, and not originally requested by the Trust. Elements identified from this study have shaped the overall integrated management system through identifying the need for a sustainability and business continuity policy. This was useful for the CSBT as a number of elements of good practice were identified and also some areas for improvement. Recommendations were made for each of the identified areas for improvement and the organisation stated a commitment to consider how to address them. The application of the framework developed in Chapter 8 to structure the study which then adds resilience as the sixth capital to the capitals already identified in the Halstar model was novel.

The approaches to two different technical projects were presented in Chapter 11. Design structures matrices (DSM) were applied to propose an alternative way of reviewing the structural risk assessment of the bridge, considering the interactions of components under loading. This was an exploratory study to understand the potential for application and it would require further work to be implemented in detail. However, it has potential use in identifying risks resulting from interactions rather than just the individual performances of components. This has potential to also be applied at an organisational level and could be used to identify interactions between different branches of the integrated management system. A better understanding of the interactions and interdependencies could enable identification of unintended consequences of proposed actions before they become problematic. No similar applications of DSMs were found in literature and with an increasingly complex and uncertain operating environment and the need to take a system wide and full life cycle approach (Institution of Civil Engineers 2013) such approaches have potential use at a broader infrastructure network level.

The final study discussed was that of trying to gain a better understanding of the fatigue performance and life of the bridge suspension hangers. The brief for the work was straightforward. The researcher was to plan and carry out fatigue testing on some of the hangers that had been removed from the bridge and replaced. However, when exploring the purpose and system boundary for the work it became clear that the testing proposed by the Trust would not fulfil the required purpose of the study. This was confirmed through the literature review carried out. The output of this study was a detailed report that provided the CSBT with a comprehensive understanding of the situation, and a series of recommendations for short and medium term management of the issues together with information on what work would need to be carried out to enable the testing in future. The impact for the Trust was that they did not spend money and use up precious hanger material on testing that would not have answered their original question.

A systems approach was applied to exploring and addressing all of the problem areas identified by the Trust. The value to the Trust was that rather than simply carrying out the task as requested, the approach taken explored the question being asked, and identified whether the preconceived solution would provide the answer required. The systems approach focused on identifying the purpose, requirements and boundary of the problem. This meant in some cases that planned work was not carried out (i.e. the hanger testing) or that work was carried out in a different way (i.e. development of an integrated management system as opposed to an asset management system). By doing this, it was then possible to provide the trust with the information required in order for them to make decisions on the way ahead or to employ experts for further specialised support.

12.6 Suitability of Research Questions

The research questions identified were useful in structuring the research and in addressing the problems identified by the CSBT. They also addressed gaps in the body of knowledge on asset management. The questions evolved, particularly over the first year spent at the CSBT, when it became clear that there was no standardised definition or approach to asset management within the engineering community. This was further compounded by the range of views internally at the Trust on the need for and purpose of asset management. A further research question that would complement the work carried out would be:

“Is asset management adequate to meet the needs of the asset intensive organisation?”

This would expand on research question 3 (which was specific to the CSBT) to identify whether the findings from the specific case study can be generalised to industry more widely. This would also be an opportunity to develop the qualitative study on organisational purpose and stakeholder requirements into a more user friendly process for use in conjunction with the ISO 5500x standards.

12.7 Addressing the Gaps in the Literature

As outlined in Chapter 3, there were a number of gaps found in the literature on asset management. The first was a lack of a general definition of infrastructure assets and asset management. This was partially addressed through the definitions proposed in Chapter 3 for asset and asset management. In addition, the identification of research priority areas in infrastructure asset management contributes to this. In order to validate these definitions, they require further testing. This could firstly be through application at other infrastructure asset intensive organisations and secondly through publication in a relevant peer reviewed journal.

It was noted that there is no clear approach for classification of asset management approaches or paradigms. The simple classification of asset management approach developed in Chapter 6 goes some way to addressing this gap. There is significant potential to expand this further and link to the research priority areas in infrastructure identified in Chapter 3.

No examples were found in the literature of large scale studies taking a holistic approach to asset management across an entire organisation. This thesis presents such a study that sets out a holistic systems approach to the implementation of asset management to the CSBT organisation. The study is broad and was conducted over a period of 4 years. It considered all areas of the organisation and aimed to address how the CSBT could apply a systems approach to asset management. The approaches taken could be further refined, through application to other organisations, and then formalised for the use of other asset managers.

12.8 Conclusions

There are a large number of different systems approaches that could be implemented in infrastructure asset management and this study is in no way exhaustive. The aim of this research was to address specific issues for the CSBT in a way that ultimately enabled them to continue to achieve their purpose. In each case, the aim of the researcher was to address the research questions while demonstrating that taking a systemic and holistic approach to asset management can bring about benefits.

The main approach to this research work presented in this thesis was to continually explore purpose, identify the stakeholder requirements and consider the system boundary. As this has been a case study conducted over a four year period, it has provided the opportunity to address issues at all levels of the organisation from the top-level strategy down to the detail of hanger fatigue performance. It therefore covers many of the areas identified in the standard list of research priorities, given in Table 12.1. This means that there is likely to be something of interest and relevance to most asset managers.

As discussed, the body of work presented in this thesis has had significant impact for the CSBT and has contributed to the body of knowledge in infrastructure asset management. In addition, many areas of potentially valuable follow on work have been identified.

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Appendix A

1.0 Introduction

This document reports on an initial study carried out by the Clifton Suspension Bridge Trust to capture internal stakeholder views on asset management. The purpose of the document is to present the findings from the study. The information presented in the following sections is entirely based on the data collected directly from those who were interviewed and as such are fully representative of the trustees' views. In some cases the data may not be novel but is included as it shows what the trustees know, feel and think about the bridge and the trust. The intention is that this report may generate discussion, surface ideas not previously discussed and provide a cohesive shared view of the organisation. The data provided could also be used to supplement the mission statement, giving a more detailed statement on organisational purpose and objectives. Finally, this data shall be used as an input to the process of developing an asset management system.

1.1 Asset Management Standard

The new ISO 55000 family of standards comprise the following sections:

- ISO 55000: Overview, Principles & Terminology
- ISO 55001: Management Systems – Requirements
- ISO 55002: Management Systems – Guidelines for the Application of ISO 55001

They were published in January 2014 and are largely based on the Publicly Available Specification PAS 55 for asset management, which was widely adopted internationally (Woodhouse, 2014). As the ISO 55000 series is the most recent standard, it may be considered as the state of the art. The ISO 55000 series has been taken as a starting point for exploration of the process of developing an asset management system for the CSBT.

This new standard presents a holistic approach to asset management that is not limited to purely physical assets but considers management of people, information, finances etc (Woodhouse, 2014). The ISO 55000 standards define asset management as the "co-ordinated activity of an organisation to realise value from assets" (International Standards Organisation, 2014).

The standard describes the elements of an asset management system and the relationships between them. The standard shows stakeholder and organisational context feeding into the asset management system at the top level. This framework is shown in Fig. 1.

Appendix A

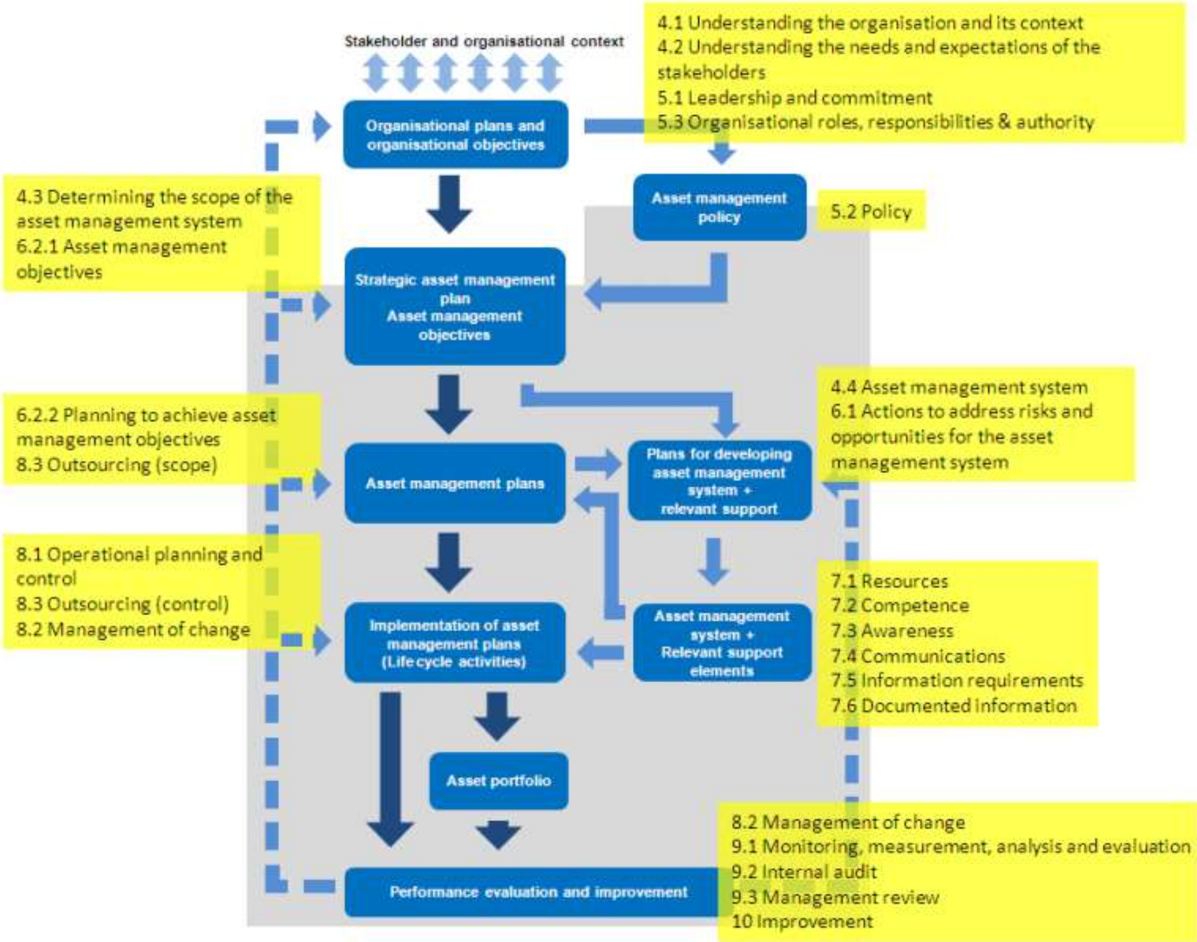


Figure 1: ISO 55001 Elements of an asset management system (International Standards Organisation, 2014)

1.2 Application of Standard

The first section of the ISO standards specifies the requirements for identifying and understanding the organisational context, including needs and expectations of stakeholders and determining the scope of the asset management system. In light of this, the following report presents the findings from an initial study carried out with a sample of internal stakeholders, to investigate their needs and expectations and also organisational context and purpose for the Clifton Suspension Bridge Trust.

The views were captured through semi structured interviews. From the data collected, a process of coding was used to extract information relating to organisational context, purpose and stakeholder needs. This was then sorted into the following themes: Political, Economic, Social, Technological, Legal, Environmental, Historical and Organisational. These themes were selected as each provides a different perspective from which the organisation can be considered. The following sections give a summary of the data captured. In addition, requirements for an asset management system were also extracted from the data and are listed in Table 1.

Appendix A

2.0 Political

The CSBT has to operate within the 1952 and 1986 Acts of Parliament, which set out the requirements of the organisation and defines what they are permitted to do. The act states that the bridge is managed by a trust and levies a toll in order to maintain and operate bridge.

It may be considered unusual that a major transport link connecting Bristol and North Somerset is owned and operated by a charity. However, the trust ownership and management of the bridge could also be seen as a strong business model as it enables independence from local and central government. This independence in turn allows high standards to be set and achieved.

It is acknowledged that in future the trust may not be able to continue to manage and maintain the bridge with the available funding. If this is the case then the local council or central government may need to take over responsibility for the bridge. Similarly if some catastrophic event was to occur, the trust ownership would be in jeopardy if there were insufficient funds to address that eventuality.

The trust recognises a need to be aware of the potential for changing relationships with local and central government and the affect that may have on the purpose, ownership and running of the bridge.

3.0 Economic

The trust is absolutely reliant on the toll money to fund management, maintenance and operation of the bridge. There is no other means by which the trust can raise funds other than through their own efforts. The trustees recognise that they need to be aware of continuity of funding and conscious of how the funding shall be maintained in the future in order to achieve the mission statement.

The cost of future maintenance work is effectively limitless while the income is very much limited by volume of traffic and how much people are prepared to pay. They must ensure that the finances are properly managed and that sufficient tolls are charged to operate and maintain the bridge and also to provide a reserve fund for unexpected or emergency work. The trust has therefore expressed a need for a control and reporting system to support them in logical allocation of funds, dependent on need and with flexibility to react to future issues. This will give a traceable, auditable account of spending and prioritisation.

Effectively, the bridge will only continue as it is if the public want to pay for its maintenance. Currently, people are willing to pay to cross the bridge but the trust should not assume that this will always be the case. The impact of the recent toll increase and the overall reduction in bridge crossings due to changing commuter behaviour needs to be considered. There are mixed feelings on the impact of the £1 toll increase, ranging from it being reasonable to it being significant and negative. It was pointed out that the people making the decision about requesting a toll increase are actually effectively immune to its effects.

Appendix A

4.0 Social

Both the history of the bridge and its connection to Brunel are highly valuable. The trust is mindful of its purpose to preserve the bridge as both a historic structure for future generations to enjoy but also as an operational asset, providing a vital transport link. This requires a careful balance between continuity of service and preservation of historic integrity and aesthetic value. In addition, there is increasing public regulation that must be satisfied and this may become more of an issue in future.

The Clifton Suspension Bridge is a major tourist attraction and a huge asset for Bristol. Part of the trust's purpose is to provide for the enjoyment of visitors to the bridge and this includes informing and educating the public. The trust recognises that it is their responsibility to provide this and that the emphasis on learning and education should perhaps be stronger.

The trustees wish to make travelling across the bridge as pleasant an experience as possible for those who choose to use it in order that people are more likely to use it regularly. This is important as the future continuation of the bridge and the organisation is dependent on public opinion and willingness to pay. There is currently a lot of goodwill attached to the bridge and the trust needs to cultivate this.

There is an awareness that the trust may be perceived as being old fashioned and very private, almost secretive in its operations. Also, the process of selecting trustees is not open. There is little publicly available information about the organisation. The trust fulfils its legal obligations in terms of providing access to information but does not typically go beyond those requirements. It was felt, however, that the trust could be better at enabling public access to information and could be more transparent as they have nothing to hide. There is an acknowledgement that where possible the public should have access to as much of the bridge as is practicable. There is a perceived need to improve the trust's public relations and communication with the public.

The trust has a role to play in interacting with the public and encouraging them to be possessive of what is effectively their bridge. Amongst the trustees there is a feeling that while technically the trust owns the bridge, they are actually more like custodians and the bridge is actually owned by everyone. The public pay for it and therefore they are the stakeholders.

5.0 Technological

Maintaining something forever is an interesting technical challenge. In order to keep the bridge going for as long as possible, the trust requires a greater understanding of its weaknesses and strengths. In order to do this the trust needs sufficient income for both short term maintenance and to provide a reserve fund for future uncertainty.

A balance has to be found between the bridge as a crossing and the bridge as an historic structure. The trust needs to weigh up how much importance is placed on each. In order to continue to look after the bridge, the trust needs to establish a good level of knowledge on the current condition and to continue to monitor this for the future, considering how any deterioration will affect the strength or lifespan. This will then help to define the work required to maintain the bridge in an acceptable condition.

Appendix A

The bridge maintenance is a major part of the trust's activity and most of the planning and control in place is related to managing this. A proactive approach to maintenance is considered vital. The trust aspires to manage the maintenance and project work effectively to ensure best value for money and it is carried out in a timely fashion.

Both the size and age of the structure means that it is considered to be a relatively complicated system. It is difficult to keep track of all of the work carried out and changes made over the years. Many things have been forgotten and the information that the trust owns is not particularly well organised. In addition there is an increasing quantity of data being produced at ever greater levels of detail. Both public and internal access to information is very limited. There is a vast quantity of documentation that needs to be made more accessible. The trust recognises that developing a better understanding of how the bridge works and ensuring continuity of that knowledge and experience is incredibly important. In addition there is an increasing quantity of data being produced at ever greater levels of detail.

It is felt that in order to ensure that the bridge is maintained in the best possible way, the trust should be actively seeking out and exploiting state of the art techniques for inspection, test and analysis. This may then result in the trust contributing to the body of knowledge in that field.

6.0 Legal

The bridge is a grade 1 listed structure and this status requires the organisation to preserve the historic integrity and fabric of the bridge.

The trust was set up under an Act of Parliament which clearly defines what they are required and permitted to do as an organisation. The trustees have collective responsibility and a duty of care. The trust is responsible for both owning and managing the asset and as such need to ensure it is safe, well maintained and that the historic aspect is preserved for the future.

The trust is a registered charity and hence has to be self funding. The charity commission can audit the trust and so there is a need for an easily understandable approach to management and operation.

The trust is responsible for both structural and operational safety. The trust has a policy and written arrangements which state how the trust manages safety and specifies its responsibilities. It is felt however that more attention could be focused on this and that perhaps the trustees should be actively reviewing safety more regularly.

Although the trust owns the bridge there is a feeling of it being a quasi public body and that is really belongs to Bristol. If there were to be problems in future that meant the toll income or reserves were no longer sufficient then the ownership may need to be reviewed with the government or local authority. However, there may well be reticence on the part of the local and central government regarding a change of ownership.

7.0 Environmental

The majority of the components on the bridge are original and from the 19th century. The trust's desire to prolong and preserve these is not only from a historical point of view but also because it reduces the environmental burden.

Appendix A

8.0 Historical / Heritage

It is recognised that there is a great deal of history associated with the bridge. The Brunel connection is highly valuable, together with the historical, aesthetic and visual appeal.

The trust recognises its challenge is to achieve an appropriate balance between the historical element and the current operational usage, complying with increasing public legislation. The trust has an obligation to maintain the bridge in perpetuity, retaining its original fabric as much as possible.

There is an increasing need to record data and access existing information to improve the understanding of the structure. However, the bridge and organisation is old with information stored in various locations and much that seems to be missing. Certain aspects of the bridge and the organisation have also been forgotten over the years. There is therefore a need to address the data management and also, critically, the continuity of knowledge and experience.

9.0 Organisational

The purpose of the trust is to keep the bridge going in perpetuity for both the people who use it as a crossing and those who come to visit. In order to achieve this, the trust feels there is a need for a system to help them in managing the maintenance and operation in order to achieve the overall mission. An asset management system should enable the trust to better understand their goals and purpose, which will in turn enable them to manage the asset more effectively,

The trust organisational structure itself is relatively old, even archaic and private, however there is a feeling that it works well. The trustees consider that the ownership of an asset, with the ability to raise funds and employ professionals as required is a strong business model.

The trustees have overall responsibility for the maintenance and management of the bridge, they have a collective responsibility, a duty of care and are accountable for achieving the organisational purpose and complying with all relevant legislation. However, despite running an infrastructure asset for public utilisation the trust are not subject to any sort of operational audit. They must also be seen to be managing the assets professionally and going through organised and responsible procedures in order to maintain the safety of the bridge.

New trustees are selected by the existing trustees for their experience or skills. This gives the trust the opportunity to retain a high quality, diverse group of trustees with a broad range of experience, skills and backgrounds. Due to the nature of managing the bridge and the heavy focus on engineering, this charity is more complicated than many others and hence there is a need for experienced, knowledgeable technical people. The trust structure and ability to select the best candidates may be considered as one of the assets of the organisation.

There are few disagreements amongst the trustees; however there is also a willingness to reflect on the different opinions and to put forward counter views. Open discussion and different opinions are respected. The trustees are aware of their responsibility to contribute and it is considered important to ensure that this continues in the future. The selection process needs to ensure appointment of appropriate trustees to maintain the high standards, act responsibly and have the capability and knowledge to input meaningfully.

The trust’s workforce is small and as such the individual responsibilities and overall purpose are clear. The organisation of the trust is such that the Bridgemaster is effectively the chief executive of the business and the trustees act at a much higher level. The Bridgemaster has a lot of responsibility, including management of the bridge and the external consultants and needs to ensure that everything operates in an integrated way. When the current Bridgemaster retires, there will be a need to ensure selection of a highly qualified, experienced engineer, who has broader capabilities in management to run this bridge.

Prioritisation and decision making are two important aspects of the trust’s work. It is recognised that in a sense the trust is privileged as they only have one asset to manage. The aspiration is that the asset management system will ensure that every year, after the annual inspection, the trust reviews the structural risk assessment and the required maintenance work and prioritises the tasks. In addition to actually prioritising the work, the process of arriving at those priorities and decisions needs to be captured and reviewed. The trust needs to be able to practice and demonstrate effective, appropriate prioritisation and decision making.

Major decisions are made by the board of trustees however they should all be based on the advice of an expert. In addition to the employees of the trust, there are also external experts employed to provide expert advice. The trustees consider the advice given but ultimately have the responsibility for decision making. To that end there is a requirement for a decision making and audit tool to support the trust.

A lot of the trust’s organisational processes are implicit as a result of established working practices that are not written down. The issue with this is that things get forgotten and if personnel change then the knowledge can be lost. It is felt that there is a need to capture these processes and make them explicit to ensure that things don’t get neglected, ignored or forgotten. An asset management system may be a means of achieving this by ensuring that the right questions are asked at the right time. Such a system could also give structure to how things are done, the required resources and how they are organised.

There are different opinions within the organisation as to what constitutes an asset, ranging from simply the structure of the bridge to more encompassing views of the organisation, personnel and knowledge required to maintain and operate the bridge. The purpose and content of an asset management system will vary depending on the perception of what constitutes an asset. It could be seen as a structure that ensures the trust do not forget or neglect certain aspects of its responsibilities, a tool that asks the right questions at the right time, a means of capturing and organising the organisational knowledge, a database to record and monitor the condition of the structure or a part of the holistic enterprise management.

10.0 Organisational Requirements

Appendix A

The following table lists specific requirements that were explicitly stated during the interviews. Some are at a higher, more abstract level while others are far more detailed and specific. These all relate to the organisation and its purpose and in some cases specifically refer to asset management.

This is envisaged as being a starting point for defining a more comprehensive list of requirements. This type of list of top level requirements may be used to define the organisational objectives and plans as shown in Fig. 1 and will need to be considered as requirements of the asset management system.

Table 1: Organisational Requirements

Theme	Requirements
Responsibility, Governance & Ownership	Comply with and fulfil requirements of Acts of Parliament
	Consider long term governance and ownership of the bridge
Management & Organisational Processes	Holistic organisational management approach
	Capture implicit processes and make them explicit
	Provide / define processes and procedures Define resources and organisation of resources
	Be open about management processes, demonstrate that bridge is well managed
	Manage all work effectively with the aim of achieving best value
	Clear approach
	Enable identification of organisational goals
	Identify and review long term issues
	Ensure that all work carried out satisfies a need
Finance	Ensure income matches planned expenditure with a reserve fund
	Good knowledge of financial situation, under regular review, identifying current and future risks
	Reporting and control system to enable prioritisation of spending
People	Define requirements of trustees Define process for identification and selection of trustees
	Define requirements of a Bridgemaster Define process for identification and selection of a Bridgemaster
	Provide clarity of responsibilities for all work
	Address long term continuity of knowledge and experience
Health & Safety	Comply with all applicable H&S requirements
	Ensure safety
	Increased focus on health and safety of staff and public

Appendix A

	Comply with all applicable legislation
Engage With Public	Provide the means to educate and inform the public
	Actively engage with the public and provide access to as much of the structure as reasonable practicable
	Strive to make crossing the bridge a pleasant experience for all
Maintain & Preserve	Maintain bridge in order to keep it open and able to withstand current volume and weight of traffic, without degrading the appearance of it
	Maintain as working highway for longevity (no fixed life span)
	Establish current condition and monitor deterioration Establish life span of components Identify actions required over given timescale to prolong life and ensure required strength
	Continue to develop the understanding of the bridge
	Preserve the bridge and look after it
	Preserve historic aspects of the bridge
	Retain the original fabric of the bridge wherever possible
	Maintain the historic integrity of the bridge
Decision Making & Prioritisation	Support decision making
	Ensure decisions and consensual and that all concerned are comfortable with them
	Decision support tool
	Support decision making, particularly around the balance between historical importance and day to day use
	Support effective prioritisation Understand what effective prioritisation means for the trust

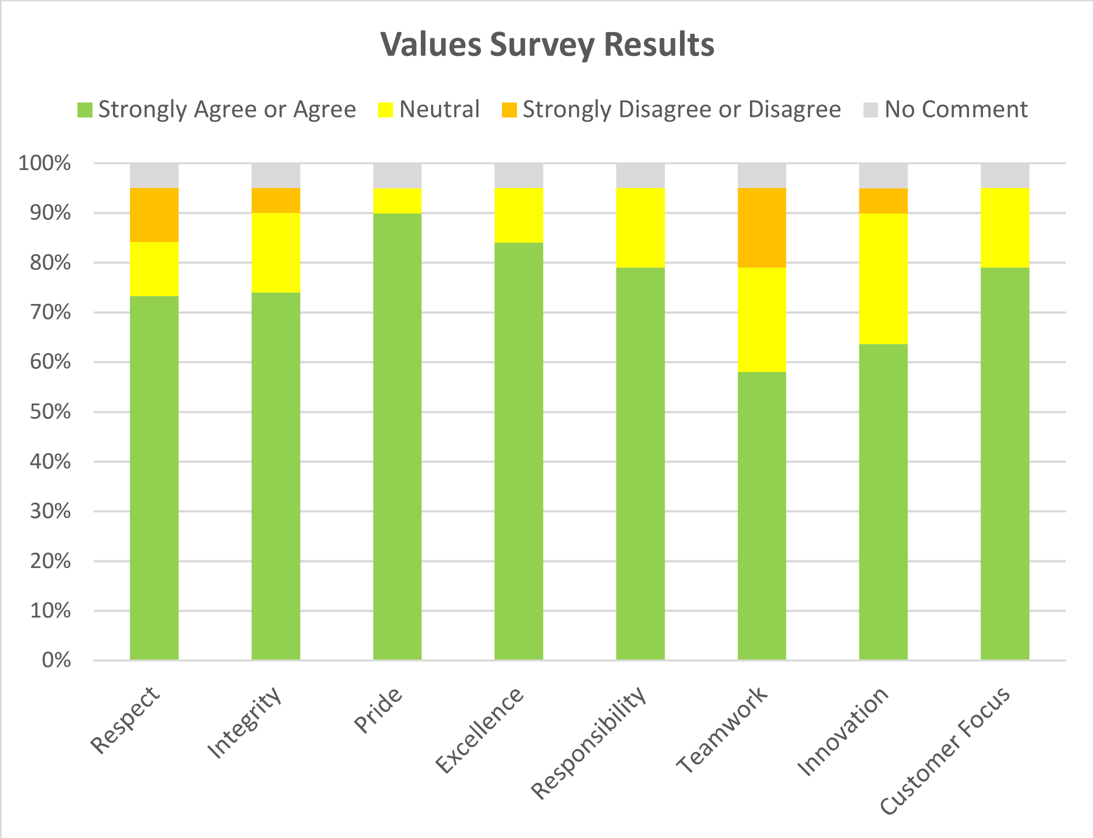
Appendix A

11.0 References

INTERNATIONAL STANDARDS ORGANISATION 2014. ISO 55000 Asset Management. *Overview, Principles and Terminology.* British Standards Institute.

WOODHOUSE, J. 2014. Briefing: Standards in asset management: PAS 55 to ISO 55000. Available: http://www.icevirtuallibrary.com/content/article/10.1680/iasma.14.00013.

Appendix B: Feedback to Staff on Survey Results



Thank you to those who completed the survey on values. We had responses from over 85% of staff!

From the chart, you can see which values people thought best fitted the Clifton Suspension Bridge Trust. The 4 most popular values were Pride, Excellence, Responsibility, and Customer Focus.

Teamwork was the least popular choice. However, it has been selected as a value for the organisation because teamwork is important to the way we work. We recognise that further work is required for the Trust to improve in this area.

So, the CSBT values are as follows:

- Pride: We take pride in the Clifton Suspension Bridge and its history, heritage, and environs. We strive to share this with visitors, commuters, and bridge users. We demonstrate our pride through our work and performance.
- Excellence: We always aim to do our duties to the best of our ability, demonstrating excellence in everything that we do.
- Responsibility: We always take responsibility for our actions and ensure that our colleagues and volunteers can rely on us. We understand that our actions impact others around us.
- Customer Focus: The satisfaction and safety of our customers is central to everything that we do. We aim to deliver a high-quality service and ensure that everyone who uses the bridge has a positive, enjoyable, and informative experience.
- Teamwork: At the Clifton Suspension Bridge, we work together as one team and support each other in achieving the Trust's goals.

Appendix C

CLIFTON SUSPENSION BRIDGE TRUST

Clifton Suspension Bridge Trust

Five Year Strategic Plan 2017 – 2021

Reference: STR 1.0.0

Due for Review: January 2018

Revision	Status	Date	Author	Checked	Approved
A	Draft for Review	28/11/2016	A Turner	T Johnson	
B	First Issue	01/01/2017	A Turner	T Johnson	

Contents

Executive Summary

The Clifton Suspension Bridge is a key part of Bristol's road network, connecting the city with North Somerset. It is also an historically and culturally important icon for Bristol and beyond. The Clifton Suspension Bridge Trust (CSBT) is the independent organisation responsible for the maintenace and operation of the bridge and the provision of visitor and educational services to the public.

The Trustees and staff of the CSBT have developed this strategic plan to capture the purpose and key features of the organisation in relation to the social and economic environment it exists within. This document provides the basis from which more detailed plans are then established.

The strategic plan outlines the mission, vision and values on which the organisation is based. It defines the strategic objectives for the next five years, necessary to enable the organisation to achieve its purpose. The strategic objectives have been been grouped depending on which area of the organisation and its activities they relate to. The groups are: organisational; asset management; visitor services and public engagement; knowledge and data; environment, health and safety; finance and people.

These groupings form the basis of an integrated management system. The integrated management system is being developed to ensure that the top level objectives within this strategy are achieved. It does so by capturing the policies, detailed plans and day to day processes and activities necessary to ensure that the CSBT achieves its overall purpose.

The Clifton Suspension Bridge

The Clifton Suspension Bridge was founded in 1931 and opened in 1864. Between 1860 and 1952 is was privately manager by the Clifton Suspension Bridge Company. The Clifton Suspension Bridge Trust (CSBT) was then incorporated under the Clifton Suspension Bridge Act of 1952. The Trust has managed and operated the bridge continuously since then.

The bridge forms a key part of Bristol's road network and has over 3.2 million vehicle crossings per year. In 2014 the new purpose built Clifton Suspension Bridge Visitor Centre opened, the first ever permanent visitor centre for the bridge. The visitor centre recieves around 68,000 visitors per year from all over the world.

The CSBT is a charity and private organisation, operated by a Charitable Trust. The 1952 Act of Parliament sets out the main requirements regarding:

- The operation and maintenance of the bridge
- The powers and duties of the Trustees
- The building up and maintenance of a reserve fund

The organisation is responsible for all activities related to maintenance, management and safe operation of the bridge, while also providing visitor services and operating the visitor centre.

Appendix C

Our Purpose and Culture

Purpose

The purpose of the CSBT is to provide value to those who use the bridge, whether for transport, leisure or education, while ensuring their safety and maintaining the Trust's assets. This value may be generated through:

- Managing and operating the bridge as a vital crossing service
- Maintaining and preserving the bridge, balancing the operational needs with the heritage of the structure
- Providing education, outreach and engagement with the public
- Maintaining and promoting the social, educational and historical value of the bridge

Mission

The CSBT's mission statement is:

"It shall be the mission of the bridge Trust to preserve the Clifton Suspension Bridge in perpetuity, to the highest possible standards, for the utility of the public, and to provide information and facilities for the enjoyment of visitors to the bridge."

Vision

Our vision is:

- To be recognised as a leader in the sustainable management and operation of an historic bridge
- To be the primary source of public education and engagement relating to the Clifton Suspension Bridge
- To maintain and preserve records relating to the history, maintenance and engineering of the bridge

We shall achieve this while providing and maintaining an effective and safe crossing over the Avon Gorge for vehicles and pedestrians. Alongside this we shall maintain productive relationships with the local community. We want everyone who uses the bridge to have a positive and enjoyable experience.

Values

Values define how we want to conduct ourselves and our business and help us to create a great experience for all the users of the Clifton Suspension Bridge.

- **Pride:** We take pride in the Clifton Suspension Bridge and its history, heritage and environs. We strive to share this with visitors, commuters and bridge users. We demonstrate our pride through our work and performance.
- **Excellence:** We always aim to do our duties to the best of our ability, demonstrating excellence in everything that we do.

- **Responsibility:** We always take responsibility for our actions and ensure that our colleagues and volunteers can rely on us. We understand that our actions impact others around us.
- **Customer Focus:** The satisfaction and safety of our customers is central to everything that we do. We aim to deliver a high quality service and ensure that everyone who uses the bridge has a positive, enjoyable and informative experience.
- **Teamwork:** At the Clifton Suspension Bridge we work together as one team and support each other in achieving the Trust's goals.

Organisation

Assets and services

The CSBT has a range of assets and utilises them to provide a number of services to its customers. There are two main asset groups:

- The operational assets, including the bridge and access systems, toll houses, operational and maintenance building, skills and expertise of staff etc.
- The visitor centre and heritage assets, including the visitor centre, collections and archives, historical knowledge etc.

The CSBT utilises its asset to deliver the following services:

- Provision of a safe and convenient crossing point across the Avon Gorge
- Free crossing to pedestrians, cyclists and emergency services
- Efficient collection of the toll
- Provision of the option for toll prepayment through crossing card
- Bridge tours, both revenue generating for groups and free for the public
- Education programmes, both onsite and offsite
- Tourist information relating to the history and engineering of the bridge and facilities in the local area

Management

Responsibility for the Trust rests with 12 Trustees, comprising 10 Resident Trustees, chosen for their technical and business expertise, and two Representative Trustees nominated by Bristol City Council and North Somerset Council.

The board of Trustees also form three sub-committees, the Technical Committee, the Investment Committee and the Property Committee. These sub-committees have some delegated authority, they closely manage certain activities under their responsibility and report into the board.

The Trustees employ a Bridge Master who deals with the day to day management of staff, operations and technical issues. Some responsponsibility is further delegated to a Visitor Services Manager, Maintenance Chargehand and Office Manager.

The Trust also employ external experts and consultants, as required, to provide specialist advice to the Bridge Master and Trustees.

Organisational Structure and Roles

Approximately 23 full time and part time staff are directly employed by the Trust. This includes 13 bridge attendants who are employed on a shift working basis to provide 24 hour coverage on the bridge. There are approximately 64 volunteers who provide a range of services including working in the visitor centre and giving guided tours. The CSBT organisational structure is shown in Fig.1.

Capabilities and Competences

The Trustees are selected for their skills and experience to ensure that there is a broad range of competence across the board. This will include expertise in engineering, business, law or heritage. The Bridge Master is a Chartered Civil Engineer and all staff appointments are made through a competency based interview process. The Trust ensures that all staff has access to training and development opportunities to ensure they are suitably knowledgeable and skilled to carry out their role within the organisation.

Contracts

Contracts are in place for a range of services and works including major engineering projects, consultancy services, access equipment, tolling system and IT services.

The Trust is a private organisation and complies with all UK legislation, directives and standards relating to its charitable status, its role as an employer and the technical processes it carries out.

Appendix C

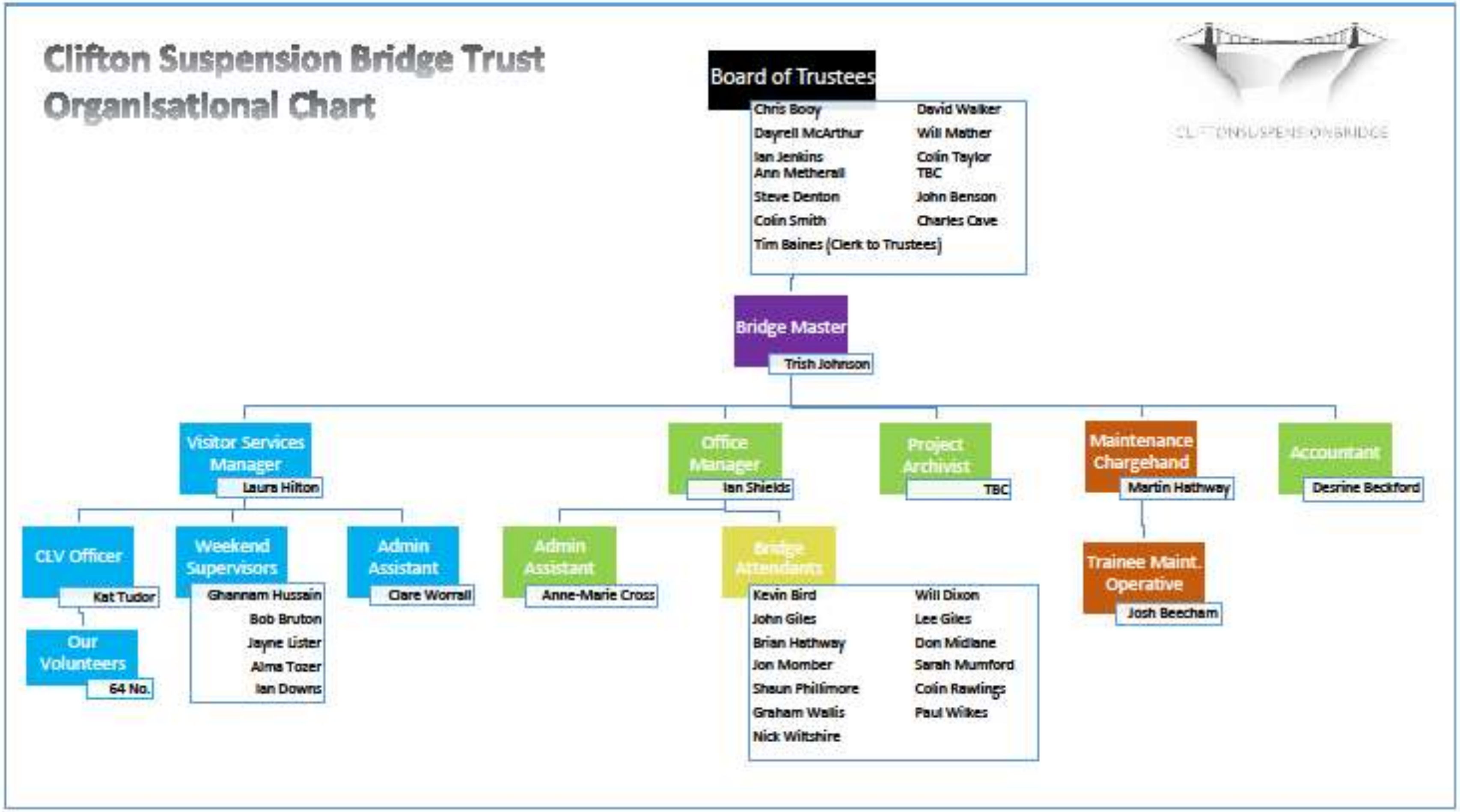


Figure 1: CSBT Organisational Structure

Strategic Evaluation

The CSBT's strategic direction has been developed to reflect the environment that the organisation exists within. This includes taking account of the strengths and weaknesses of the CSBT, the opportunities and threats in the wider environment, the stakeholder requirements and the overall organisational risks.

Strengths, Weaknesses, Opportunities & Threats

The organisational context considers the internal strengths and weaknesses of the CSBT and the external opportunities and threats. These are summarised in Table 1.

Table 1: CSBT Strengths, Weaknesses, Opportunities & Threats

Strengths	Weaknesses
• Assets owned by the Trust • Government backing for the CSBT's operations and responsibilities through Act of Parliament • Good working relationship with both Bristol City Council and North Somerset Council through Representative Trustees • Bridge is cultural and historical icon for the city • Bridge forms important link in Bristol's transport network	• Reliant on toll income for operation and maintenance • Reliant on visitor centre shop and tours for operating visitor services • Need for constant maintenance and repairs • Major inspections and maintenance can impact bridge availability • Grade 1 listed structure – requires special permissions and can result in more costly works • Bridge crosses a Site of Special Scientific Interest – requires more control of operations
Opportunities	**Threats**
• Increase national and international reputation to attract more visitors • Enhance Bristol's strong connections to Isambard Kingdom Brunel • Additional funding for visitor services through enhanced offering • Potential third part income stream • Further opportunities to highlight structure and increase revenue through media and events	• Unforeseen structural failure • Continuity of funding – public continuing to be willing to pay (enough) for the services provided • General economic climate – people being able to pay for service • Congestion and parking in Bristol make driving a less attractive option • Alternative routes are free from toll and improved in terms of traffic

Stakeholders

The CSBT has a broad range of stakeholder groups, both internal and external to the organisation. The Trust considers the needs of these stakeholders when developing organisational strategy and objectives. The stakeholder groups are represented in Figure 2.

Figure 2: CSBT Stakeholders

Competitors

The competitors of the CSBT, in terms of providing a crossing point for the Avon Gorge, are the other bridges along the river. The next adjacent ones are the Cumberland Basin flyover and the Avonmouth Bridge. The Avonmouth Bridge is a motorway bridge and a 14 mile round trip from the CSB. The Cumberland Basin is a busy road interchange, close to the city centre.

The main competitor in terms of historical and cultural landmark is likely to be the SS Great Britain, another Brunel artefact. It resides in the floating harbour, one of the other main tourist attractions in the city.

Strategic Risks

Table 2: CSBT Strategic Risk Register

Risk Type	Description of Risk
Health & Safety	Severe injury or harm to a member of public caused by bridge structure, working practices etc.
Health & Safety	Severe injury or harm to a member of staff / contractor
Reputational	Negative media coverage
Structural	Failure of components of the structure
Business	Cyber-attack / computer failure leading to loss of data or ransom of data
Structural	Loss of consultants / contractors / personnel with intrinsic knowledge of structure
Financial / Reputational	Failure of major projects in fulfilling their contracts
Financial	Failure of tolling system
Structural	Terrorist attack resulting in damage to structure
Reputational	Local pressure to prevent works on structure
Business	Loss of personnel / skills in key posts

Strategic Objectives

The strategic objectives have been developed to enable the CSBT to achieve its overall purpose, mission and vision given the context, stakeholder requirements and overall risks. There are overall organisation level objectives and then more specific objectives aligned to the different elements within the proposed integrated management system, which are:

- Asset Management
- Visitor Services and Public Engagement
- Knowledge and Data
- Environment, Health and Safety
- Finance
- People

The top-level structure of the integrated management system is shown in Figure 3.

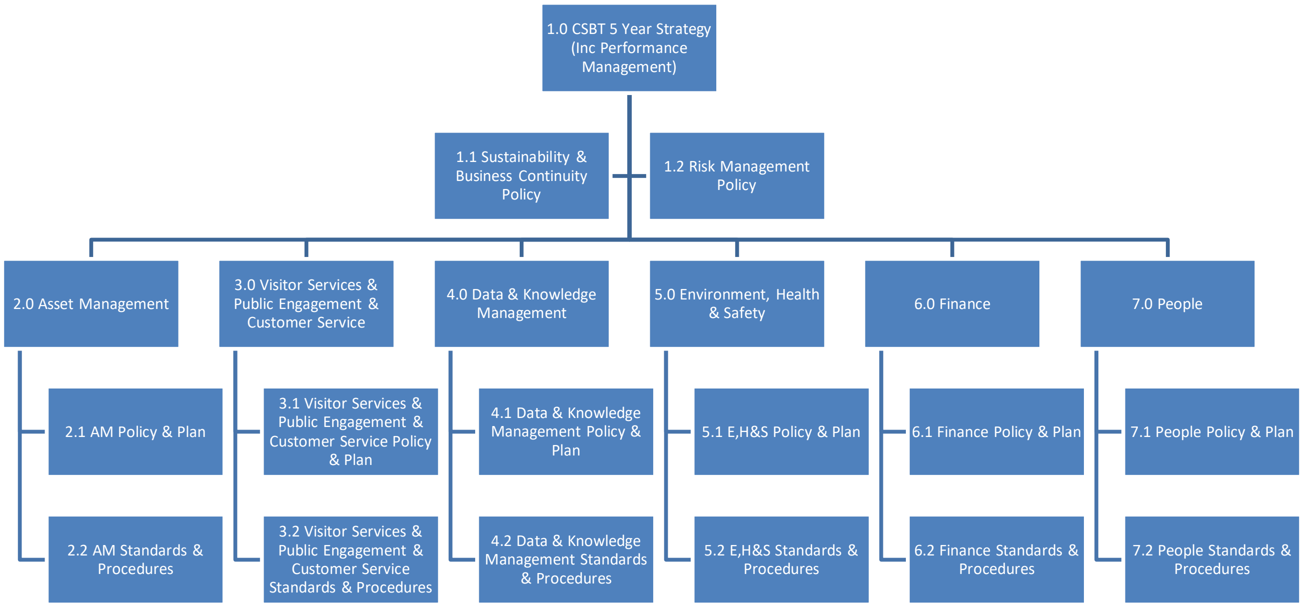


Figure 3: CSBT Integrated Management System Structure

Organisational

Purpose: The purpose of the CSBT is to provide value to those who use the bridge, whether for transport, leisure or education, while ensuring their safety and maintaining the Trust's assets.

Objectives:

- Develop and implement an integrated management system that enables the Trust to manage the organisation and its assets effectively and efficiently
- Demonstrate good governance through traceability and accountability of decision making, authority and accountability
- Develop and implement an organisational level risk review and management policy
- Develop and implement an organisational level performance management policy
- Carry out an annual review of the 5 year strategy to ensure continuing relevance and assess progress against objectives
- Ensure that the CSBT continues to meet all of the requirements of the Acts of Parliament and Charity Commission and fulfils all legal obligations and complies with all relevant standards and codes of practice

Asset Management

Purpose: To enable the CSBT to deliver a safe, efficient service, providing value for the customers, while addressing the needs of the assets.

Objectives:

- Maintain or improve the service provided to motorists, pedestrians and visitors whilst considering our neighbours and the local community
- Manage and operate the bridge to ensure it is a convenient, efficient and safe transport link into and out of Bristol
- Maintain and preserve the bridge, balancing the operational needs with the heritage of the structure whilst complying with listed building and SSSI requirements
- Develop and implement an asset management system to ensure the appropriate and adequate management of all assets

Visitor Services and Public Engagement

Purpose: To provide education, information and enjoyment for visitors to the bridge, to engage with the local community and to ensure all bridge users have a positive experience.

Objectives:

- Maintain and promote the social, educational and historical value of the bridge
- Provide education, outreach and engagement with the public
- Develop and implement a 5 year strategy for visitor services and community engagement
- Ensure CSBT takes a consistent and professional approach to working with members of the public
- Seek additional income streams to enhance offering to the public

Knowledge and Data

Purpose: To enable the CSBT to gain maximum value and utility from its data, information and knowledge, in order to support internal processes, engage and educate the public and to preserve the history of the organisation.

Objectives:

- Improve the CSBT's ability to find, access, utilise, share and preserve its data
- Develop and implement a data management system to ensure the appropriate and adequate management of all data and information

Environment, Health and Safety

Purpose:

To ensure the safety of all staff, contractors, visitors and customers, to ensure that the CSBT is up to date with the latest legislation, standards and practices and to minimise the organisation's impact on the environment.

Objectives:

- Provide and maintain a safe place of work, for all employees, contractors, visitors and members of the public, so far as is reasonably practicable
- Develop and implement an environmental policy to capture how the CSBT intends to minimise its impact on the environment

- Develop and document plans for responding to foreseeable emergencies to ensure that those involved are not placed at greater risk by confusion and lack of incident control
- Carry out regular reviews of the environment, health and safety policy and management system to determine whether it is up to date with the latest guidelines and legislation, whether it is fit for purpose and whether the objectives are being achieved

Finance

Purpose: To ensure that the CSBT produces and manages its revenue to ensure the indefinite preservation, maintenance and operation of the bridge, to fund visitor services, education and community engagement and to maintain an emergency reserve fund.

Objectives:

- Ensure that annual toll revenue does not fall below necessary budget expenditure for the indefinite maintenance, operation and preservation of the bridge, other than in an exceptional year
- Maintain the Emergency Reserve Fund at a level which would allow the Trust to self-fund up to two major maintenance failures, short of a full bridge replacement
- Ensure that annual visitor service income is sufficient to provide for and maintain the visitor services

People

Purpose: To develop a contented, motivated and positive workforce and provide them with the appropriate skills for their role.

Objectives:

- Develop and implement an annual review process for all staff and volunteers, providing them with the opportunity to discuss training needs and development opportunities
- Implement and maintain formal and informal communication processes within the organisation
- Ensure staff and volunteers receive the necessary training and development to fulfil their roles

Delivery and Performance Management

An annual action plan will be produced with key deliverables and measures against these objectives.

Review Process

This 5-year strategy shall be reviewed annually by the Trustees and management and updated as required. This strategy document is valid for the period 2016 to 2021. Thereafter a new strategy document shall be prepared by the Trustees and management.

Appendix A: Stakeholder Analysis

Stakeholder Group	Concerns & Requirements
Trustees	• Fulfil requirements of Acts of Parliament • Manage to the best of their ability • Be seen to be managing appropriately • Achieve value for money • Ensure security for the future
Staff & Volunteers	• Job security • Safe working environment • Engaging & interesting working environment
Public Bodies	• Maintain the original fabric of the structure wherever possible (due to listed status) • Be mindful of & protect the Avon Gorge SSSI
Department for Transport	• Requirements of Acts of Parliament are fulfilled
Charity Commission	• Fulfil legal requirements & Trustees carry out duties • Publish accounts
Commuters	• Value for money (if paying) • Safe & efficient crossing • Convenient service
Visitors	• Opportunity to learn about the CSB • Space to enjoy the bridge in its setting
Local Authorities	• Ensure traffic flow & be mindful of other transport routes • Attractor to the region & focal point for the city • Maintain the original fabric of the structure wherever possible • Be mindful of & protect the Avon Gorge SSSI
Local Residents, Public Interest & Community Groups	• Ensure traffic flow • Preserve the aesthetic quality • Minimise any disruption • Low impact on community • Low cost / value for money
Downs Society	• Minimise impact on the Downs • Preserve the aesthetic quality • Be mindful of & protect the Avon Gorge SSSI
Funders e.g. Heritage Lottery	• Requirements of any funding agreements are met
Tourism Partners e.g. Destination Bristol	• Ensure that a high quality visitor experience is provided and that the general public, corporate visitors, film, TV and media have a good impression of the city

Appendix D

CLIFTON SUSPENSION BRIDGE TRUST

Clifton Suspension Bridge Trust

Data Management Policy

Reference: PO 4.1.1

Due for Review: TBC

Revision	Status	Date	Author	Checked	Approved
A	Draft for Review	28/11/2016	A Turner		

1 Introduction

The Trustees and staff of the Clifton Suspension Bridge Trust (CSBT) have developed this data management policy to capture the purpose of data management, its objectives and how these objectives contribute to the overall purpose of the organisation. The policy also outlines how the CSBT intends to deliver the objectives and how performance shall be measured and reviewed. This document provides the basis from which more detailed processes and procedures will then be established.

For the CSBT, data management includes the following:

- General processes – including risk management, valuation & insurance, responsibilities, resource & competence and performance management
- Creation & collection of data, records & collections
- Maintenance & preservation of data, records & collections
- Utilisation of data, records & collections
- Disposal of data, records & collections

2 Purpose & Objectives

The purpose of the CSBT is to provide value to those who use the bridge, whether for transport, leisure or education, while ensuring their safety and maintaining the Trust's assets. Appropriate data management supports the organisation in achieving this overall purpose. It does this by enabling the organisation to gain the maximum value and utility from its data, information and knowledge to support internal processes, engage and educate the public and to preserve the history of the organisation. Specifically, this will:

- Demonstrate appropriate management and governance
- Provide deeper understanding of elements of the organisation (technical or otherwise)
- Maintain & preserve the history of the bridge & organisation
- Help solve technical issues as they arise, and to support inspection and maintenance planning
- Prevent duplication of work
- Provide evidence to underpin proposals to upgrade and change the bridge
- Generate greater engagement with the public
- Support research & education in partnership with the Brunel Institute, the University of Bristol Special Collection & other similar organisations or collections

To achieve the purpose of data management and realise the associated benefits, the objectives are as follows:

- Develop and implement a data management system to ensure the appropriate and adequate management of all data and information
- Capture the data management processes in place, identify gaps and address these
- Enable visitors and the public to access selected archive data
- Ensure compliance with all legislation regarding data and where appropriate follow applicable standards and codes of practice
- Develop an approach to capture implicit knowledge & processes

3 Policy Purpose

The purpose of this policy is to document the CSBT's approach to data management, the persons responsible for enactment of this policy and the processes contained within it. This will provide

clarity for the organisation, allow data to be processed more effectively and enable more value to be gained from the data.
This policy is not intended to force the organisation to dispose of data. The policy is intended to encourage a conscious approach to choosing what data to keep. Justification's can be made to keep material that falls outside the scope or requirements of this policy. Following the processes within this policy should ensure that data is recorded & stored appropriately and that it can be found again in future.

4 Review Date

The Bridge Master and Technical Committee should review this policy annually and more frequently if necessary. Once reviewed, the document should be updated to reflect the latest review date.

5 Definitions

- Archive: a collection of data, typically historical, in storage. For the CSBT the archive is the Brunel Institute, which holds historical material in appropriate conditions.
- CSBT Database: database or list where all items of CSBT data are recorded, including details such as title, date, part of bridge referred to, keywords etc. The database makes it possible to identify if material exists and to find out its location.
- Data: recorded symbols or signal readings, can be recorded in words or numbers or other recognised symbols, typically raw data before meaning is associated with it
- Disposal: permanent removal of data from the CSBT collection when the data is no longer interesting, useful, relevant, or current. Disposal methods will depend on data format and sensitivity.
- Explicit knowledge: can be articulated and communicated clearly, can be expressed as numbers or words, and captured in some format
- Information: when data is arranged, or processed in some way and meaning is made of it, a message that provides an input for decision making
- Knowledge: the recognition or cognition, capacity to act and understanding contained in an individual's brain (or collectively by a group) based on input data and / or information
- Policy: a series of related ideas or plans to support decision making and guide action towards a desired outcome
- Process: a series of actions taken to achieve a particular result
- Repository: storage location for data. For the CSBT the repository is offsite at the Crown record storage facility.
- Tacit knowledge / implicit knowledge: knowledge gained by experience or doing, typically not written down

6 Scope & Exceptions

7 Scope

7.1 Type of Data

This policy covers primarily documents, drawings and other paper based material and digital versions thereof. Objects shall be covered by a separate Collections Policy, controlled by the Visitor Centre Manager. The exception to this is that objects created as part of an engineering activity e.g. models, rock samples, parts of the bridge that have been removed etc. will be managed in accordance with this policy.

The scope of this policy extends to include contemporary and historical material regarding:

- Construction
- Technical & other major projects
- Inspection
- Maintenance
- Management of the bridge, including the historical and contemporary minutes from the Clifton Suspension Bridge Company & Clifton Suspension Bridge Trust meetings

The intention is to ensure that data is available and accessible, to support future decision making and help reduce areas of uncertainty. Data shall also be retained and preserved to maintain the organisational history and to provide a resource for the future.

7.2 Required Criteria

7.2.1 General

Only data which meets the following conditions should be retained.

- Data has title
- Author / creator is known
- Creation date is known
- Content / subject is clear from the item
- Content / subject is relevant to the CSBT
- The item is the latest physical and / or digital version (i.e. not a copy)
- The item is an older version (i.e. not a copy) if there is sufficient reason to keep out of date version
- Physical or digital copy if there is sufficient justification e.g. back up, different file format or annotated

Data that does not fall into the above categories but is considered important may be kept if specific justification is given. This shall be considered on a case by case basis.

7.2.2 Pre-1952 Data

If the data is known to predate 1952 then it may be kept providing the following conditions are met:

- Data has provenance
- Content or subject is relevant to the CSBT
- Item is a unique physical and / or digital version

7.3 Required Criteria

Only data which meets the following conditions should be kept, accessioned into the data management system and recorded in the CSBT database:

- Data has title
- Author / creator is known
- Creation date is known
- Content / subject is clear from the item
- Content / subject is relevant to the CSBT
- The item is the latest physical and / or digital version (i.e. not a copy)
- The item is the original physical and / or digital version (i.e. not a copy) if sufficient reason to keep out of date version
- Physical or digital copy with if sufficient justification e.g. back up or different file format

Data that does not fall into the above categories but is considered important may be kept if specific justification is given. This shall be considered on a case by case basis.

In particular, if the data is known to predate 1952 then if may be kept providing the following conditions are met:

- Data has provenance
- Content or subject is relevant to the CSBT
- Item is a unique physical and / or digital version

8 Categorisation of Data

All CSBT data can be categorised depending on its age, its content and whether it meets the requirements of Section 7.

8.1 Category 1

Category 1 data is that which meets the conditions of Section 7 and predates 1952. As this includes the oldest data, some of it may already be fragile and it will all need adequate care and appropriate storage to prolong its life.
If the material predates 1952 but does not meet the conditions of Section 7, then sufficient justification must be given as to why the data needs to be treated as Category 1 data.

8.2 Category 2

Category 2 data is that which meets the conditions of Section 7, dates from 1952 or more recent and falls into one of the following types of data:

- Inspection report
- Risk assessment report
- Technical committee meeting minutes
- Technical or academic report
- Maintenance record

Some of the older material may already be fragile and it will all need adequate care and appropriate storage to prolong its life.
If the material is dated from 1952 or more recent, but does not meet the conditions of Section 7.2 and / or it does not fall into one of the types of data outlined above in Section 8.2, then sufficient justification must be given as to why the data needs to be treated as Category 2 data.

8.3 Category 3

Category 3 data is that which meets the conditions of Section 7, is from 1952 or more recent and falls into any of the following categories:

- Technical project health & safety file
- Drawings
- Environment, health & safety information
- Operating procedure, process or policy

If the material is dated from 1952 or more recent, but does not meet the conditions of Section 7 and / or it does not fall into one of the categories in Section 8.3, then sufficient justification must be given as to why the data needs to be treated as Category 3 data.

8.4 Category 4

Category 4 data is all data that does not fit within Categories 1, 2 & 3 as described in Sections 8.1, 8.2 and 8.3.
In some cases it may be felt that this information could be useful in future and that it should be kept. This shall be considered on a case by case basis and sufficient justification must be given. A

decision needs to be made on whether to assign it as Category 2 or Category 3. Thereafter the data shall be treated as belonging to that category. Examples of this type of data could include:

- Material of high importance / relevance to the CSBT
- Material identified as having future value
- Records of unique events

9 Retention Period of Data

The retention period of the material depends on the category of the data.

9.1 Category 1

Category 1 data shall be kept indefinitely in its original format.
If the material predates 1952 but does not meet the conditions of Section 7, then sufficient justification must be given as to why the data needs to be treated as Category 1 and retained indefinitely.

9.2 Category 2

If the material meets the conditions of Section 7 and 8.2, it shall be kept indefinitely, in its original format.
If the material is from 1952 or more recent, but does not meet the conditions of Section 7 and / or does not fall within one of the categories in Section 8.2, then sufficient justification must be given as to why the data needs to be treated as Category 2 and retained indefinitely.

9.3 Category 3

If the material meets the conditions of Section 7 & 8.3 then it shall be kept in its original format for 10 years or until it is updated.
If it is updated, the time period of 10 years is reset. If it is not updated then the material shall be disposed of after 10 years. If superseded before 10 years, then the superseded material shall be disposed of at that point.
In some cases there may be a need to keep some of this material over a longer term or indefinitely e.g. in the case of drawings of specific interest or technical project files for major works. These should be judged on a case by case basis and if deemed appropriate then it shall be reassigned as Category 2 Data.
If the material does not meet the conditions of Section 7 & 8.3, then sufficient justification must be given as to why the data needs to be treated as Category 3 and retained for 10 years.
Category 3 digital data shall be retained indefinitely.

9.4 Category 4

Category 4 data should be retained while it is still live and being actively used. Once it is no longer of use e.g. the project it concerns is complete or the enquiry has been resolved, then the data should be disposed of.
In some cases it may be felt that this information could be useful in future and that it should be retained. Sufficient justification must be given as to why the data needs to be retained and a decision needs to be made on whether to assign it as Category 2 or Category 3. Thereafter the data shall be retained according to Sections 9.2 or 9.3.

10 Storage of Data & Records

Where and how material is stored will vary depending on the category and format of the data. The typical formats of data & material owned by the CSBT are as follows:

Table 1: Data Formats

Data	Physical Format	Digital Format
Hand written material	Original	Scan or photograph
Typed material	Original	Scan or photograph
Computer word processed material	Print	Original
Drawings	Original Print	Scan or photograph Original
Film	Original video tapes	Original and / or copy digital media file
Photographs	Print and / or negative	Original and / or copy digital media file
Objects	Original	Photograph of object

10.1 Physical Data

Physical data is currently stored in one of the following locations:

- CSBT Bridge Master's Office, Leigh Woods
- CSBT Visitor Centre, Leigh Woods
- Brunel Institute, Bristol (archive)
- Crown Records storage facility, Avonmouth (repository)

The material stored in the Bridge Master's office is either in the fireproof cabinet or on shelving. The Bridge Master holds an index of the material in the fireproof cabinet.
The material stored in the Visitor Centre is either on display or in storage. The Bridge Master holds an index of this material but it requires updating. This material will continue to be held in the Visitor Centre.
The material stored at the Brunel Institute is maintained under archive conditions and an index of this is available on request from the Brunel institute. This data will all be Category 1 as it predates 1952. This material will continue to be held here until further notice but no further material is to be stored here unless under joint agreement of the CSBT & the Brunel Institute.
The material stored at the Crown Records storage facility is in cardboard archive boxes with a unique identification number on the outside. The Bridge Master Currently holds an index of the material stored here.
Apart from the Brunel Institute (which only has Category 1 data), the other locations typically contain a mixture of categories of data. As Categories 1 & 2 have to be retained indefinitely, they should be stored wherever possible according to the following conditions to prolong their life (taken from http://www.archivesandmuseums.org.uk/scam/Infosheet3.htm, accessed on 04/03/2016):

- Material should be boxed or wrapped to limit the effect of any environmental changes & restrict light
- Storage material such as boxes, envelopes, wrappers should be low-acid or acid free – do not re-use old envelopes, brown paper or newspaper as wrappers
- Only use acid free tissue paper
- Fragile items can be given additional stability by storing in inert polyester sleeves ('Melinex'), but these must not be sealed on all sides as some circulation of air is important
- Inert polyester sleeves are also suitable for the storage of photographs
- Use brass paperclips to hold papers together, replacing steel pins and staples where possible as they will rust and stain paper

- Do not use sticky tape or 'magic tape' to repair tears – tears should be properly repaired, or the torn item put into a protective sleeve, until repairs can be carried out
- Do not use elastic bands to hold bundles together – bundles can be tied using unbleached cotton tape
- Do not allow frequent photocopying of the same document – if it is a popular item make a photograph or 'reference' copy from which further copies can be made
- Ideally, paper and parchment items should be stored at about 15oC and 55% relative humidity to restrict mould growth and limit the speed of any chemical processes occurring within the paper
- Ideally, photographs should be stored cooler and drier than paper, at about 5C or less and 20-35% humidity.
- Do not store archives near sources of heat, or where temperatures (and therefore relative humidity) will fluctuate wildly e.g. near water pipes or on floors where a possible flood could damage material.
- Do not stack boxes more than two or three high on shelves

In addition, Category 1 & 2 physical data should be digitised wherever possible and this copy then treated as the equivalent category digital data.

10.2 Digital Data

The CSBT shared drive is the storage location for all Category 1, 2 & 3 digital data owned by the CSBT. The CSBT shared drive is backed up on a weekly basis by the Office Manager onto an external hard drive, which is then stored in the fireproof cabinet in the Cash Office.
If there is any Category 1, 2 & 3 digital data stored on standalone PCs, external hard drives, pen drives, CDs or DVDs then it should be uploaded to the shared drive.
All digital data should be saved in the best resolution file format available. In the case of photographs and scanned images this is preferably the raw data format or alternatively the Tagged Image File (TIF). For other file formats e.g. word processing, the files should be reviewed whenever there is an update to the operating system or specific software package used by the CSBT.

10.3 Category 1 Data

Category 1 material may be kept in any of the locations detailed in Section 10.1. Wherever possible, the material should be kept in one of the offsite locations unless in constant regular use. It should be stored according to the storage conditions given in Section 10.1, however it is recognised that at present only the Brunel Institute fully meets these requirements. Digital copies should be made of all of this material and these copies should according to Section 10.2.

10.4 Category 2 Data

If available in physical format, Category 2 material may be kept in any of the locations detailed in Section 10.1. Wherever possible, the material should be kept in one of the offsite locations unless in constant regular use. It should be stored according to the storage conditions given in Section 10.1, however it is recognised that at present only the Brunel Institute fully meets these requirements. If not already available, digital copies should be made of this material and these copies should be stored on according to Section 10.2. If the original version is digital then this should also be stored according to Section 10.2.

10.5 Category 3 Data

Physical Category 3 material shall be kept in the Bridge Master’s office until it is due to be disposed of. If the decision is made to keep this data for longer it shall continue to be stored in the Bridge Master’s Office. If it is reassigned as Category 2 it shall be stored in accordance with Section 10.4.

Digital data shall be backed up onto the CSBT shared drive as well as being temporarily stored wherever it is needed e.g. Bridge Master's PC until it is due to be disposed of. If reassigned to Category 2, it shall be stored according to Section 10.4.

10.6 Category 4 Data

Physical Category 4 material shall be kept in the Bridge Master's office until it is due to be disposed of. If it is reassigned as Category 2 or 3 it shall be stored in accordance with Section 10.4 or 10.5.
Digital data shall be temporarily stored wherever it is needed e.g. Bridge Master's PC until it is due to be disposed of. If reassigned to Category 2 or 3, it shall be stored according to Section 10.4 or 10.5.

10.7 Material Held by External Parties

As mentioned, the Brunel Institute holds some of the CSBT's Category 1 data. This is under joint agreement between the CSBT and the Brunel Institute on the basis of a long term loan. The material held there is kept in archive conditions. Public access to this material is provided at the Brunel Institute. Some of this material has been digitised (scanned or photographed) and some has also been transcribed. It is the intention of the CSBT to continue digitising this material. The digital version of this material is Category 1 and should be treated as such.
Flint & Neill, the consulting engineers, also hold some data. This is partly CSBT data held at their premises as it is used by them and also data that they have generated since they were appointed to advise the CSBT. Data held by Flint & Neill that belongs to the CSBT should also be categorised and stored according to this policy and should be recorded in the CSBT Database. Data that Flint and Neill have generated themselves will be stored and managed according to their internal data management policy.

10.8 Review of Storage Conditions & Locations

The Brunel Institute is the only storage location that fully achieves the conditions of Section 10.1. However, not all of the Category 1 & 2 data is stored here and it is not possible to store more material here. There is therefore a need to review the storage locations and conditions for the CSBT data to determine the most appropriate long term storage solutions. The long term storage & back up of digital data should also be reviewed to ensure best practice and identify any areas for improvement.
This review should take place within the next year (i.e. should be complete within a year of this policy being published) and should include all physical & digital data. The output of the review should be a plan for the long term protection of this data. This should include transferring the material to a more suitable location, repackaging it appropriately, ensuring that the CSBT Database entries for the material are accurate and digitising it where possible. The plan for future protection & storage of this data should enable the conditions of Section 10.1 to be met. In particular, storage options for digital data should be considered e.g. cloud storage.
This policy should be updated to reflect changes implemented as a result of the review.

11 Accession of Data

If data meets the requirements of Section 7 then it shall be incorporated into the body of data that the CSBT maintains. This means that it shall be categorised according to Section 8, retained according to Section 9, stored according to Section 10 and added to the CSBT Database.
This process shall be applied to all newly created data and data new to the CSBT from the date of first issue of this policy. In addition, this process shall be applied to all existing data such that it also meets the requirements of this policy and is recorded in the CSBT Database. This should be completed by the Database Manager.

12 Access to Data

The intention is to get the most effective use out of the data that belongs to the CSBT to aid decision making and reduce uncertainty. As such, all CSBT staff & Trustees shall have access to the data.
Data that is already stored in the Brunel Institute is publically accessible on their premises, under supervision and with proof of identification.
Individuals and organisations, external to the CSBT may request access to CSBT data. While not obliged to provide anything the Bridge Master and / or Trustees may consider the request and provide information. This shall be carried out on a case by case basis and the outcome will depend on the cost incurred or time required of the CSBT to fulfil the request.
If the information requested is confidential or sensitive in any way it will not be shared. Confidential or sensitive information includes but is not limited to:

- Anything subject to the Data Protection Act 1998
- Security information
- Commercial information
- Tenders

If access is granted and the data is digital, a copy may be sent electronically. If the request is for a physical item then, if possible, a copy will be made and given out. If it is necessary to provide access to the original and it is to leave CSBT premises, a loan form is required to be completed by the CSBT & other party. Both the CSBT & the other party keep a copy of this. A blank loan form is given in Appendix C. The individual or organisation borrowing the material shall demonstrate that they have read and understand this policy and that they are going to use and look after the material appropriately.

13 Movement of Data

Material shall only be moved permanently in accordance with Sections 9 & 10 regarding retention period and location. When data is moved permanently, whether to a different location or for disposal, this shall be recorded in the CSBT Database. The data location in the CSBT Database shall always be up to date.
It may be necessary to move data from one location to another e.g. it may be relevant to current work and so needs to be taken out of long term offsite storage. Temporary movement of data lasting more than 1 day shall also be recorded in the CSBT Database such that the current location is always up to date.
In the case of movement of old, fragile items, professional advice shall be sought on the best way to move and protect them.
Only persons authorized by the CSBT Trustees or staff shall move CSBT data.

14 Disposal of Data

Material shall only be disposed of in accordance with Sections 7 & 9 regarding scope and period of retention.

14.1 Physical Data

14.1.1 Paper Records

The Bridge Master or CSBT Trustees shall decide whether the data to be disposed of is sensitive or not. If it is, it shall be disposed of in the confidential paper waste. If not, it shall be disposed of with the normal paper recycling.

14.1.2 Other Physical Data

The CSBT Visitor Manager shall be consulted regarding whether there is a place for the material within the Visitor Centre collection. If so then the item shall be accessioned into that collection. If not then it shall be disposed of appropriately, depending on the nature of the material. Professional advice may be needed regarding disposal of physical non-paper data.

14.2 Digital Data

Category 1, 2 & 3 digital data shall be retained indefinitely on the CSBT shared drive. Category 1, 2 & 3 digital data shall be removed from stand alone PC's & other local storage locations when they are no longer of frequent use & in line with Section 9. Category 4 data shall be disposed of as soon as it is no longer of use, in line with Section 9.
The Bridge Master or CSBT Trustees shall decide whether the data to be disposed of is sensitive or not. Professional advice may be needed regarding disposal of both confidential and non-confidential disposal of digital data.

15 Security & Protection

All data shall be kept in a secure location, such that access is only granted by the Bridge Master, a Trustee, a CSBT employee or by designated personnel (e.g. Brunel Institute staff). Physical data shall be kept in a secure physical location as described in Section 10.1. Digital data shall be stored on the shared drive as described in Section 10.2 and this is backed up as described in Section 10.2.

16 Data Ownership

All data remains the property of the CSBT throughout its life. Exceptions to this include but are not limited to the following:

- Material loaned to the CSBT by an external individual or organisation
- Technical & academic reports produced by external individuals & organisations and not commissioned by the CSBT
- Material related to the CSBT but owned by an external individual or organisation

17 Collaborative Projects

From time to time collaborative projects are undertaken between the CSBT and external individuals and organisations. Before any such project is undertaken, the access rights to existing data and ownership of future data should be agreed and documented. This should include physical data, digital data and intellectual property. Issues such as short & long term storage, data format and confidentiality shall be considered.

18 Special Requirements

There may be times when data is used as part of a display in the visitor centre. In such cases the data location shall be updated in the CSBT Database to reflect the new location. The material shall be handled and displayed appropriately given its category, age and fragility. The Visitor Centre manager shall be able to ensure this and if necessary, professional advice may be needed.
If it is felt that any material is very fragile and / or damaged then it may be necessary to take further steps to protect and preserve it. Professional advice may be needed to assess and advise on this.

19 CSBT Data Management Database

The CSBT Database shall be used to keep an accurate record of all data belonging to the CSBT. The data shall be recorded in the database if the conditions of Sections 7 & 9 on scope and retention period are met. The database shall capture meta-data on each item, including the information required by Section 7 and also current location, condition, owner, confidentiality and some keywords to enable more effective searching.

The CSBT Database shall be kept up to date by the database manager. The database shall be updated within a week of the change in some details of an item of data, the creation of new data or disposal of data at the end of its life. The database shall provide a means for searching for data, to find out whether something exists and also where it is stored. The database shall include details of information held by external organisations on behalf of the CSBT. The database shall be introduced within a year from commencement of this policy & the policy will require updating to incorporate any changes or additional processes related to the database.

20 Application & Responsibilities

20.1 Applicability

This policy is applicable to all staff, Trustees and personnel employed by the CSBT, whether temporarily or permanently. They should therefore be made aware of the policy and have access to it at all times. It is the responsibility of the Bridge Master to ensure that this happens.

In addition, this policy applies to any external individual or organisation that accesses or borrows any data belonging to the CSBT. The Bridge Master is responsible for ensuring that they have access to the policy and they should demonstrate that they have read & understood it.

20.2 Responsibilities

Table 1 defines the responsibilities for the different elements of this policy:

Table 1: Data Management Responsibilities

Element	Responsible Person(s)	Action Required
Data Management Policy	Bridge Master	Day to day implementation Point of contact for policy Annual review Update as required Appointment & supervision of Database Manager Communication with staff / contractors etc Approving access to data for external individuals or organisations
Data Management Policy	Trustees	Allocation of resources to enable policy to be implemented Annual review Approving access to data for external individuals or organisations Approvals & amendments to policy
Database	Database Manager	Update & maintenance of database Data entry Report creation (as required) Support & training for other staff
Technical Project Data Capture	Bridge Master / Project Engineer	Technical project health & safety file compilation Addition of project health & safety information into bridge health & safety file Entry into database
Maintenance Data Capture	Bridge Master / Database Manager	Capture details of maintenance work completed in maintenance record Update of bridge health & safety file Entry into database
Contractor / Supplier Generated Data	Bridge Master / Project Engineer / Database Manager	Drawing creation / update Update of bridge health & safety file Entry into database
Consulting Engineer Generated Data	Database Manager	Inspection report creation & entry into database Risk assessment update & entry into database
Historical Data	Database Manager	Digital versions stored Transcriptions of original material stored Entry into database Provision of public access

21 Related Policies, Documents & Standards

Table 2 outlines the documents related to this policy, both external & internal.

Table 2: Related Documents

Document Reference	**Document Name**	**Details**
ISO 55001	Asset Management. Management Systems – Requirements	Details of requirements for information for asset management
ISO 55002	Asset Management. Management Systems – Guidelines for the Application of ISO 55001	Guidelines on meeting the requirements for information for asset management
ASTM E2812 - 11	Standard Practice for Uniform Data Management in Asset Management Records Systems	Standard provides guidance on establishing and maintaining uniform asset data within an asset management records system
SCAM Info Sheet 3	Standing Conference on Archives & Museums, Archives in Museums, Archive Preservation & Conservation	Storage conditions for archive material
CSBT Archives Held in the Bridge Master's Office	CSBT Archives Held in the Bridge Master's Office	List of material as created in 2003
CSBT Archives Held in the Suspension Bridge Visitor Centre	CSBT Archives Held in the Suspension Bridge Visitor Centre	List of material as created in 2003
CSBT All Crown Records Archives	CSBT All Crown Records Archives	List of all material stored at Crown Records, listed by subject & by box/container
CSBT Loan Form	CSBT Loan Form	Record of items lent & individuals / organisations borrowing them

Appendix E

Clifton Suspension Bridge
Hanger Investigation & Testing: Background Report
Draft

Contents

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1.0 Introduction

The Clifton Suspension Bridge has 162 hangers which connect the three suspension chains to the bridge deck via the longitudinal girders. They are numbered outwards from the mid span of the bridge, starting at 0 in the centre. Along with the number, each hanger has an unique identification which locates it on the bridge according to the following:

- CN: Clifton North
- CS: Clifton South
- LWN: Leigh Woods North
- LWS: Leigh Woods South

Each hanger sub assembly is comprised of several components:

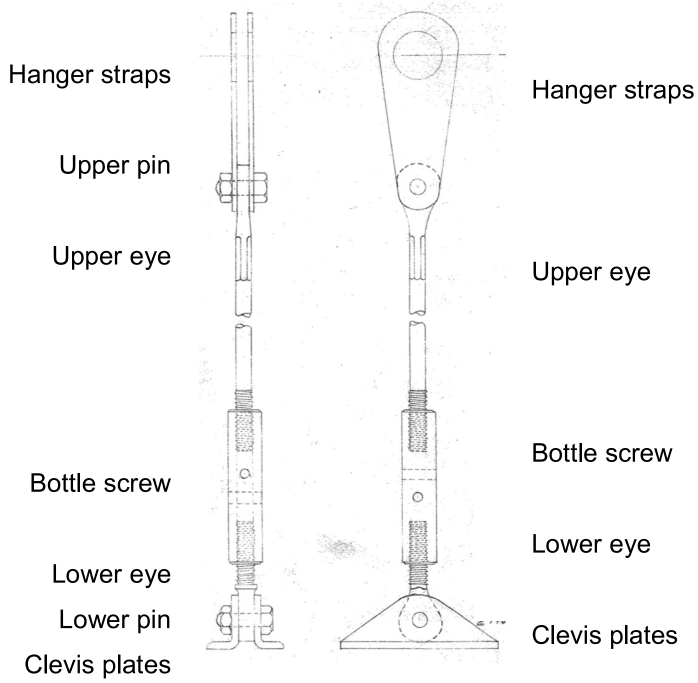

Figure 1: Hanger Sub Assembly

The hanger strap connects to one of the three suspension chains at a link pin position. The hangers are attached to the hanger straps through the upper pin. The hangers are attached by a lower pin to the clevis plates, which are in turn bolted to the upper flange of the longitudinal girder with eight bolts.

The hanger itself is comprised of three components, the upper eye, bottle screw and lower eye. The upper and lower eyes have external threads and the bottle screw has two internal threads. The lower eye has a right hand thread and the upper eye a left hand thread, such that the bottle screw can be used as a turnbuckle to increase or decrease the overall hanger length.

For the purposes of this report, the sub assembly is considered to include all of the components shown in Figure 1.

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2.0 Background

On the 4th of April 2009, a member of the public reported that hanger LWN3 was broken. The bridge was closed to vehicles and pedestrians while supports were put in place. A temporary hanger was then manufactured and fitted. The broken hanger was examined by Bodycote Testing Ltd to determine the cause of failure. The testing and inspection of the broken hanger found that the hanger failure was due to fatigue cracking, initiating from surface and sub-surface cracks in the material (Flint and Neill, 2009b).

Magnetic particle inspection (MPI) of the remaining hangers commenced to determine their condition. The short hangers in the middle third of the bridge were fully inspected using MPI and the long hangers were inspected at the top and bottom, believed to be the critical locations. The MPI found cracks and indications in the hangers but only those that met all of the following criteria were generally considered significant enough to warrant further investigation:

1. Cracks/indications near the top or bottom of the hanger as this was where fatigue cracking was most likely to occur
2. Cracks/indications running horizontally and perpendicular to the bridge axis
3. Cracks/indications greater than 10 mm in length

The defects meeting these criteria were removed by gentle grinding with a Dremel to a maximum depth of 3 mm. If the defect was still present after grinding then the hanger was replaced. This was the case for CN4, LWS8, LWS13, LWN24 and LWS34.

Hangers LWN5, LWS16 and LWS31 were found to have severe longitudinal laminations in the bottle screws and so were also replaced. Hanger LWN17 had been permanently deformed in the past. This was thought to be caused by overloading in compression during previous hanger removal procedures. This hanger was also replaced.

Table 1: Hangers Removed & Replaced in 2009

Hanger Number	Hanger Length (mm)
LWN24	7284
LWN17	4139
LWN5	1118
LWS8	1518
LWS13	2738
LWS16	3735
LWS31	11768
LWS34	13990
CN4	1037

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3.0 Purpose of the Hangers & How They Work

The purpose of the hangers is to suspend the bridge deck from the suspension chains and transmit load. As such the hangers need to be appropriately attached to both the chains and the deck and they need to be capable of withstanding the loading they are subjected to. They need to perform this function for an indefinite period of time. For the purposes of this report, the definition of the orientations of the hangers shall be as follows:

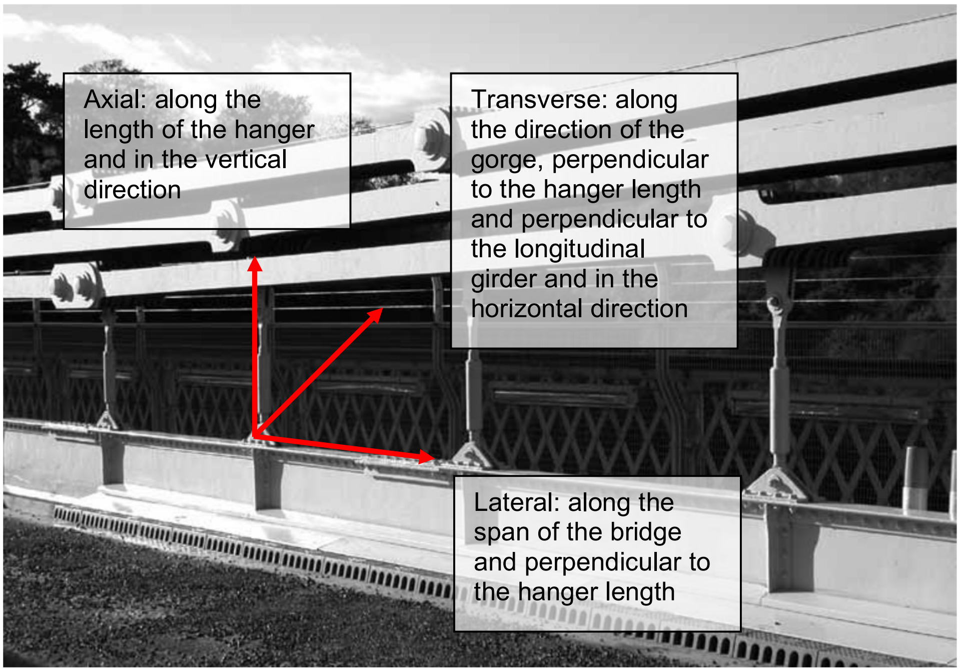

Figure 2: Loading Directions for the Hangers (Image: A. Andrews)

3.1 Loading and Constraints

The bridge is subject to dead load from its own weight and live loading from traffic (vehicular and pedestrian), weather (including temperature and wind) etc.

The hangers need to be able to carry tensile load in an axial direction. This load includes their share of the dead load and live load (mostly due to traffic). The hangers are also loaded in the lateral and transverse directions, mostly due to live (weather) loading.

The dead load of the bridge itself is static while the live loading is dynamic. Dynamic loading in a structure can lead to fatigue. Fatigue is the progressive process of loss of strength in a material (or structural element) during its life. It may result in failure at a much lower level of stress than the predicted ultimate stress level. Fatigue occurs when cyclic or fluctuating stresses and strains are applied.

In analysis of the structure, it is generally assumed that all hangers carry their share of the load. This however relies on the hanger lengths being such that they are able to carry their share and it is difficult to achieve this in a highly redundant structure. When one hanger length is adjusted there is a knock on effect on the surrounding hangers. However, when the hangers were removed for inspection, the load required to free the pins was recorded. It was found that each hanger was indeed carrying load, although not a precisely equal share (Clifton Suspension Bridge Trust, 2009).

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The hangers are pinned at either end. This enables axial load from the bridge deck to be transferred into the chains. This also allows rotation at either end around an axis in the transverse direction. The rotation means that when the bridge deck and chains are moving relative to one another, there is no bending load induced in the hanger. This is particularly important for the short hangers (from hanger 0 in the centre out to approximately hangers 16, on both sides, north and south) as they are not long enough to shed load by bending. The longer hangers (from hangers 16 outwards) do not need articulation as they are long enough to bend when a lateral load is applied. This is supported by the fact that no cracks are observed in the paint around the pinned joints on the longer hangers. In addition, Flint and Neill carried out an influence line study for the hangers which confirms that the rotations are greatest for the central hangers (Flint and Neill, 2009a). During recent work to free the joints, the pins have been installed at a lower torque so that there is reduced clamp force in an attempt to ensure that rotation can occur.

In the transverse direction, there is no articulation between the hanger and chains and hanger and longitudinal girder. However, loading in the transverse direction (likely to be due to weather) will induce a bending load in the hangers. Some relative movement between the chains and the deck in this direction is also possible if there is looseness in the joints, particularly wear of the pin holes.

3.2 Load Cases

Various load cases have been considered for analysing the hanger sub assembly. Barlow (Barlow, 1867) considered that the “greatest weight that can come upon a pair of rods, including their maximum load, is about 13 tons, which would produce a strain of $4^1/_4$ tons per square inch”.

Howard Humphreys carried out a risk assessment in 1999, where loads on the various members were calculated. The load case used was two 2.5 ton axles on one cross girder plus local footpath loading. This gave a maximum ultimate load in the hangers of 110.8 kN. The stresses were then calculated for the different elements of the hanger sub assembly under normal loading, for one failed hanger and for two failed hangers. These calculated results are given in Table 2.

By calculation they also determined that when hangers fail, the load is redistributed through the longitudinal girder to the surrounding structure. If one hanger fails then the load in the adjacent hangers increases by 50% and if two hangers fail then the load increases by 100%.

Table 2: Stresses Calculated in Hanger Components

Element	Allowable Ultimate Stress (MPa)	Stress Under Normal Loading (MPa)	Stress With One Failed Hanger (MPa)	Stress With Two Failed Hangers (MPa)	Capacity One Failure	Capacity Two Failures
Hanger	177	83	125	166	0.71	0.94
Hanger Straps	177	62	93	124	0.53	0.70
Pins	118	48.6	73	97	0.62	0.82
Clevis Plate (Axial)	177	62	93	124	0.53	0.70
Clevis Plate (Shear)	118	8	12	16	0.10	0.14
Bottom Bolts	155	161	242	322	1.55	2.07
Turnbuckle	177	30	45	60	0.25	0.34

(Howard Humphreys and Sons, 1999)

As can be seen in Table 2, the clevis plate to longitudinal girder bolts are the most highly stressed components in the sub assembly. They are overstressed in normal conditions and 50% overloaded if one hanger fails. The recommendation from the risk assessment was to replace these bolts, and this was carried out in 2006 and 2007. For the remaining components, failure of one hanger or two adjacent hangers will not result in overstressing. However, if two hangers fail there will only be a 6% margin before progressive failure occurs, assuming the given live loading is realistic (Howard Humphreys and Sons, 1999). The live loading considered is the vehicular & pedestrian worst case loading assuming that the weigh in motion system prevents any overweight vehicles entering the bridge. This load case does not, however, consider the effect of live loading from other sources e.g. weather.

Flint and Neill currently consider the load case for analysis of hanger performance as the combination of dead load, two 2.5 ton axles and the maximum pedestrian loading possible per cross girder with no distribution of load. In their influence line study (Flint and Neill, 2009a), they also found load sharing between the hangers due to the stiffness of the longitudinal girder.

3.3 Material & Manufacturing

The original hangers are thought to have been manufactured in the 1860s by Cochrane & Co at their Woodside Foundry near Dudley. They are manufactured from wrought iron, specifically believed to be Low Moor Iron, which was known to be of high quality. It is believed that the hanger eyes and rods were forged as independent components and then the eyes were forge welded onto the rods using a tilt hammer. The bottle screws are believed to have been forged and then drilled with opposing right and left hand screws (Flint and Neill, 2009b). Cullimore reports on the construction of the components “Tension tests made in 1923 showed that the lower threaded ends were welded on to the rods” (Cullimore, 1972). These welds can contain slag inclusions and, unlike the well dispersed slag threads found within the iron which add to the strength, these discontinuities can form stress raisers and areas for the initiation of corrosion.

In 1910 and 1911, 103 of the 1 ½ inch upper and lower eye bolts from the hangers were replaced and others were removed, oiled and replaced. The bolts that had to be replaced were steel but had suffered significant section loss. They were replaced with Farnley Iron bolts. During the period from 1978 to 1981, in the central third of the bridge, all upper and lower bolts were replaced with 25mm diameter stainless steel bolts fitted in mild steel collars in the hanger straps and clevis plates and PTFE coated bush in the hanger eyes (Howard Numphreys, 1980).

The only known details on hanger material chemical composition come from the testing carried out on LWN3 broken hanger. Table 3 gives the breakdown of percentage composition of elements commonly found in wrought iron (Bodycote Testing Ltd, 2009).

Table 3: Chemical Composition of CSB LWN3 Hanger Material

Chemical Element	Percentage Composition
Carbon	0.011
Silicon	0.19
Manganese	0.07
Phosphorous	0.2
Sulphur	0.011
Chromium	<0.01
Molybdenum	<0.01
Nickel	0.02
Aluminium	0.02
Copper	0.02
Titanium	<0.01

Hangers were removed in the past and tensile testing was carried out by the University of Bristol in 1923. It is unclear which hanger(s) was used and the test report has not yet been found. The results of these tests are summarised in Table 4 (Howard Humphreys and Sons, 1952).

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Table 4: Tensile Test Results for Unspecified CSB Hanger Material

Specimen	Ultimate Tensile Strength (MPa)	Extension (%)	Comments
A	287	2	Broke at weld
B	341	13	Good fracture
C	351	14.4	Yield at 15.9 ton/in^2

In 2009, LWN3 hanger was also tested in tension and these results are given in Table 5 (Bodycote Testing Ltd, 2009).

Table 5: Tensile Test Results for CSB LWN3 Hanger Material

Component	0.2% Proof Stress (MPa)	Ultimate Tensile Stress (MPa)	Elongation
Upper (Broken) Eyebolt	216	341	26.5% on 40mm
Bottle Screw	257	366	27.0% on 40mm
Lower Eyebolt	223	368	25.0% on 40mm

Bodycote also carried out Charpy impact testing on selected areas of hanger LWN3 and the results are given in Table 6 (Bodycote Testing Ltd, 2009).

Table 6: Impact (Charpy Impact at -20˚C) Test Results for CSB LWN3 Hanger Material

Specimen Position	Fracture Energy (Joules)
1	9
2	16
3*	5

* Position 3 was taken across the grain.

3.4 Environment

The hangers are exposed to the elements at all times. They are protected with a paint system that is generally comprised of a micaceous iron oxide epoxy coating, high build epoxy undercoat and acrylic urethane finish coat on, in places, a variable number of earlier coatings. Due to the geometry of the upper and lower eyes, when the pins are fitted, moisture traps can form allowing corrosion to take place. This creates surface pitting and results in loss of section.

Relative movement between components e.g. pin and eye can cause fretting and subsequent wear of the components. This also leads to loss of section and a change to the surface finish of the components.

3.5 Historical & Aesthetic Considerations

As the majority of the bridge components are original, dating from the 1830s through to the 1860s, there is a strong desire to maintain the historical and aesthetic integrity of the bridge. This is enforced by the bridge being a Grade 1 listed building, meaning that English Heritage have to be consulted on matters relating to a change in the fabric or appearance of the bridge. As such, although non-original hangers are manufactured from steel, they have the same geometry as the original hangers.

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3.6 Leigh Woods North 3 Hanger Failure

When hanger LWN3 broke on the 4th of April, it was unexpected. No indication or crack had been observed previously. It was removed and sent for testing to determine the cause of failure. The testing carried out included the following (Bodycote Testing Ltd, 2009):

- Visual inspection of the components, material condition & fracture surfaces
- Scanning electron microscopy (SEM) of the fracture surfaces
- Magnetic particle inspection (MPI) of the components to detect indications in the material
- Radiography of the components to determine soundness of welds and detect indications
- Chemical analysis of material to give percentage composition of elements
- Tensile testing to give 0.2% proof stress (yield), ultimate tensile stress and percentage elongation of specimens taken from:
    - Upper eyebolt
    - Bottle screw
    - Lower eyebolt
- Charpy impact testing to give an indication of the toughness of material
- Microscopic examination to determine the microstructure of material at various locations
- Macroscopic examination of etched surface to identify grain flow & direction

The conclusion reached was that the hanger LWN3 failed due to fatigue cracking, with both surface and sub-surface defects acting as the crack initiation locations (Flint and Neill, 2009b). Either one or both of the pinned joints must have become seized, inducing a bending load in the hanger. The bending load being applied cyclically will have acted to fatigue the component and the existing defects will have provided the crack initiation locations.

There is a report of hangers having snapped in the past due to high winds, when two on the north side and three on the south side failed (Cottrell, 1928).

The hangers are inspected by Flint & Neill as part of the annual bridge inspections. Since the failure of LWN3, the tops and bottoms of the short hangers and the bottom of the long hangers are also inspected monthly by CSB staff. It is therefore important to determine whether these inspection intervals are suitable to identify an indication before failure occurs. In order to do this is will be useful to identify whether possible future failure modes are ductile or brittle, as ductile failure will be slower and more gradual. The potential for a crack to initiate at an internal flaw and only become visible just before or at failure needs to be investigated and understood.

If brittle failure is possible, then the risk of that failure needs to be evaluated. From analysis carried out (Howard Humphreys and Sons, 1999), if a hanger fails then the neighbouring hangers are capable of taking up the load with no damage to any other part of the structure. The exception to this are the end hangers (LWN40, LWS40, CN40 & CS40) as there are no more hangers outside to distribute the loading to. However, these hangers have a larger diameter than the others (2” compared with 1 5/8”).

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4.0 Existing Data on Wrought Iron

4.1 History of Wrought Iron

Wrought iron was a popular structural material in the 1800s due to its improved ductility and higher performance over cast iron. Development of the puddling furnace by Henry Cort enabled the first large scale, industrial production of wrought iron (Moy et al., 2009). After the introduction of the Bessemer process in the 1860s, commercially produced steel gradually replaced wrought iron as the primary structural metal (Morgan, 1999, Moy et al., 2009) and after 1900 virtually all structural metal was steel (Morgan, 1999).

In the second half of the 20th century there has been an increased interest in wrought iron as many of the historic bridges still in use (particularly in the UK and USA) are of wrought iron construction. Some of these bridges require repair (Morgan, 1999) and others analysis (Kelton et al., 2011) to ensure that they can remain operational and withstand the increased loads of modern traffic. In order to do this a better understanding of the material properties is required.

4.2 Manufacturing Process

The manufacturing process of wrought iron directly affects its material properties. Cast iron is remelted and puddled (stirred) to oxidise it and remove impurities. After this, a semi solid ball of slag iron mixture is removed from the furnace for further processing. The material is then subjected to mechanical treatments (e.g. rolling) and further heating to produce varying grades of bar. The quality, strength and ductility of the bar increases with each of the subsequent mechanical treatments, up to a maximum of 6 stages. This is due to the slag being broken down into smaller sizes and dispersed more evenly throughout the material. The breaking down and dispersing of the slag through the material improves the strength and the ductility (Morgan, 1999, Moy et al., 2009, O'Sullivan and Swailes, 2009).

4.3 Challenges for Historic Bridges

Due to the number of wrought iron bridges still in existence in the UK and USA, there is a need to maintain them in working order where possible. This requires an understanding of the material properties. However, as the properties can vary from bridge to bridge and even within a single structure, local testing is often required. Also, many of these bridges are considered to be of “architectural importance”, repair and renovation must be carried out using traditional materials where possible (Morgan, 1999). Due to the historical value of the original material of these structures, there is rarely material available to test and removal of structurally significant parts is either undesirable or unfeasible. Where there is little material available, testing will not always be able to give statistically significant results (Sparks, 2008).

4.4 Properties of Wrought Iron

It is argued that in many cases the geometry of bridge structural members is relatively straightforward to understand. It is instead the material properties that pose the greater unknown when trying to analyse the overall structure. For the Clifton Suspension Bridge, there is much redundancy in the structure and the effects of friction not completely understood. However, a better understanding of the material properties will help to identify failure mechanisms and potential risks.

4.4.1 Chemical Composition

The chemical composition of the material will first of all confirm that it is indeed wrought iron and will also give an indication of how ductile it is likely to be. The malleability and ductility of wrought iron is due to its low carbon content, typically between 0.02% and 0.05% (Moy et al., 2009). Unlike cast iron, wrought iron always contains slag, which may be up to 3% of the weight. Well dispersed threads of slag through the wrought iron actually contribute to the strength of the material.

Different sources suggest different maximum chemical compositions of wrought iron. Exceedance of these values does not necessarily mean rejection, but instead indicates that further investigation may be required.

Table 7: Maximum Suggested Chemical Compositions

Element	Max Composition (Sparks, 2008)	Max Composition (O'Sullivan and Swailes, 2009)
Carbon	0.1%	0.05%
Phosphorous	0.3%	0.16%
Sulphur	0.04%	0.05%
Manganese	Not Specified	<0.1%
Silicon	Not Specified	<0.2%

A higher level of phosphorous will result in higher yield and ultimate tensile strengths but will reduce the ductility and impact resistance significantly (O'Sullivan and Swailes, 2009).

4.4.2 Tensile Strength

The yield and ultimate tensile strength will vary greatly depending on where the material was produced, how many times it was worked, orientation of use etc. As the properties vary from one structure to next and there is seldom opportunity to carry out extensive destructive testing, it is not always clear if a representative strength value can be obtained.

Cullimore's work (Cullimore, 1967) was concerned with investigating the effects of corrosion on strength. He found that generally, the static tensile strength was not affected by corrosion of the material, but there may be some reduction if the loss of cross sectional area was severe.

Morgan (Morgan, 1999) wanted to evaluate the "likelihood of obtaining a representative strength figure for a batch of wrought iron, where there is only sufficient "spare" material to enable a very limited number of strength tests to be carried out". He carried out further analysis of Kirkaldy's results (Kirkaldy, 1863) and showed that when the elongation at fracture is greater than 10%, the strength value measured in a single tensile test is likely to lie within 90% of the average strength of the bulk material. This suggests that ductility is a key indicator of the tensile strength of the material and that from his experience "any tensile test of wrought iron producing only a small elongation at fracture should be considered to be suspect until proven innocent" (Morgan, 1999).

Moy (Moy et al., 2009) reports on the heterogeneity of wrought iron, finding the ultimate tensile strength greater along the grain while the proof stress similar in both directions. This indicates that care must be taken over the direction in which the material is loaded.

Kelton (Kelton et al., 2011) reports on the size effect found in wrought iron, which is that test specimens taken from thinner bar tended to have a greater tensile strength than samples taken from thicker bar. This is believed to be due to the extra working required to reduce the diameter of the thinner bar resulting in a better distribution of the slag in the material (resulting in higher strength and ductility). In addition, when investigating the size effect, the relationship between the strength and thickness seemed to be more obvious for yield strength rather than tensile strength. Although the strength tends to be lower for the larger specimens, the strength remaining beyond yield is greater. Mechanical property variation in the wrought iron was generally lower for different members within a bridge than for a single member type across many bridges. Kelton also finds that while the strength of wrought iron varies from structure to structure, the yield strength seems to vary more than the tensile strength.

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Table 8 gives a selection of strength values for wrought iron, from a variety of sources, together with values obtained from the Clifton Suspension Bridge, including the failed hanger LWN3.

Table 8: Yield & Ultimate Tensile Strengths for Wrought Iron

Study	Date of Study	Av. Tensile Strength (MPa)	Min Tensile Strength (MPa)	Max Tensile Strength (MPa)	Av. Yield Strength (MPa)	Min Yield Strength (MPa)	Max Yield Strength (MPa)
Kirkaldy (Kirkaldy, 1863)	1862	358	255	468			
Beardslee (Kelton et al., 2011)	1879	364	317	427			
Johnson's Materials of Construction (O'Sullivan and Swailes, 2009)	1939		327	358			
Tredgold (Morgan, 1999)	1862	414	345				
Morgan (Morgan, 1999)	1999	384	358	417			
UK Highway Standard BD21	2001				220		
O'Sullivan & Swailes (O'Sullivan and Swailes, 2009)	2009				185		
Cullimore (Cullimore, 1967)	1967	321	278	352	222	195	258
Kennedy (Cullimore, 1967)	1884		323	392		198	264
Moy et al (Moy et al., 2009)	2009	348	232		250	190	
CSB Hanger LWN3 Upper Eyebolt	2009	341			216		
CSB Hanger LWN3 Bottle Screw	2009	366			257		
CSB Hanger LWN3 Lower Eyebolt	2009	368			223		
CSB Hanger Specimen A (Howard Humphreys and Sons, 1952)	1923	287					
CSB Hanger Specimen B (Howard Humphreys and Sons, 1952)	1923	341					
CSB Hanger Specimen C (Howard Humphreys and Sons, 1952)	1923	351					

4.4.3 Ductility

According to Sparks, "Ductility is essential for fracture toughness. It assures microscopic crack attenuation, allows the material to tolerate minor internal defects such as inclusions, and permits redistribution of stresses at extreme loads. This results in gradual rather, than catastrophic, failure. The resistance of good wrought iron to brittle fracture can be explained by the ability of the fibrous microstructure to attenuate crack growth by delamination and crack branching. But it is the ductility of the ferrite matrix than enables the fibrous character to be beneficial rather than detrimental (Schindler)." (Sparks, 2008)

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A measure of ductility can be obtained in various ways e.g. measuring elongation at failure, measuring reduction in cross sectional area at failure, measuring hardness or measuring impact energy. Some sources suggest that the preferred method is to measure the percentage reduction in area at tensile failure (Kelton et al., 2011, Sparks, 2008, Kirkaldy, 1863).

Moy (Moy et al., 2009) proposes that Charpy impact tests give an indication of the ductility of the material. In his study these tests were carried out on specimens along the grain and specimens taken across the grain to compare. It was found that the fracture energy along the grain was more than double that across the grain. This corresponds to a much greater ductility along the grain.

O'Sullivan et al (O'Sullivan and Swailes, 2009) propose that "Toughness is the property that should be used in assessing the quality of wrought iron. Toughness is determined by both strength and ductility". It is therefore not necessarily a lack of strength that results in structural failures but instead a lack of toughness in the material. They have reported that according to impact testing data, the toughness of wrought iron is variable.

Cullimore observed that surface condition was linked to the ductility of the material. A highly pitted specimen demonstrated a much lower percentage elongation to fracture than a lightly pitted specimen, which in turn was much lower than a specimen with machined surfaces. This was thought to be because "surface pitting localises the area of plastic flow and so reduces the overall elongation" (Cullimore, 1967).

Morgan (Morgan, 1999) found that when the elongation of a test specimen is greater than 10%, the strength value obtained in a single tensile test is likely to lie within 90% of the average strength of the bulk material. As elongation is a measure of ductility, this suggests that ductility is an indicator of the tensile strength of the material.

From Moy's work (Moy et al., 2009), elongation was found to be much greater along the grain rather than across the grain. Therefore failures along the grain tend to be ductile and failures across the grain tend to be brittle.

4.4.4 Hardness

Hardness is primarily of interest because according to Kelton "there is often a good correlation between hardness and strength in homogenous metals". However, due to the heterogeneity of wrought iron this relationship may not apply (Kelton et al., 2011). The interest in this method is that hardness testing is a non-destructive method that can be applied in the field. Therefore no original material has to be sacrificed and testing can be carried out in-situ. Unfortunately, Kelton only finds a weak correlation between hardness and ductility. However, the samples with the highest hardness had a lower ductility, suggesting that this could be used as a screening test

Sparks (Sparks, 2008) suggests a typical range of Brinell Hardness Numbers (BHN) to be expected for wrought iron and also a maximum value. Exceedance of the maximum is not in itself a failure of the material but indicates that further investigation may be required.

Table 9: Brinell Hardness Numbers for Wrought Iron

Brinell Hardness Numbers for Wrought Iron	
Typical Range	High Range
95 - 120	130*

* Local values in areas of phosphorous segregation may reach 160 BHN (Sparks, 2008)

4.4.5 Critical Flaw Size

Critical flaw size is linked to the ductility and fracture toughness of a material. Critical flaw size is the flaw size for a given applied stress, which will continue to grow unstably with no further increase in the applied stresses. It is therefore important to know what the critical crack length is before inspecting tensile structural members. The critical flaw size can drive the decision on inspection methods as it must be possible to detect flaws of this size. Typically in wrought iron that has reasonable ductility, the critical flaw sizes are large enough that visual or ultrasonic inspection techniques are sufficient (Sparks, 2008).

4.4.6 Fatigue Strength

Fairbairn carried out some early work looking at the effects of continuously changing loads over time on iron. This study was carried out as the effects of fatigue on wrought iron were not well understood at that time. It was concluded that “wrought-iron girders of ordinary construction are not safe when submitted to violent disturbances with a load equivalent to one-third the weight that would break them. They, however, exhibit wonderful tenacity when subjected to the same treatment with one-fourth the load” (Fairbairn, 1863).

Cullimore (Cullimore, 1967) carried out a study into the effect of weathering on fatigue strength. The aims of this study were to better understand the effects of cyclic stressing, ageing and corrosion on the material’s residual fatigue strength. Failure of the material was found to be due to a combination of corrosion and fatigue. This was caused by a loss of ductility as a result of significant surface pitting. For severely corroded specimens, the residual fatigue life was found to vary considerably. The fatigue limit of wrought iron was found to be approximately one third of the ultimate tensile strength.

Cullimore (Cullimore, 1967) suggests that in order to get a realistic value for the fatigue strength of a structure, it is desirable to carry out a full scale test of the components. There is a higher likelihood that the full scale component will contain flaws compared with a specimen, but these flaws may be less critical. This is because the crack will need to grow much further before failure occurs.

He states that “when assessing the fatigue strength of existing wrought iron structure, particular attention should be paid to those members of the structure to which any of the following factors are relevant:

1. High stress fluctuation, including stress raisers
2. Large number of previous load cycles
3. Presence of corrosive environment
4. Surface damage or loss of cross sectional area”

Cullimore, referring to the Clifton Suspension Bridge, states that “Consideration has been given to the possibility of finding the rate of propagation of a fatigue crack, once started, to enable an estimation of the survival of a cracked component to be made. Because of the uncertainty of obtaining consistent results with wrought iron, and the necessity of making measurements on the bridge to discover the number of loadings causing damage which the component is likely to suffer, this has been deferred” (Cullimore, 1972).

4.5 Implications for the Clifton Suspension Bridge

For the Clifton Suspension Bridge, it would suggest that identifying the material properties of the hangers is important. This has already been done for hanger LWN3 (and tensile strength is available for another unknown hanger) but as properties can vary from one member to another or even within a member it is important to establish in order to understand the sub assembly performance. Consideration must also be given to the statistical significance of any testing carried out due to the limited quantity of material which will restrict the number of test specimens available.

The chemical composition should be established to confirm that the hangers are indeed wrought iron and to give an indication of the material tensile strength and ductility. For the testing carried out on LWN3 (Bodycote Testing Ltd, 2009), the chemical composition showed a level of phosphorous higher than the maximum recommended by O'Sullivan et al (O'Sullivan and Swailes, 2009). Higher levels of phosphorous may result in higher strength but reduced ductility, and is therefore relevant to the performance of the material in the structure.

The yield and ultimate tensile strength of the material varies with many factors and so testing should be application specific. It may also be of use to establish the tensile strength of material from other areas of the bridge as a comparison. Tensile results for specimens that show less than 10% elongation at failure should be investigated further before accepting the results (Morgan, 1999). Consideration should be given to the grain direction when designing the test specimens to ensure the tests are representative of the loading on the components. Consideration should also be given to the size effect in wrought iron. It is believed that the outer four hangers are the strongest as they have a diameter of 2" compared to the others which have a diameter of 1 5/8". However, testing has found that specimens from thinner bars have a higher tensile strength due to the increased working (rolling) required to obtain a smaller diameter. With more information on the tensile strength of the material, a better review can then be carried out of how the CSB hanger material compares to other test data and generally accepted standard values.

Ductility is very important for wrought iron structures as it enables the material to cope with defects and allows load redistribution (Sparks, 2008). Toughness is a combination of strength and ductility. A lack of toughness may lead to structural failures more than a simple lack of strength. Ductility can be measured by a percentage elongation in the specimen at tensile failure, a percentage reduction in cross sectional area at tensile failure, the impact energy of the material or by the hardness number. It would be useful to try out different methods and compare the findings. It would be interesting to analyse the results to determine if there is a correlation between ductility and strength (or any other property). Again, consideration should be given to the grain direction when designing the test specimens to ensure the tests are representative of the loading on the components. As the material surface condition affects ductility, testing should include specimens with surfaces typical of the hanger condition.

In certain materials there is a correlation between hardness and strength and it was found by experiment that a weak correlation may exist between hardness and ductility (Kelton et al., 2011). Testing of CSB hanger material should be carried out to determine if there is any correlation and if non-destructive hardness testing could be useful to indicate material strength or ductility. If the Brinell Hardness Numbers are found for the material, they can be compared with those suggested by Sparks as typical for wrought iron (Sparks, 2008).

Critical flaw length gives the length a crack needs to reach, after which it will continue to grow unstably with no further increase in the applied stresses. Calculating this length for the hangers, under realistic load cases, will give the minimum size of indication that inspection techniques need to be able to find. This will allow a review of inspection processes to ensure that they are appropriate. Calculating the time to failure once a crack length reaches the critical flaw length would then allow a review of the inspection intervals. It is important to ensure that there is sufficient time for a planned inspection to take place before failure of the component.

Residual fatigue life is affected by corrosion because it reduces ductility. Where severe corrosion has taken place, the residual fatigue life can vary considerably. Test specimens from the CSB hangers should be chosen to represent the typical and worst case examples of corrosion. It is suggested that better results may be obtained from carrying out full scale tests (Cullimore, 1967). However, there are only a limited number of hangers available to care must be taken in the experimental design. Finally, Cullimore also states that finding the rate of propagation of fatigue cracks will be difficult for the CSB. This is due to determining the level of load and number of loading cycles that the component is likely to encounter (Cullimore, 1972).

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5.0 Further Work

5.1 Gaps in Knowledge

The following points are suggested for further investigation, to improve the understanding of how the hangers work and why they fail:

- A better understanding of the material properties
- The effect of live loading on the structure in all degrees of freedom
- A more detailed understanding of how the joints transfer load and where the weak points are
- Analysis of critical flaw length for hangers under typical and worst case loading
- Fatigue performance of the hangers and residual fatigue life

5.2 Testing

It has been proposed that the nine hangers removed from the bridge are used for testing. The purpose of the testing would be to gain a better understanding and confidence in the performance of the hangers. Due to the unexpected and relatively sudden nature of the LWN3 failure, the hangers remain as an item of concern on the risk assessment. This is because some areas of the long hangers that have not yet been inspected using the MPI technique and there is also concern over the hanger straps as they are difficult to access for inspection or remedial work.

The Clifton Suspension Bridge Trust (CSBT) wish to confirm that the hangers are working as expected. The CSBT recognise the need to better understand how safe the hangers are and whether an unsafe situation or load case is likely to occur. They wish to gain more confidence in the material properties that are assumed in bridge analysis and the properties found from the study on LWN3. The testing will hopefully also provide a better understanding of how the joints and sub assembly perform overall. A better understanding of the material, joints and sub assembly will help to justify the factors of safety already used and should identify whether the level of conservatism used in hanger analysis is appropriate.

5.3 Recommendations

From the information available and the perceived gaps in knowledge it is recommended that the testing is designed to address material properties, static joint behaviour, fatigue joint behaviour and potentially also the fatigue strength of the entire sub-assembly.

Before testing, however, it is important to review the load cases to ensure that the testing is carried out for typical and realistic worst cases. The hangers should be inspected using a non-destructive technique to identify inclusions in the material, flaws in the welds etc. This will allow specimens to be selected from the appropriate locations. The critical flaw length should be calculated as this will help to define the inspection techniques required and testing can be carried out to evaluate the number of cycles to failure after critical flaw length is reached.

It may be beneficial to instrument one (or several) of the hangers in-situ on the bridge to better understand the loading, and stresses and strains in the components. This will help to identify the most critical joints and load cases which will in turn help when designing the experiments. This will also help to determine the level of loading and number of cycles that cause damage to the structure which will be important for defining the fatigue testing.

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6.0 Failure Mechanisms

Failure of the hangers may be the result of several interacting factors. Failure may occur at the material level, be due to specific joint configuration or may only be possible in the overall assembly when the loads and constraints are applied.

In the case of LWN3, the conclusion reached was that it failed due to fatigue cracking, with both surface and sub-surface defects acting as the crack initiation locations (Flint and Neill, 2009b). Either one or both of the pinned joints had become seized, inducing a bending load perpendicular to the length of the hanger. The cyclical bending load will have acted to fatigue the component and the existing defects will have provided the crack initiation locations.

This means that there were defects or cracks at a material level. The components, joints and constraints were such that lateral loading could not be relieved in any other way e.g. through articulation. Then the overall assembly was subjected to cyclic loading in the lateral direction which it was not designed for. This caused the fatigue failure which occurred at the failure initiation locations provided by the material flaws.

Therefore, to identify the possible failure mechanisms, each level must be explored to understand how it may contribute overall. Then combinations of these factors and interactions between them should be analysed to understand how the failure may occur.

Factors that will influence failure:

- Material properties including material type, strength, ductility and how it is likely to fail (also possibilities that are low probability but high consequence)
- Geometry of the components and the joints, what are the possible failure modes, what are the load paths, load levels, and constraints on these joints, are there stress concentrations, do we understand how they work and how do the material properties influence these failure modes
- Assembly of material properties, components and joints, how do these factors interact, what is the load path through the overall structure, are there external influences on the hangers that are not accounted for in the design, what load cases should be considered

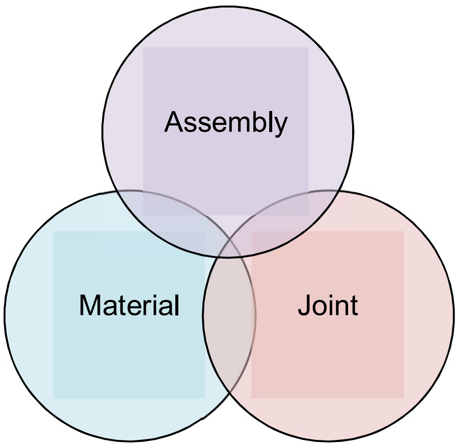

Figure 3: Factors Influencing Hanger Failure

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6.1 Material Failure Mechanisms

The following table (Table 10) gives an overview of the possible mechanical failure modes for materials and structural components. Alongside each mode there is a comment relating the failure to the CSB hangers.

Table 10: Mechanical Failure Mechanisms for Materials & Components

Failure Mechanism	Description/Definition	Risk to CSB Hangers
Buckling	Sudden failure of a structural member subjected to high compressive stresses, where the actual compressive stress at failure is less than the ultimate compressive stresses that the material is capable of withstanding	Hangers are normally in tension, risk when jacking chain and longitudinal girder together to remove hanger, however loading then reverts to tension and member will still carry tensile load
Corrosion	Gradual destruction of materials by chemical reaction with its environment	Iron is susceptible, paint system provides level of protection however corrosion is seen to occur resulting in section loss and surface pitting
Corrosion Fatigue	Fatigue in a corrosive environment resulting in the degradation of a material under the joint action of corrosion and cyclic loading, the only requirement is that the sample be under tensile stress	As reported by M.S.G. Cullimore, the hangers are exposed to the elements and subjected to cyclic loading, investigate through test of specimens with typical surface corrosion
Creep	Creep is the tendency of a material to move slowly or deform permanently under the influence of mechanical stresses	Not sure wrought iron is susceptible to this (although cast iron appears to be), more likely at high temperatures, unlikely for the hangers as they are in ambient conditions
Fatigue	The progressive and localised structural damage that occurs when a material is subjected to cyclic loading	Iron is susceptible to fatigue and hangers in particular, depending on constraints and magnitude and direction of loading, would be beneficial to get a better idea of fatigue strength from testing and identify variability
Fracture	Fracture is the separation of an object or material into two or more pieces under the action of stress, almost always due to the development of displacement discontinuity surfaces within the solid.	Wrought iron can contain discontinuities, fracture could occur. Hangers subjected to constant stress.
Hydrogen Embrittlement	The process by which various metals become brittle and fracture following exposure to hydrogen	Wrought iron not thought to be susceptible
Impact	Where a high force or shock is applied over a short period when two or more bodies collide, a high velocity collision does not give enough time for the energy to be converted into deformations and vibrations and as a result the material behaves as though it is much more brittle than it is	Possible if something impacts the bridge at high speed e.g. another part of the bridge, foreign objects etc. Has to be reasonably high load at very high speed.

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Table 10: Mechanical Failure Mechanisms for Materials & Components Continued

Failure Mode	Description/Definition	Risk to CSB Hangers
Mechanical Overload	The failure of a product or component in a single event is known as mechanical overload, occurs because the product is weaker than expected (maybe due to a stress concentration) or the applied load is greater than expected and exceeds the normal tensile strength, shear strength or compressive strength of the product	Due to tensile or shear loading. Likely due to overloading or material properties being lower than expected. Therefore beneficial to get a better idea of material strength through test and load cases through evaluation/measurement. Try to understand the variability in material and properties and also if there is an issue with reduced ductility. Corrosion that has caused net section loss could contribute to this. Also surface corrosion can increase brittleness in material. Compressive failure very unlikely as members are in tension except when jacking to remove hangers, if too much load was applied to a short hanger (that could not bend) that was seized and unable to articulate then it is possible.
Stress Corrosion Cracking	The growth of cracks in a corrosive environment leading to the sudden unexpected failure of normally ductile metal subjected to tensile stress, corrosion (such as pitting) leads to the development of brittle cracks, growth and failure.	Iron is susceptible to this, possible but unlikely as the material is protected from the corrosive environment with appropriate paint systems & inspected regularly to ensure that there is no significant corrosion or visible cracking. More likely at elevated temperatures which is not applicable for the hangers.
Thermal Shock	This occurs when a thermal gradient causes different parts of an object to expand by different amounts. The differential expansion can be understood in terms of stress or strain. At some point this stress may exceed the strength of the material, causing a crack to form.	Wrought iron not thought to be susceptible, requires material to be exposed to a thermal gradient, only likely to be difference between direct sun and shade
Wear	Wear or erosion is the sideways displacement of material from its derivative and original position on a solid surface performed by the action of another surface	Wear can occur between moving components of the hangers
Yielding	The yield strength or yield point of a material is the stress at which a material begins to deform plastically, this is a soft failure mode as is does not normally result in catastrophic failure or ultimate failure unless it accelerates buckling	Tensile yield, wrought iron and hangers susceptible to this

For the CSBT hangers, the following failure modes are potentially applicable: corrosion, fatigue, corrosion fatigue, fracture, impact, mechanical overload, yielding and wear.

Corrosion and wear are unlikely as failure modes in themselves because regular inspection monitors the section loss due to wear and corrosion. Protective paint systems, bushes, bearings and PTFE (polytetrafluoroethylene) washers between moving parts also reduce the chance of corrosion and/or wear resulting in failure. The impact of corrosion on other failure modes should be considered however, including fatigue (corrosion fatigue), yield (reducing the ductility of the material), mechanical overload (section loss) and fracture (creating fracture initiation locations). Test specimens with representative levels of corrosion should be included in any testing carried out.

Fatigue life should be investigated as it was the failure mechanism for LWN3 and is a concern if there is seizing of the hanger eyes.

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Mechanical overloading may occur if there is either not enough material to carry the load or if the loading is greater than what the material can sustain. Section loss will reduce the material available to carry load and unexpected loading or material properties being lower than expected may result in a load greater than what the structure can carry. Understanding the yield behaviour is also important when considering mechanical overload and it can be established by test while determining the ultimate tensile strength of the material (and ductility).

Impact is unlikely to be a failure mechanism for the hangers due to their position above the roadway. It would be difficult for a vehicle or other object to strike them hard and fast enough to cause immediate failure. Impact testing of the material can be carried out however to give an indication of the ductility and to determine the fracture energy.

The CSB hangers are under constant stress and so fracture is likely to be the ultimate failure mechanism. Impact testing will help to determine the fracture energy (and fracture toughness) of the material. Tensile and fatigue testing will help to determine whether fracture is typically ductile or brittle for the material.

6.2 Joint Failure Mechanisms

As shown in Figure 1, the hanger sub assembly is comprised of five main components (excluding pins and bolts). There are six main joints in the sub assembly. Table 11 gives an overview of the possible component and joint failure modes for the CSB hangers. Some of the failure modes are more likely than others and will depend on live loading, existing wear in the components, corrosion, material flaws etc.

Table 11: Component & Joint Failure Modes for CSB Hangers

Component	Joint	Connection	Failure Mode
Hanger straps	Hanger strap to chain link	Chain link pin	Ultimate strength failure of the lug due to tension across the net section (net section failure)
			Ultimate strength failure of the lug due to localised bearing failure
			Ultimate strength failure of the lug due to shear tear out
	Hanger strap to upper eye	Upper pin	Ultimate strength failure of the lug due to tension across the net section (net section failure)
			Ultimate strength failure of the lug due to localised bearing failure
			Ultimate strength failure of the lug due to shear tear out
			Shearing of the pin
			Bending of the pin
Upper eye	Upper eye to hanger strap	Upper pin	Ultimate strength failure of the lug due to tension across the net section (net section failure)
			Ultimate strength failure of the lug due to localised bearing failure
			Ultimate strength failure of the lug due to shear tear out
			Shearing of the pin
			Bending of the pin
	-	-	Tensile failure
			Fatigue
			Buckling
	Upper eye to bottle screw	Threaded bar in threaded recess	External thread stripping

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Table 11: Component & Joint Failure Modes for CSB Hangers Continued

Component	Joint	Connection	Failure Mode
Bottle screw	Bottle screw to upper eye	Threaded bar in threaded recess	Internal thread stripping
	-	-	Bursting
	Bottle screw to lower eye	Threaded bar in threaded recess	Internal thread stripping
Lower eye	Lower eye to bottle screw	Threaded bar in threaded recess	External thread stripping
	-	-	Tensile failure
			Fatigue
	Lower eye to clevis plate	Lower pin	Ultimate strength failure of the lug due to tension across the net section (net section failure)
			Ultimate strength failure of the lug due to localised bearing failure
			Ultimate strength failure of the lug due to shear tear out
			Shearing of the pin
			Bending of the pin
Clevis plates	Clevis plate to lower eye	Lower pin	Ultimate strength failure of the lug due to tension across the net section (net section failure)
			Ultimate strength failure of the lug due to localised bearing failure
			Ultimate strength failure of the lug due to shear tear out
			Shearing of the pin
			Bending of the pin
	-	-	Shear failure of clevis plates
	Clevis plate to longitudinal girder	8 clevis plate bolts	Tensile failure of bolts
			Shear failure of bolts
			Pull out / pull over of clevis plate
			Pull through of clevis plate

There are concerns over the hanger plates due to their partially obscured position within the chain links. This makes inspection more difficult so there is an increased risk of corrosion, wear or cracks going undetected. Also, as they attach through the main chain link pins, removal and replacement would be complicated and time consuming.

The connection of the hanger plates to the upper eyes is not thought to be high risk as these are inspected regularly and the hanger are removed periodically to allow inspection of the pin and lugs and to ensure articulation.

The upper eye sections of the shorter hangers are susceptible to fatigue failure if the hanger is constrained from articulating around the upper and/or lower eyes. This was how LWN3 failed, enabled by some material defects.

In the past there was also concern that bursting of the bottle screws was a likely failure mechanism. This is not well understood at present.

The lower eye section is probably unlikely to fail as this section is short (the bottle screw is close to the lower eye) and is the same for each hanger. The lower eye connection to the clevis plates is also considered to be lower risk (similarly for the upper eye to hanger plate connection) as this is inspected regularly and the hangers are removed periodically to allow inspection and ensure articulation.

Flint and Neill believe that the clevis plates are critical parts of the hanger assembly and that this is due to the orientation of the loading. It is thought that the tensile loading will tend to have a peeling or prising effect on the bolts through to the longitudinal girder.

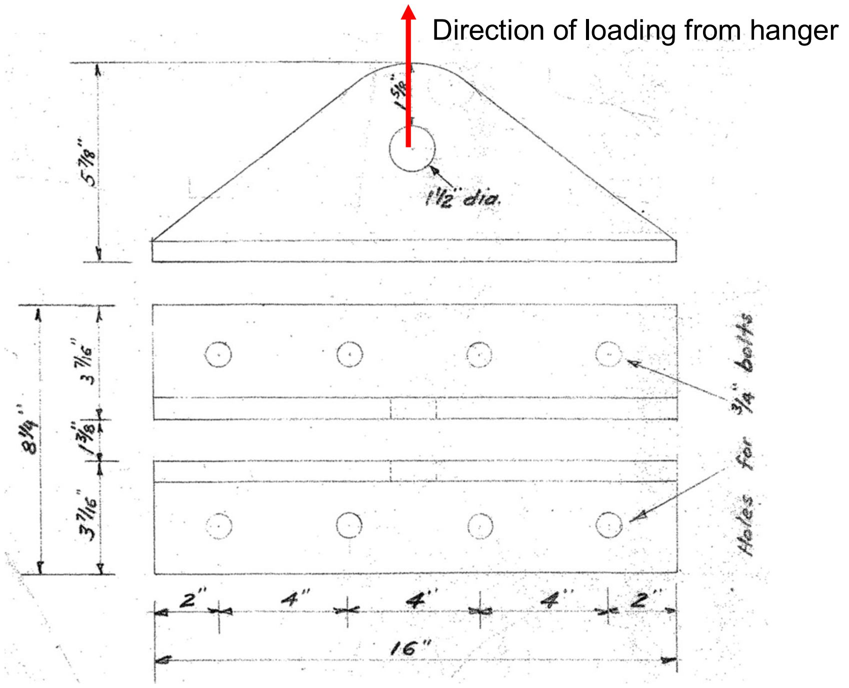

Figure 4: Clevis Plates

All of the middle third (shortest hangers) have been inspected completely for cracks or indications in the material that could lead to fatigue failure. The most likely locations for these cracks in the longer hangers have also been inspected i.e. the top and bottom of these hangers.

Static loading is relatively straightforward to apply to the structure and is taken as stated in section 3.2 to be the combination of dead load, two 2.5 ton axles and the maximum pedestrian loading possible per cross girder with no distribution. When applied to the structure and taking the material yield strength as 220MPa, the hangers are more than capable of carrying the load. Dynamic loading in different directions is more difficult to analyse. Fatigue loading and residual fatigue life is more complicated to understand. The cyclical loading applied to the structure would need to be measured to determine what level of loading actually contributes to reducing the fatigue life and what the resulting stresses and strains are in the structure. Under normal operating conditions, if the hangers are free to articulate and there are no material defects, it is believed that there should be no fatigue failure. However, this statement needs to be validated or supported with evidence.

6.3 Assembly Failure Mechanisms

In the overall assembly there may be factors that combine and interact to cause failure. Possible failure mechanisms of the entire assembly will depend on a combination of material performance, joint interactions and also how the overall sub assembly works.

Once there is a better understanding of the material properties, the likely material failure mechanisms and joint failure modes, the assembly as a whole should be reviewed.

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Measurements of the actual stresses in the structure together with a review of the load cases and constraints will help with understanding the behaviour of the assembly.

It is important at this stage to review all of the possibilities, even if there is a (perceived) low probability. There may be failure modes that we are not aware of or have not considered. Testing should provide evidence for or against a possible proposition. Care should be taken not to assume a failure mode and look for evidence to support that theory as alternative risks may be inadvertently missed.

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7.0 NDT Techniques

As previously stated, NDT techniques (magnetic particle inspection, ultrasonic and visual) have been used on the bridge and on the hangers in particular. Depending on the predicted failure modes and indications, different techniques may be appropriate for in situ inspection. Additionally, for the test material available, it may be useful to use different methods in the laboratory or to test the capability of alternative techniques in a controlled environment. Table 12 gives an overview of the main NDT methods and comments on the suitability of the method for the CSB hangers.

Table 12: NDT Techniques & Suitability for CSB Hangers

Technique	Capability	Advantages	Disadvantages	Suitability for CSB Hangers
Ultrasonic (UT)	Can detect cracks, damage, corrosion, dis-bond and material thickness in metallics and composites as these affect how the ultrasonic pulse travels through and reflects within the specimen. Amplitude of return signal gives information about the size of relfector and time taken gives information about the distance.	High sensitivity	Requires a skillful inspector for interpretation	Yes, has been used in-situ on chain links
		High penetration without losing sensitivity	Not good in high attenuation material	Detect cracks and indications of cracks
		Portable	Single layer inspection only	Calibration required due to heterogeneous nature of wrought iron
			Notch has to be normal to probe for detection	Requires skilled inspector
Magnetic Particle Inspection (MPI)	Defects are detected as they disrupt a magnetic field created (which will always flow north to south) in the material. The disruption causes magnetic flux out of the component which attracts magnetic powder which makes the defect visible.	Do not need to remove paint (as long as electrical conduct can be made)	Can create arcing	Yes, has been used on hangers
		Sensitive to steel parts	Odd shaped parts are difficult for complete coverage	Detect cracks and indications of cracks
		Possible to carry out the process in-situ with portable permanent magnets or electromagnets	Difficult to know how the field will flow through the part so it is possible to miss an area	Requires removal of paint
			Difficult to know how much current to use	
			Only for ferromagnetic materials	
Eddy Current (ET)	An alternating current passed through a coil which is passed over the specimen will generate eddy currents in the specimen. These eddy currents will be affected by cracks, flaws and inclusions in the specimen. However, there are lots of variables in the process.	Portable system	Many variables in process	Could potentially be used on hangers (wrought iron)
		Immediate response	Low sensitivity if flaw is deep in material	Best for surface defects, cracks etc
		High sensitivity	Only for conductive materials	
		No direct contact with component surface is required		
		Can be used on complex geometry		

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Table 12: NDT Techniques & Suitability for CSB Hangers Continued

Technique	Capability	Advantages	Disadvantages	Suitability for CSB Hangers
Radiography (RT)	Can detect defects, cracks, internal corrosion and inclusions in material as these will alter the amount of radiation passing through and creating the image on a film.	Produces overall image of the component	Issues of working with and storing radioactive sources	Would require removal of component and transportation to test facility
		Good penetration power, can penetrate through thick material	Low sensitivity, lower than MPI, ET, UT, FPI	Would not require paint removal however
			Requires familiarity with structure being inspected	Has been used to inspect LWN3
			Expensive set-up costs	Will identify weld defects and cracks
			Defect orientation sensitive	
Penetrant Inspection or Fluorescent Penetrant Inspection (FPI)	Can detect corrosion, cracks and scratches. Penetrant fills cracks by capilliary action, developer provides reverse capilliary action to draw penetrant back out & UVA lighting allows fluorescent penetrant in defects to be seen.	Simple, easy to understand	Creates pollution, penetrant rinsed off with water into drainage & needs to be treated	Will only identify surface defects
		Direct image	Time consuming for single items	Will require removal of surface paint
		Not sensitive to direction	Can cause skin irritation	May require removal of components for inspection
		Good for large areas of inspection	Only works for surface defects	
		Low cost	Not suitable for porous material	
Acoustic Emission (AE)	Pulses of elastic strain energy are are released when a solid is subjected to stress that results in deformation. This energy is released as sound. AE equipment can detect this and process to determine the location and type of deformation.	Can cover large areas	Not all discontinuities emit detectable AE	Would only give information on growing discontinuities
		Provides information about growing discontinuities	It will depend on how loads are applied to the structure	More novel technique
		Can locate the discontinuities	Noise, geometry or absorption can obscure the signal	Would require calibration in-situ
		Can be used in inaccessible areas	Cannot be used to determine size of discontinuity	
		Can be used in-situ	No standard method of data interpretation	
		Can be used to give continuous real time data		
Visual Inspection Techniques	Can detect surface defects or corrosion by eye or with small hand lens providing between x2 and x4 magnification. This is the primary method of inspection for the CSB.	In situ method	Only detect surface defects	Currently primary method of inspection
		Simple, easy to understand	Slow for large areas	Can be done in-situ by eye or low magnification
		Direct image	Need checks/controls to ensure areas are not missed	For better magnification component will need to be removed
		Low cost		Can detect surface cracks, indications, corrosion and loss of section

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Visual inspection techniques will be suitable for detecting surface defects however for sub surface cracks or indications in the hangers, methods such as MPI, radiography and ultrasonic inspection are appropriate. Radiography will also be able to evaluate the quality of the welds. Radiography and ultrasonic testing do not require removal of the paint which is time consuming and may require additional health and safety measures depending on the type of paint. Penetrant inspection is a straightforward method for identifying surface defects that may otherwise be too small to be observed with the naked eye. Eddy current is also useful for detecting surface defects on complex geometries and is a portable process. However, there are a lot of variables in the process and can be difficult to achieve high sensitivity if the flaw is deep in the material. Acoustic emission is a less well established process and is appropriate for monitoring the growth of discontinuities. This may require extensive calibration to factor out the process noise and would need characterisation of the acoustic signatures associated with crack growth. It may however, be useful to be implemented during the tensile or fatigue testing process.

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