Exploring the Value of Infrastructure Systems and its Impacts on Decision-Making for Sustainability

by

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Abstract

Infrastructure choices and decisions widely employ the language of value, whether to articulate what is worthwhile or to debate which principles or approaches are most appropriate to specific contexts. Infrastructure value delivery is consequential given the critical nature of these systems: they enable the mobility of people and goods and provide access to essential services such as drinking water and electricity. In this sense, infrastructure systems are the most valuable technological systems in modern society. As the world strives to achieve long-term sustainability goals, incorporating sustainability values into infrastructure decision-making becomes increasingly important.

However, published conversations on value have often lacked convergence due to inconsistencies in what is meant by value and how it is measured and implemented. This dissertation bridges several gaps in the literature of value and sustainability assessment for infrastructure systems through three main research avenues: (i) providing a conceptual framework for value in *academic literature*; (ii) exploring how value is integrated in long-term *computational modelling* and multi-criteria decision-making through an example of water distribution networks; and (iii) exploring the value challenges, opportunities, and perspectives embedded in current *urban infrastructure policy*, namely, Circular Economy strategies for large cities.

Chapter 2 reviews how the concept of value has been used to position different sustainability dimensions of infrastructure. This chapter discusses how value concepts interact in the context of infrastructure, and outlines avenues for its improved assessment. Chapter 3 implements these ideas in a modelling context by developing a dynamic computational model to evaluate the performance of long-term pipe maintenance strategies in Water Distribution Networks that allows for an improved assessment of multidimensional value while discussing the implications of diverse stakeholder perspectives. Chapter 4 discusses the value implications of urban infrastructure policy, exploring the applicability of Circular Economy (CE) policy to the management and assessment of infrastructure systems and analyzing current CE policies in six large cities from the perspective of value preservation and enhancement. Finally, Chapter 5 draws conclusions of this dissertation, summarises the key research contributions and suggests pathways for future research.

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Chapter 1
Introduction

1.1 Problem Statement

The critical question that motivated this dissertation relates to decision-making for large infrastructure systems: *what is the value of large infrastructure projects and systems? how is this value measured?* Naturally, there is no unique answer to these questions; infrastructure systems provide access to basic services, they are vital to most socio-economic activities, and shape the (built) environment of communities around the world. Infrastructure benefits and impacts are measured through many quantitative and qualitative metrics (e.g., profit to operators, amount of people served, quality of life indices, etc.), and the same infrastructure is experienced differently by different stakeholders.

However, part of the challenge in answering this question concretely is not only the broad scope, but also that the conversations regarding value in the context of infrastructure systems are often divergent. Planners, practitioners, and academics use the term under different meanings, assumptions, measures, and implications. For instance, in traditional project planning, the value of infrastructure products is thought of from an economic standpoint, usually being limited to the direct operation and profit of the system. Meanwhile, policymakers refer to value as the delivery of broader positive outcomes, measuring how these contribute to societal goals. Others may refer to different value systems to express the different priorities in their relation to the features of the built environment. Ultimately, the notion of value reflects important expectations and objectives for all stakeholders affected by infrastructure systems.

Thus, bringing together different discourses of value and integrating them into design and operation practices is critical to provide infrastructure that is inclusive of different stakeholder expectations and needs, and is equipped to tackle the complex challenges facing the infrastructure sector. Some key challenges for infrastructure include the management of aging assets, the adaptation of systems to the escalating effects of climate change, and the development of infrastructure that is aligned with short- and long-term sustainability objectives. Further, it is important to study the delivery of value in the specific context of infrastructure systems, given that existing efforts to conceptualise and assess value are not focused on the unique challenges and features of these systems, such as their long lives, fuzzy impact boundaries, interdependencies, and complexity.

This thesis investigates the meaning, assessment, and implementation of *value* for large horizontal infrastructure, with a particular focus on tackling sustainability issues. It provides insight on the implications of using different notions of value in design- and operation-related decisions for large infrastructure networks, ranging from the conceptualisation of value to its modelling methodologies and infrastructure policy applications.

1.2 Background and Motivation

Civil infrastructure—distributed horizontal systems such as road networks, as well as power supply, water supply, and sewerage networks—are the foundation of essential socio-economic activities such as the transportation of people and goods, the provision of drinking water and management of wastewater and stormwater, and the generation and distribution of energy. These systems have crucial short- and long-term impacts on their surrounding environments, resulting from design, construction, and operational decisions. Horizontal infrastructure systems play a defining role in the quality of life of most individuals and communities (Kasraian et al., 2016; Rezvani et al., 2015). Additionally, infrastructure systems both operate and evolve in a highly uncertain and dynamic environment and thus need to adapt to changing contexts including climate change, technological change, rapid urban expansion, and population growth (Gillespie-Marthaler et al., 2019; Sánchez-Silva, 2018).

However, infrastructure systems lack a consistent and general framework of value, crucial when tackling complex socio-ecological challenges such as incorporating sustainability into the built environment (Rawluk et al., 2019). This gap has limited interdisciplinary efforts for improvement in infrastructure at every stage, where different understandings of ‘value’ obstructs the alignment of expectations, objectives, and needs across users, governments, developers, and operators (Fischhoff, 1991). For instance, methodologies used for infrastructure products that refer to value (e.g., value for money, value engineering) have a strong monetary focus, which contrasts the multidimensional, goal-oriented understanding of value present in sustainability frameworks such as the Triple Bottom Line (TBL) or existing collective objectives for sustainability such as the Sustainable Development Goals (SDGs) (Elkington, 1999; United Nations, 2015). In addition to lacking a well-defined concept of value, many applications in the field still lack mathematical decision-making models that integrate value (beyond the monetary) while also being responsive to the particular features of large infrastructure systems. Some of these features include long lives that often exceed their initial planning horizon, deep uncertainty, and strong interdependencies (Groves et al., 2019; Rinaldi et al., 2001; Saxe and MacAskill, 2021).

Engineering decision-making very often relies on quantitative measures of value that express direct preference, particularly through money or utility. However, there are several drawbacks with these approaches, particularly in the context of infrastructure and sustainability. Firstly, in sustainability-related fields, the exclusive focus of planners on monetary value has led to criticism of the Triple Bottom Line as a sustainability framework, as it has been used widely as a way to introduce the ‘sustainability’ discourse into financial assessments rather than to perform multi-dimensional analyses of the ways in which infrastructure and businesses create or destroy value (Elkington, 2018). Further, the assumptions behind monetary valuations often make comparisons across projects challenging, which limits the understanding of their interactions and aggregate consequences (Atkins et al., 2017). The use of monetary (and more generally, instrumental) values also adds the implication of substitutability or fungibility in different sources of value which may not be replaceable or that add value in non-interchangeable ways (Chan et al., 2012; Fischhoff and Furby, 1988). This can lead to planning that omits important goals; for instance, previous studies have revealed that even when infrastructure development has been tied to economic growth or indicated to deliver value by monetary measures, this is not necessarily followed by improvements in economic prosperity as measured by alternative indicators such as unemployment levels or distribution of wealth (Bivens, 2014; Samli, 2011). Lastly, cost-benefit analyses used to measure the delivery of value in most infrastructure projects often happen in a context where there are incentives to go forward with the implementation of projects, further distorting the value of infrastructure projects for stakeholders (Atkins et al., 2017; Flyvbjerg, 2014). This is exacerbated by the limited and regulatory scope of the assessment of other impacts (e.g., social, environmental), which is often perceived as a hurdle by project developers instead of an opportunity to create value (Ward and Skayannis, 2019). Thus, providing a conceptual and quantitative framework that facilitates a more holistic assessment of value in infrastructure systems is essential to incentivise more integral and sustainable practices.

Monetary valuation is often predictive and made at the outset of projects, overlooking the dynamic nature of impacts and the relational nature of some of the potential benefits of infrastructure systems. In other words, the design of infrastructure systems often presupposes certain environmental and external conditions that often change in unforeseen ways once the project has been developed affecting the successful delivery of value; this may come in the form of radical changes in demand, environmental or business conditions, or technological advancement (Gilrein et al., 2019; Markolf et al., 2018; Saleh et al., 2009; Vickerman, 2007). While the best approach to manage this uncertainty in infrastructure systems is still debated among infrastructure experts and academics, the field generally calls for the inclusion of improved probabilistic analyses for the life cycle analysis and decision-making related to infrastructure products (Chester and Allenby, 2019; Sánchez-Silva, 2018; Saxe and MacAskill, 2021). Ultimately, these tools allow for a more integrated approach to infrastructure planning that recognises the system-of-systems nature of infrastructure and that better captures critical feedback mechanisms that may undermine the assumptions and modelling choices made during planning and design stages.

Another important aspect of valuation is the dynamic nature of value and performance delivery. Infrastructure systems are long-lasting endeavours, and thus the priorities that drive performance goals and the goals themselves will likely evolve throughout its life cycle. However, infrastructure is many times designed and analyzed from a static, deterministic framework of objectives and standards (Ward and Skayannis, 2019). This contributes to the obsolescence and underwhelming performance of projects in the long term. Infrastructure projects that do not include provisions for changes in technology, demand, environmental conditions, or regulatory environments can become obsolete and result in lock-in scenarios with sub-optimal performance (Lemer, 1996). While this is a challenge that infrastructure planners cannot overcome completely and design practices must make assumptions, traditional monetary analysis based on discounting can distort the magnitude and consequences of obsolescence, undermining the importance of future scenarios and end-of-life considerations (Lemer, 1996). On the other hand, it may also lead to an undervaluation of the future benefits and opportunities provided by these systems, which are particularly relevant for achieving long-term objectives such as decarbonisation or significant renovations in infrastructure stock (Webb, 2013). Longer time horizons also have significant impacts on operation efforts, due to the increased use of the infrastructure under increasing deterioration, which hinders the performance of the system and may lead to scenarios of large failures with major consequences.

Ultimately, existing approaches for value conceptualisation and assessment have not been conducive to a successful integration of sustainability considerations in infrastructure research and practice and are ill-suited to many key characteristics of large infrastructure systems. In turn, these limitations hinder our ability to better design, construct, and operate infrastructure that aligns with the wide range of needs and objectives of the many stakeholders involved, and to meet the sustainability demands of our time.

1.3 Research Objectives

The main objective of this dissertation is to explore how different approaches and framings for the *value* provided by infrastructure can change choices about what is built, when it is built, and how it is constructed, with a particular focus on sustainability assessment. Towards this main objective, the following sub-objectives and associated research questions were developed:

1. Investigate how the concept of 'value' has been used to study different sustainability dimensions of large infrastructure systems in the academic literature.
    a. What are the different ways in which the value delivered by infrastructure systems is understood in existing academic literature?
    b. How do published notions of value translate to evaluation and assessment practices?
2. Explore how different notions of value integrate into decision-making models for long-term operation of infrastructure systems, using water distribution networks (WDN) and its field-specific modelling practices as an example.
    a. How do pipe repair and replacement strategies affect long-term outcomes across multiple performance dimensions: logistic, service quality and reliability, monetary, and environmental?

   b. How does value alter the assessment of different maintenance strategies for different stakeholders (e.g., network operators, users, regulators) affected by WDN operations?

   c. What are the implications of common WDN assumptions and modelling choices on the representation of value in maintenance decisions?

3. Explore the integration of value in urban infrastructure policy, namely, Circular Economy (CE) strategies for infrastructure products at the city level, focusing on long-term value preservation and value maximisation as key objectives.

   a. How do some of the key characteristics of infrastructure value delivery and maintenance align with CE principles and strategies?

   b. How are current urban CE policies aligned with value preservation and enhancement in infrastructure?

1.4 Outline of Dissertation Chapters

This dissertation consists of 5 chapters. Chapter 1 is the current chapter, which delineates the motivations, objectives, and scope of this research. Chapters 2 to 4 were written as individual papers, presenting novel insights on value assessment for infrastructure through different lenses, as summarised below. Finally, Chapter 5 summarises the contributions and conclusions of this dissertation and reflects on its limitations and avenues for future work.

Chapter 2 studies value through the lens of existing academic literature by reviewing how the concept of value has been used in published studies to position different sustainability dimensions of large infrastructure systems. Specifically, a conceptual framework of value is used to highlight different notions of infrastructure value under four general headings: value as a magnitude of preference, as a contribution to specified goals, as a means of communicating key priorities, and as a representation of historical relations. This chapter has been published in the peer-reviewed journal *Environmental Research: Infrastructure and Sustainability* with the following citation:

- Zuluaga, S., Karney, B. W., & Saxe, S. (2021). The concept of value in sustainable infrastructure systems: a literature review. *Environmental Research: Infrastructure and Sustainability* 1(2): 022001. DOI: 10.1088/2634-4505/ac0f32

Chapter 3 studies value integration into decision-making modelling, exploring maintenance decisions for WDN as an example. This chapter proposes a computational model to evaluate the performance of long-term pipe maintenance strategies through Monte Carlo simulations of sequential pipe maintenance activities, capturing the probabilistic nature of pipe failure and its impacts across multidimensional performance metrics. Additionally, the proposed model is used to explore how operator priorities affect the choice of different repair and replacement strategies, and the effects of these value profiles across multiple dimensions including both system-level performance and the perception of different stakeholders such as users and service regulators. This chapter has been published in the peer-reviewed *Journal of Water Resources Planning and Management* from the American Society of Civil Engineers (ASCE) with the following citation:

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Chapter 4 studies value from a policy perspective, discussing the relations between Circular Economy (CE) strategies and the management and assessment of infrastructure systems, focusing on the potential of CE to enhance the value of infrastructure systems while reducing their environmental footprint. This chapter examines current CE policies for the management of infrastructure in six large cities in the Americas and Europe, studying if—and how—these cities plan to employ circularity strategies to enhance the value provided by their infrastructure systems. This chapter is currently being prepared for submission in the peer-reviewed journal *Sustainable Cities and Society*.

For Chapters 2 to 4, whether already published or being prepared for publication, I conceptualised all research questions and objectives, designed and implemented the methods, and wrote all initial and subsequent drafts. These publications were co-authored by my supervisors, Professor Shoshanna Saxe and Professor Bryan W. Karney. Professors Saxe and Karney contributed by questioning, discussing, and assisting my research objectives, methods, and approaches, as well as providing overall guidance on the scope and conclusions of my work. They also edited and commented iteratively on the drafts of each paper.

Chapter 2

The concept of value in sustainable infrastructure systems: a literature review

This chapter is based on a published paper with the following citation:

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2.1. Chapter Overview

Infrastructure choices and decisions widely employ the language of value, whether to articulate what is worthwhile or to debate which principles or approaches are most appropriate to specific contexts. As the world strives to achieve long-term sustainability goals, incorporating sustainability values into infrastructure decision-making becomes progressively more important. Yet, the term 'value' has been used under different meanings and implications throughout the infrastructure sustainability literature, obstructing the debate on which values are important and what is valuable to infrastructure decision-making processes. This chapter reviews how the concept of value has been used to position different sustainability dimensions of large infrastructure systems. Specifically, a conceptual framework proposed by Tadaki et al is used to highlight different notions of infrastructure value under four general headings: value as a magnitude of preference, as a contribution to specified goals, as a means of communicating key priorities, and as a representation of historical relations. This review shows that the discussion of infrastructure value has often focused on monetary measures to the exclusion of other relevant measures of value. However, if long-term sustainability goals are to be met, a transformation of the ways that value is understood and measured in the context of infrastructure systems is required. This review discusses key similarities, interdependencies, and disparities between published notions of infrastructure value in order to provide a conceptual reference guide that highlights the variety of perspectives that are both implicit and explicit among practitioners and academics.

2.2. Introduction

Infrastructure systems play crucial roles in the functioning of urban areas, are extensive in spatial scope, have immense financial costs as well as human implications, and are controversial in both form and function. How these systems are defined, used, and evaluated is thus crucial, and often contested within industrial societies. What is built—and how it is built—is a clear indication of the priorities and values of a society and will be critical in determining the extent to which global societies live up to local and international sustainability needs and commitments. Infrastructure commissioning and decision-making widely uses the language of value: both to explore what is valuable (i.e., worthwhile), and to debate which values (i.e., principles) are most relevant in specific contexts. As the relationship between sustainability and infrastructure has received increasing attention in the public discourse and academic literature, a growing body of work has been written on the value of infrastructure in sustainability. Throughout this literature, the term 'value' has been used in different ways to express different things. This review chapter explores how the concept of 'value' has been used to study different sustainability dimensions of large infrastructure systems in the academic literature. Using a conceptual framing value developed by Tadaki et al (2017) in the context of ecosystem services, I classify the reviewed literature under four separate concepts of value.

The term 'infrastructure' herein refers primarily to distributed horizontal systems such as roads, bridges, and both water supply and sewerage networks. Further, this chapter focuses on large-scale systems, which are usually identified by their significant capital costs and their impact on large populations (Sheng, 2018). Projects of this scale have long planning horizons, several layers of physical and institutional complexity, and are often owned or commissioned by public authorities (Chester et al., 2019). Although the focus is thus primarily on civil infrastructure (e.g., transport, water), the discussion is generally applicable to several other infrastructure systems such as energy or telecommunication systems. Moreover, the chapter also accesses in passing green (natural) infrastructure and ecosystem services.

While the notion of the value these infrastructure systems provide is often explicitly and implicitly discussed in the context of public infrastructure decision-making and academic research, the published conversations have often diverged due to inconsistencies in both meaning and implication of 'value' and 'values'. This divergence has sometimes interfered with interdisciplinary conversations, the very conversations that are so vital if complex socio-ecological challenges are to be tackled (UN Habitat, 2020). As one example, consider the ongoing discussion of how the concept of 'sustainability' should be included in infrastructure decision-making, where different levels of abstraction, context dependence, and valuation methods have led to diverging understandings of what is valuable across social, environmental, and economic dimensions (Rawluk et al., 2019). This chapter seeks to gather diverse conversations together to provide a discussion with the goal of clarifying the multidimensional, dynamic, and interdependent nature of 'value' in infrastructure. A conceptual framework proposed by Tadaki et al. (2017) is used to frame different notions of infrastructure value under four general headings: value as a magnitude of preference, as a contribution to specified goals, to communicate key priorities, and as a representation of historical relations. This framework provides a holistic and complementary view of preference and value that facilitates exploration of complex notions such as sustainability and focuses on the particularities of decision-making and the valuation related to natural (and built) environments. Although the focus of this discussion are different concepts of value and their implication, this chapter also explores the methodologies used to measure or describe these values. The methods through which value is operationalised provide critical insights into the assumptions and implications behind different concepts of value.

Large infrastructure systems provide the foundation for most activities in modern societies and strongly influence their surrounding environment, both in the short- and long-term. As such, infrastructure plays a defining role in the quality of life and environmental sustainability of most individuals and communities (Kasraian et al., 2016; Rezvani et al., 2015). Further, these systems both operate and evolve in a highly uncertain and dynamic environment. Infrastructure needs to adapt to changing pressures including climate change, technological change, rapid urban expansion, and population growth (Gillespie-Marthaler et al., 2019; Sánchez-Silva, 2018). The development and operation of infrastructure systems thus inevitably involve a wide range of stakeholders (owners, community members, engineers) who often have conflicting interests (Vuorinen and Martinsuo, 2019). Consequently, infrastructure development and implementation are frequently controversial, competing over priority, resources, mechanism, and participation (Barclay and Klotz, 2019; Pekkanen and Pearson, 2018; Thomas Ng et al., 2012). Conflicting interests arising from fragmented responsibilities across parties can also hinder systemic management and innovation of infrastructure systems.

The development of infrastructure is closely related to the collective objectives of societies (Alford and O'Flynn, 2009; Mu et al., 2015). Yet, converging on these objectives is often challenging due to lack of agreement between stakeholders, and the mechanisms used to aggregate their preferences (O'Flynn, 2007). Being the physical representation of collective objectives, infrastructure plays a central role in the way priorities materialise in the built environment. For instance, the choice of the scale of a system is usually motivated by a balance of priorities including ownership structure, reliability, and impacts on sustainability (Alanne and Saari, 2006). An example of collective objectives that reflect public values are the sustainable development goals (SDGs) adopted by the United Nations (United Nations, 2015), which provide a comprehensive framework for sustainable development. The SDGs explicitly highlight the importance of infrastructure in achieving significant progress towards social, environmental, and economic objectives (Thacker et al., 2019). Some of these goals require significant infrastructure investment, such as the provision of universal access to drinking water, sanitation, and electricity by 2030 (Oxford Economics, 2017). Infrastructure systems are expected to deliver adequate, reliable services (e.g., access to drinking water, safe modes of travel) while promoting other socio-economic objectives such as equity and accessibility (Koppenjan et al., 2008).

Most often the value or preference towards infrastructure projects is assessed in monetary terms. Further, infrastructure development has often been driven by subjective motivations such as biases towards technological innovation or the search for increased political visibility (Flyvbjerg, 2014; Frick, 2008; Pearce, 1983). More recently, methodologies such as life cycle assessment (LCA) and multi-criteria methods (MCM) have been used to account for other aspects relevant to overall preference, such as social and environmental performance. However, decision makers often disagree on the evaluation of social and environmental dimensions, and their role in overall preference (Mouter et al., 2013). Moreover, these dimensions often have largely different scopes, limitations, levels of detail, and assessment methodologies. For instance, it is common for infrastructure projects to give priority to cost-benefit analyses that focus on benefits and cost that can be readily monetised (e.g., travel time savings in road projects); in contrast, environmental and social impact assessments usually receive less or delayed attention, perhaps only considered after the design is essentially completed (Ward and Skayannis, 2019). Further, the results of environmental and social impact assessments are often limited due to high levels of uncertainty (Saxe et al., 2020; Ward and Skayannis, 2019). Monetary assessments of large projects have also consistently led to faulty estimations of risk and poor economic performance (Flyvbjerg, 2014). This imbalance in the evaluation of infrastructure projects may lead to inaccuracies in the evaluation of their consequences for the public and the environment, hindering the development of infrastructure that manages to integrate the multiple facets of sustainable development.

This chapter is structured as follows: the next section provides a conceptual framework for the chapter by examining the concept of value and drawing a connection between value and sustainability. This is followed by a review of how value is represented in existing studies related to infrastructure systems. Section 3.5 uses this framework to discuss alignments, disparities, and interdependencies leading to an articulation of a more complete understanding of value for infrastructure. Finally, conclusions are drawn along with suggested pathways for future research.

2.3. Examining the Concept of Value

Value is a term widely used across disciplines under several interpretations. In the fields of philosophy, sociology, and psychology, it is used to describe the set of end-states or qualities that an individual or group could consider desirable (e.g., happiness, justice) (Brown, 1984; Ives and Kendal, 2014). Other fields such as economics or engineering refer to 'value' in quantitative decision-making applications built on measurable notions: thus, value becomes the estimated worth of an object or place for an agent, or the means of estimating this worth (Brown, 1984; Rawluk et al., 2019). While this perspective has been useful in traditional monetary decision-making, it obscures the study of more abstract goals such as sustainability, which incorporate non-material values. This clear limitation puts existing value engineering methods into question when designing decision-making processes for complex systems such as large infrastructure.

There are several published 'value' typologies that propose conceptual distinctions for the term. Some examples include the separation between 'held' and 'assigned' values (Brown, 1984), or a social-value focused typology of 'instrumental' and 'deliberative' values (Raymond et al., 2014). Different typologies highlight specific mechanisms of evaluation, i.e., the mechanism of measurement and participation through which value is assessed. These typologies also shed light on the assumptions, intended applications, and limitations of different methodologies used for evaluation (Daily et al., 2000; Rawluk et al., 2019; Tadaki et al., 2017).

Brown (1984) and Tadaki et al. (2017) have conceptualised values and preference over specific aspects of the environment and shared goods. In particular, the latter identifies four distinct concepts of value that are commonly present in the academic literature and applications from the context of environmental management: value as a magnitude of preference, value as contribution to a goal, value as a set of priorities, and value as historical relations (Tadaki et al., 2017). While the authors emphasise the natural environment and ecosystem services, their concepts can be extended to the built environment and to infrastructure systems broadly. Further, this framework provides a holistic, comprehensive, and complementary view of preference and value useful to articulate complex notions such as the one of sustainability in infrastructure systems. Thus, this chapter will focus on this framework and use it to explore existing discussions of value in the context of infrastructure systems. Summarised in Table 2.1, this section explores Tadaki et al.'s conceptualisation, its broad relevance to infrastructure, and draws a conceptual connection to the concept of sustainability.

Table 2.1. Summary of the four concepts of value discussed in this chapter; adapted from (Tadaki et al., 2017) with infrastructure examples.

Type of value	Brief definition	Example	References
Magnitude of preference	A quantitative measure of preference that an individual/group expresses for a particular object/alternative relative to others.	Person A would be willing to pay $10 to be allowed to use a faster road, and $5 to be able to use a dedicated bike lane instead.	(Farber et al., 2002; Tadaki et al., 2017)
Contribution to Goals	The contribution of an action or object to user-specified goals, objectives, or conditions.	Expert B determines that highway X has lower safety value than subway line Y.	(Huizar et al., 2018; Tadaki et al., 2017)

Type of value	Brief definition	Example	References
Priorities	The structure/hierarchy of priorities within individuals/groups that guides their decisions.	Residents of City X prioritise the aesthetics of their built environment, followed by its safety.	(Brown, 1984; Tadaki et al., 2017; Wolters et al., 2020)
Relations	An emergent property from the historical relationships between people and their local environment.	Residents of City X value street Y because it has been part of the city for centuries.	(Grubert, 2018; Rawluk et al., 2019; Tadaki et al., 2017)

2.3.1. Value as a Magnitude of Preference

The first concept of value presented by Tadaki et al., (2017) is value as a magnitude of preference, which refers to a quantitative measure of the preference that an individual or a group has for an alternative or attribute relative to others. Value as a magnitude of direct preference is not an attribute of a system or alternative, but rather a representation of a stakeholder's preference towards it. A well-known application is the idea of market valuation and willingness-to-pay, which has been widely used to measure the worth of a specific component of the (built) environment (Daily et al., 2000; Freeman et al., 2014). A typical infrastructure example is the calculation of the monetary value of providing additional water in a supply network based on water demand, supply and operating costs (Jenkins et al., 2004). Other approaches such as mapping of stated preferences and multicriteria analysis use generic utility metrics to appraise the relative preferences of stakeholders over a defined set of alternatives (Kabir et al., 2014). These analyses are used, for instance, to select a design alternative based on the mapping of experts' preferences using a multi-criteria approach that includes environmental, social, equity, and economic performance (Martin-Utrillas et al., 2015).

Assuming that the value of an alternative relative to others is quantitatively measurable implies commensurability (Tadaki et al., 2017), allowing for direct comparison and aggregation in collective contexts. For example, when quantifying the value of an infrastructure project for a group of people (e.g., users, owners, planners), one would add their individual measures of value for the project. Furthermore, commensurability also allows for value to be broken down and compared across components. For instance, monetary or utility value metrics might allow one to directly compare disparate environmental and social aspects of a proposal, even though they are different in nature. This further implies that the preference over different dimensions is fungible (i.e., interchangeable). For example, a reduction in stated preference due to poor social performance of a project could be offset by improvements in economic performance.

Recent discussions of 'value-as-magnitude' show that much of the literature on project management has used the term 'value management' to study cost reduction (Laursen and Svejvig, 2016). These studies often focus on shorter term investments that do not explicitly acknowledge a project's long-term and holistic nature. Others have discussed the differences between individual, organizational, and societal value from a monetary perspective (Lepak et al., 2007); or the importance of non-commercial values in project management, calling for a notion of preference that is broader than a purely monetary perspective (Martinsuo and Killen, 2014).

2.3.2. Value as Contribution to Goals

Value can also be understood as 'the contribution of an action or object to user-specified goals, objectives, or conditions' (Tadaki et al., 2017). This second aspect arises from the idea that the overall preference of a collective may differ from the aggregation of individual preferences (Farber et al., 2002). This notion of value captures the contribution of an object (e.g., an infrastructure product) to a set of goals or objectives (often defined by experts) measured through dedicated metrics. In contrast to value as magnitude of direct preference, this notion of value is not based in stakeholder preference but rather an attribute of a system in relation to specific goals. Collective objectives are often inadequately captured by individual utility measures such as willingness-to-pay. Further, individual evaluations may be difficult to compare and aggregate. An example of a collective goal that is inadequately captured by individual preferences is reducing greenhouse gas (GHG) emissions. This is known in economics as the 'tragedy of the commons', a market failure due to externalities where individual actors do not bear the collective cost of their actions (Fang, 2018). The notion of value as contribution to a goal recognises that shared goods such as infrastructure products are complex, which creates the need for an evaluation through attributes and goals separate from individual preference.

One of the main steps in measuring value as a contribution to a goal is the specification of appropriate metrics. However, the selection of these may be subject to disagreement and have implications to the outcomes of the assessment and the decisions they might lead to (Hubbard and Hubbard, 2019; Huizar et al., 2018; Tadaki et al., 2017). For instance, using only GHG emissions to measure the environmental impact of a new road may induce it to be built through a vulnerable ecosystem to reduce construction material use; in contrast, using a measure of ecological fragmentation might protect vulnerable areas but increase material consumption and emissions (Cornet et al., 2018). Moreover, expert-defined metrics may also embody the differing priorities between planners, operators, and users of infrastructure products (Chan et al., 2012 and Tadaki et al., 2017).

2.3.3. Value as Priorities

Value can also conceptualise individual priorities or held values (Brown, 1984; Dietz et al., 2005; Tadaki et al., 2017; Webb, 2013; Wolters et al., 2020). This notion refers to the structure of priorities within individuals, understood as the fundamental driver behind their actions and decisions. For example, some people make decisions trying to maximise their individual sense of freedom, while others might prioritise their sense of safety. This concept of value matches other relevant discussions in the public decision-making literature through the concept of 'public values', i.e., the collective aspirations that should guide public decisions and operations (Alford and O'Flynn, 2009; Mu et al., 2015; O'Flynn, 2007). Studies of the priority hierarchy for different individuals often seek to demonstrate the differences in the objectives of policy makers and users, highlighting the challenges of agreeing upon a set of societal objectives for policymaking (Wallis and Gregory, 2009).

In the context of infrastructure, the use of the concept of value-as-priorities has been used to assess the need for infrastructure development. For instance, some studies have explored the existing trade-offs between health impacts, service efficiency, and capital investment associated with infrastructure investment (Álvarez et al., 2007; Burchell et al., 2010). Further, infrastructure systems are expected to respond to public needs such as accessibility, reliability, and equity (Koppenjan et al., 2008). In practice, physical infrastructure represents a materialisation of the priorities used for its planning and design and has a long-lasting influence on the way societies develop (Bivens 2014; Eskerod and Ang, 2017; Kasraian et al., 2016).

2.3.4. Value as Relations

The final concept of value described by Tadaki et al. (2017) is the one of value as relations. This concept seeks to acknowledge the historical relationships between communities or individuals with their surrounding environment. As such, relational value is an emergent property from the unique relationships between people and their environment, instead of arising from the individual, community, or the environment itself (O'Neill, Holland, & Light, 2007). In other words, the way environments bring satisfaction or value to people or communities may challenge traditional economic or social measures, and even collective goals. For instance, fishing communities may find value in preserving this traditional activity, which may not necessarily align with economic or larger societal objectives. This concept has been used to explore the different ways in which people relate to the environment when looking for a satisfying life, emphasising that sometimes communities and individuals value their relationship to an environment beyond any social, economic, or intrinsic (e.g., value-as-magnitude and value-as-contribution) measures (Tadaki et al., 2017).

2.3.5. Value and Sustainability

While the Brundtland Report (World Commission on Environment and Development, 1987) is known for its intergenerational definition of sustainable development, it also called for the development of a broader, multidimensional notion of sustainability. Afterwards, the concept of the Triple Bottom Line (TBL) was developed to formally describe the multidimensional nature of sustainability (Elkington, 1999). The very interpretation of what sustainability means, and how it translates to physical systems such as infrastructure, is dependent on the values and background of the engineers and developers designing and operating a system (Carew and Mitchell, 2008).

The growing importance of sustainability and the prominent role of physical systems in achieving it has also led to expectations that infrastructure systems meet multidimensional performance thresholds (Ainger and Fenner, 2013). However, the extent to which this is achieved in practice remains limited, as existing infrastructure systems are often assessed through the lens of economic and monetary measures of performance, and often struggle to fully integrate or even acknowledge social and environmental goals (Atkins, Davies, and Bishop, 2017; Flyvbjerg, 2014; Glasson and Therivel, 2019; Hawkins and Jill, 2006; Purwohedi and Gurd, 2019). Therefore, it is relevant in this context to attempt to frame the concepts of value in the domain of infrastructure through an integral framework that includes broader social, environmental, and economic considerations (Glasson and Therivel, 2019; Marvin and Guy, 1997). This relevance has also been highlighted in a recent report by UN Habitat focusing on the value of sustainable urbanisation (UN Habitat, 2020). While this discussion is highly related to the one in this chapter, I provide a more specific outlook of value from the perspective of infrastructure systems.

Although this review discusses the environmental, social, and economic dimensions of value in infrastructure systems, this does not imply they are commensurable or that these dimensions should have equal importance. This ‘balance’ obscures the nested nature between these dimensions of sustainable development: “within the Earth’s single planet limit, the environment nurtures our human society, which has invented the economy, to serve its needs” (Ainger and Fenner, 2013). The discussion presented in the following sections seek to highlight the imbalances between different dimensions of sustainable development that are manifested through the different concepts of value.

2.4. Value and Sustainability in Infrastructure Systems

Google Scholar (Google, 2020), Scopus, and OneSearch (the University of Toronto’s reference search platform) were used to search for references that contained different combinations of relevant ‘value’ and ‘infrastructure’ keywords, as presented in Table 2.2. These queries resulted in an initial corpus of 853 publications. Then, I excluded duplicate references, publications that did not deal with large horizontal infrastructure such as vertical infrastructure (buildings) and ‘soft’ information infrastructure, and references that only referred to ‘value’ in the context of numerical amount or quantities. Additional references were included through cross-referencing, which allowed for the inclusion of relevant studies that refer to value implicitly and that may have been omitted otherwise. Some of the related keywords that were identified through the cross-referencing process and that were relevant to this review include ‘preference’, ‘worth’, ‘benefits’, and ‘impacts.’ After this initial review, the remaining 60 references were classified into the four concepts of value already highlighted. Note that when a study fell under several categories of value—which can happen given that the framework of Tadaki et al. is not mutually exclusive—the most prevalent concept of value in the study was reported. There are additional references cited throughout this review that complement the concepts and applications found in the existing literature.

Table 2.2. Query terms used during the literature review process.

Value-related terms	Infrastructure-related terms
Environmental value	Infrastructure
Social value	Infrastructure systems
Economic value	Large infrastructure
Value systems	
‘Value’ + ‘Priorities’	
‘Value’ + ‘Direct preference’	
‘Value’ + ‘Relations’	

Based on this selection process, the current section reviews the concept of value in the domain of infrastructure with an exploration of dimensions of sustainability. In particular, the environmental, social, and economic dimensions of sustainability are examined through Tadaki et al.’s framework of value described in Section 2.3. Emphasis is drawn on the key conceptualisations rather than attempting to be exhaustive regarding methods, metrics, or case studies. Figure 2.1 summarises the applied framework of infrastructure value and sustainability. There are clearly strong connections between these frameworks in the context of infrastructure: the 'value' of these systems drives its planning and operation, which in turn has a profound influence on the reality and evaluation of the dimensions of sustainability.

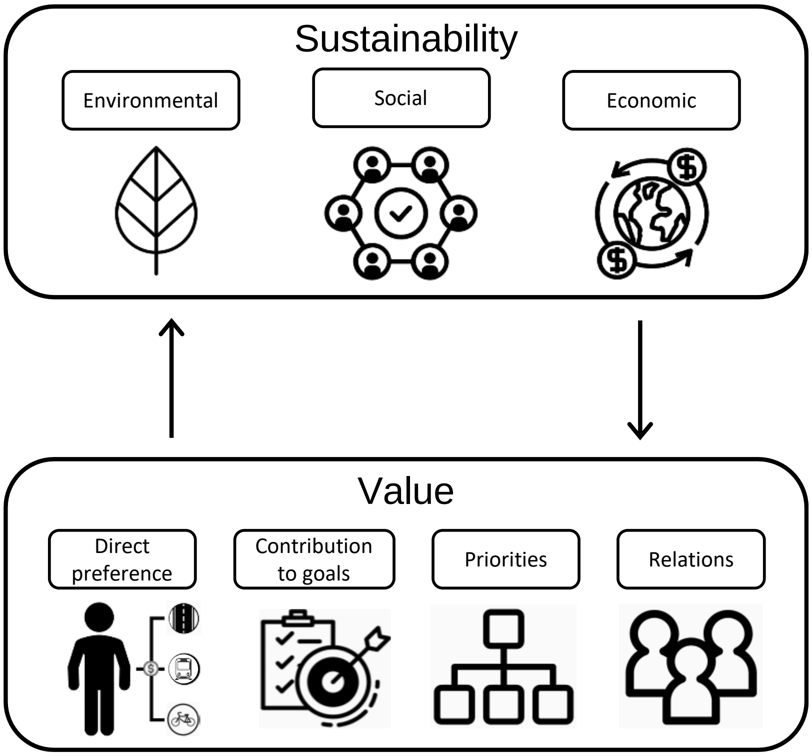

Figure 2.1. Conceptual frameworks of value and sustainability used in this review.

2.4.1. Environmental Dimension of Value

The environmental impacts of large infrastructure have long been recognised. The United States first required 'environmental considerations' in large-scale projects in 1969 through its National Environmental Policy Act (US Council on Environmental Quality, 1969); other countries such as Australia, France, and Hong Kong implemented similar policies in the following decade (Ward and Skayannis, 2019). Since, methodologies such as Environmental Impact Assessments (EIA) have emerged as tools to assess the environmental performance of infrastructure projects, with a focus on biophysical impacts such as air and soil quality, and the effects on local ecosystems (McCold, 2001). More recently, attention has been brought to the energy intensity and associated environmental consequences behind infrastructure development; in turn, methodologies such as LCA have gained importance (British Standards Institution, 2011; Infrastructure Canada, 2018; State of California, 2017; Toller, 2018). In general, these methodologies serve as supporting information for decisions related to infrastructure products, ranging from planning and design of new systems to retrofit and maintenance of existing ones. As such, they inform decision makers about key differences between alternatives in infrastructure decisions; they may also provide essential feedback and mitigation strategies in iterative design processes, although they are often part of linear assessment and development processes (Glasson and Therivel, 2019; and Vanclay et al., 2015).

There are several ways in which the environmental dimensions of infrastructure are assessed: integrating environmental impacts into monetary benefits/costs in cost-benefit analyses (CBA), measuring them through standardised metrics (e.g., CO_2eq for GHG emissions, PM levels for air quality), and performing qualitative assessments (e.g., cause-effect descriptions of impacts in biodiversity). Such methods refer to different notions of value; however, the differences in meaning and implication are rarely acknowledged. This section reviews the ways in which environmental value has been discussed in the context of infrastructure, laying out examples of the four concepts of value described in Section 2.3. Table 2.3 below provides a summary of the studies reviewed and their classification under different concepts of value and broad types of infrastructure (e.g., water, transportation, energy).

Table 2.3. Reviewed literature for the environmental dimension of infrastructure, classified by concept of value and application.

Reference	**Concept of value**				**Type of Infrastructure**		
	Value as a magnitude of preference	Value as contribution to a goal	Value as priorities	Value as relations	Water	Transportation	Energy
(Jenkins et al., 2004)	●				●		
(Melo et al., 2020)	●					●	
(Beare et al., 1998)	●				●		
(Foxon et al., 2002)	●				●		
(Foxon et al., 2015)	●						●
(Williams et al., 2017)	●				●	●	

Reference	**Concept of value**				**Type of Infrastructure**		
	Value as a magnitude of preference	Value as contribution to a goal	Value as priorities	Value as relations	Water	Transportation	Energy
(Funk et al., 2019)	●					●	
(Sahely et al., 2005)		●			●		
(Adshead et al., 2019)		●			●		●
(Arce and Gullón, 2000)		●				●	
(Balkema et al., 2001)		●			●		
(Monavari and Fard, 2011)		●				●	
(Onsarigo et al., 2014)		●			●		
(Neuman and Churchill, 2015)		●			●	●	
(Castor et al., 2020)		●					●
(Kørnøv et al., 2020)		●			●		●
(Mansell and Philbin, 2020)		●			●	●	●
(Geels, 2007)			●			●	
(Busscher et al., 2015)			●			●	
(Hamilton-Foster, 2014)			●				●

Reference	**Concept of value**				**Type of Infrastructure**		
	Value as a magnitude of preference	Value as contribution to a goal	Value as priorities	Value as relations	Water	Transportation	Energy
(Hienuki et al., 2019)			●		●	●	●
(Wolsink, 2010)			●		●		●
(Morison and Brown, 2011)			●		●		
(Foerster et al., 2015)			●		●	●	●
(McAndrews et al., 2018)			●			●	
(Zajchowski & Brownlee, 2018)			●			●	
(Wolters et al., 2020)			●				●
(Fearnside, 2002)				●	●		●
(Grubert, 2018)				●	●	●	●
(Kennedy Dalseg et al., 2018)				●		●	

Some authors focus on quantifying the monetary value of natural resources, in an effort to integrate environmental improvements, benefits, and impacts in cost-benefit analyses often used for environmental decision-making (Costanza et al., 1997; Daily et al., 2000; O'Neill et al., 2007). While these sources do not refer to infrastructure systems explicitly, they talk about the impact and the value of the built environment on the natural world and are a relevant example of how the environmental value has been assessed. In the context of infrastructure, there are numerous monetary measures. Some have studied how financial scenarios used for decision making are related to the environmental requirements for water infrastructure (Jenkins et al., 2004). More recently, studies have explored monetary evaluations in the context of green/sustainable infrastructure solutions, highlighting the uncertainty that results from high parameter sensitivity in the evaluation of environmental benefits (Melo et al., 2020), as well the irreducible nature of many uncertainties in the infrastructure provisioning process (Saxe et al., 2020). Others suggest the use of causal chains that explain and validate users' willingness-to-pay to achieve more accurate results (Sunderland et al., 2015).

Other studies focus on non-monetary metrics of direct preference such as utility or compound ratings instead of monetary measures. MCM, which express relative preference between alternatives through composite utility measures, have been widely used in the infrastructure literature (Kabir et al., 2014). In general, these studies seek to capture the direct preference of decision makers for infrastructure alternatives based on their environmental performance. Further, these measures of value imply that impacts and benefits are commensurable and aggregable with other cash flows, or sources of utility; in terms of the value framework described in the previous section, this represents the notion of value as a magnitude of preference. Finally, some authors note that expressing value as a magnitude of preference often constrains the participation of larger groups of stakeholders. This is a consequence of measuring value in contexts with fixed sets of alternatives and predefined framings (O'Neill et al., 2007). Additional examples related to environmental preferences may be found in (Beare et al., 1998; Farber et al., 2002; Foxon et al., 2002; Foxon et al., 2015; Freeman et al., 2014; Funk et al., 2019; Mell et al., 2016; Williams et al., 2017).

Other environmental assessments used in infrastructure development (e.g., impact assessments, life cycle analysis, carbon foot-printing, among others) rely on dedicated metrics (e.g., energy efficiency, GHG emissions) instead of monetary or direct preference equivalents (Ainger and Fenner, 2013). There are many examples in the infrastructure literature that describe both negative and positive 'environmental value' of large infrastructure through specific, expert-designed metrics. Some studies have focused on resource utilisation (e.g., energy, water, land use) and production of waste and pollutants (e.g., GHG emissions, wastewater, solid waste) (Sahely et al., 2005). Other authors have used externally defined goals as a framework of assessment, e.g., mapping the role and influence of infrastructure systems on the United Nations' SDGs and using dedicated performance metrics that enable the tracking of SDG targets linked to infrastructure provision (Adshead et al., 2019; Thacker et al., 2019). These studies show that infrastructure is an essential enabler of the SDGs, being directly or indirectly included in 72% of the targets (Thacker et al., 2019). While the SDGs draw important broad connections between infrastructure development and environmental, social, and economic impacts, their materialisation is open to interpretation and often presents context-based challenges. Consequently, some authors have drawn more specific connections between the SDGs and environmental assessments for infrastructure projects (Castor et al., 2020; Kørnøv et al., 2020; Mansell and Philbin, 2020).

These studies are used to find quantitative 'intrinsic' values according to a specific goal that is independent from the utility of an individual or a group of stakeholders. Consequently, the metrics used in the methodologies presented above are the result of expert recommendation and are not tied directly to the perspective of decision makers. According to the value typology discussed in Section 2.3, this follows the definition of value as contribution to a goal. In contrast to the notion of value as a magnitude of preference (which sources value in the decision maker), the concept of contribution to a goal implies value is a property of the object or system. Additional examples that showcase environmental value as contribution to a goal in infrastructure may be found in (Allende et al., 2017; Arce and Gullón, 2000; Balkema et al., 2001; Coutts and Hahn, 2015; Demuzere et al., 2014; Huang et al., 2015; Monavari and Fard, 2011; Neuman and Churchill, 2015; Onsarigo et al., 2014).

The notion of values as priorities discussed in Section 2.3.3 may also be found in studies of the environmental dimension of infrastructure. This concept refers to the hierarchy and structure of priorities for individuals and societies, instead of pointing to the preference over a particular system or object. In the context of environmental assessment of infrastructure, this is often generically labelled as 'environmental values'. Some studies describe how environmental priorities have shifted over time regarding specific infrastructure systems. For instance, transportation infrastructure planners in the Netherlands shifted from expansion-oriented demand management to demand-reducing strategies, acknowledging and prioritising the negative environmental impacts of new construction (Geels, 2007). In terms of planning, studies show that integrated and sectoral planning affect the representation of collective environmental value systems. While the former gives a clearer view of the interdependencies and environmental consequences of infrastructure projects, it often complicates project materialisation (Busscher et al., 2015). Others have highlighted the disconnection between the value system and management practices expressed by companies in the construction sector, which hinders the tracking and realisation of those values and objectives (Hamilton-Foster, 2014).

Infrastructure plays a critical role in moving into a low-carbon society, since improved environmental performance of large systems may result in more fundamental and widespread changes than changes to individual value systems (Webb, 2013). This is supported by studies that show that individuals do not strongly relate their individual well-being with the environmental performance of infrastructure systems (Hienuki et al., 2019). Additional examples of discussions of value systems and priorities in the domain of infrastructure may be found in (Chan et al., 2012; Foerster et al., 2015; Ives and Kendal, 2014; McAndrews et al., 2018; Morison and Brown, 2011; Wolsink, 2010; Wolters et al., 2020; Zajchowski and Brownlee, 2018).

Environmental impacts of infrastructure are often complex and go beyond the scope of quantitative assessments (O'Neill et al., 2007). Some authors have studied infrastructure projects from a qualitative perspective, relating specific historical contexts with the built environment. This provides a complementary exploration of the environmental impacts of infrastructure development, often focusing on the local regulatory context and the implications for specific communities; see, for instance, (Fearnside, 2002). Others highlight how infrastructure development often overlooks local value systems and historical connections to traditional infrastructure and ways of life (Grubert, 2018; Kennedy Dalseg et al., 2018). The recognition that 'valuable solutions' in infrastructure are not universal—highlighting the importance of historical relationships between users and their surrounding environment—is closely connected to the notion of value-as-relations. However, infrastructure examples that explicitly recognise the notion of relational values are rare; this could be due to the more abstract and qualitative nature of the concept, which raises challenges regarding its incorporation into quantitative assessments such as EIAs, LCA, and CBA that have led the assessment of sustainability in infrastructure systems.

2.4.2. Social Dimension of Value

Large infrastructure almost inevitably has profound social impacts—including those on health, livability, material well-being, culture, family and community structures, institutions, politics, equity, gender relations, among others (Vanclay, 2002). Through the provision of essential services, infrastructure enables individuals to engage in activities that align with their priorities (Sen, 1999). Specifically, these systems provide physical factors of urban social sustainability (e.g., decent housing, local environmental quality, accessibility); and non-physical factors (e.g., health, equity, employment, cultural traditions) (Dempsey et al., 2011). The assessment of these impacts is usually a part of planning processes and regulations for infrastructure and is usually done in parallel with EIAs through Social Impact Assessments (SIA) (Government of Canada, 2019; Tilt et al., 2009; Vanclay et al., 2015; Vanclay, 2002). In this context, the notion of social value appears as a framework to understand the social impacts, benefits, and assessment of preference related to infrastructure (Raiden et al., 2018). Similarly, social value in the domain of infrastructure is operationalised through a range of different metrics, from monetary equivalents and quantitative metrics of utility to qualitative descriptions of historical processes.

Social impacts usually have an abstract and qualitative nature, which makes it challenging to provide quantitative measures to track them. This also leaves wide space for interpretation and alternatives to measure these impacts: monetary equivalents, quality of life indices, qualitative descriptions, among others. Some aspects relevant to social value, such as the material well-being of individuals and communities, are directly related to economic prosperity, employment, income, and debt, among others (Badasyan and Alfen, 2017; Samli, 2011; Vanclay, 2002). In this sense, economic and social value are intertwined, and thus, monetary proxies have often been used to measure social outcomes. However, many social outcomes related to infrastructure development are not intrinsically monetary, and as such, they can—and should—be explored separately from economic considerations (UN Habitat, 2020). The economic objectives of infrastructure value are explored in Section 2.4.3. This section explores and classifies the social dimension of value in infrastructure in existing studies. Table 2.4 summarises the reviewed literature, classifying publications according to the concept of value discussed and its broad infrastructure application.

Table 2.4. Reviewed literature for the social dimension of infrastructure, classified by concept of value and application.

	Concept of value				**Type of Infrastructure**		
Reference	Value as a magnitude of preference	Value as contribution to a goal	Value as priorities	Value as relations	Water	Transportation	Energy
(Litman, 2003)	•					•	
(Parker, 2014)	•					•	
(Purwohedi and Gurd, 2019)	•				•		
(Eizenberg and Jabareen, 2017)		•				•	•
(Kalyviotis et al., 2018)		•				•	
(Doloi, 2018)		•				•	
(Reddy et al., 2014)		•			•		
(Siew et al., 2013)		•			•	•	•
(Cui and Sun, 2019)		•			•	•	•
(Edum-Fotwe and Price, 2009)		•			•	•	•
(Hertogh and Bakker, 2017)		•				•	
(Zeng et al., 2015)		•			•	•	
(Grum and Kobal Grum, 2020)			•		•	•	•

Reference	**Concept of value**				**Type of Infrastructure**		
	Value as a magnitude of preference	Value as contribution to a goal	Value as priorities	Value as relations	Water	Transportation	Energy
(Burgess, 2007)			•		•	•	•
(Tilt et al., 2009)			•	•	•		•
(Mulholland et al., 2020)				•			•
(Mulholland et al., 2019)				•			•
(Raiden et al., 2018)				•	•	•	•

Some authors approach social value by measuring the magnitude of direct preference of a decision maker over an alternative. Some early works in this topic estimate the monetary value of social impacts (e.g., walkability for transportation infrastructure) through direct assessments of preference such as market surveys, valuation of marginal changes in supply and demand, or spillover effects on property values (Litman, 2003). More recently, studies have explored how technological applications such as building information modelling can be used to measure equity impacts based on monetary equivalents and willingness-to-pay functions (Parker, 2014). Others have measured social value through adaptations of financial metrics, e.g., a Social Return on Investment (SROI) to quantify the delivery of social goals (Purwohedi and Gurd, 2019). These studies assume the value of social outcomes related to infrastructure development is captured by individual preference. Further, they use monetary estimates to calculate aggregate measures of well-being that are normally used in the context of CBA (e.g., cost-benefit ratio, discounting, net present values).

Other studies focus on quantifying social impacts with respect to external goals (e.g., equity, culture, livability) using dedicated metrics that do not reflect direct preference. Specifically, risk management, equity, and safety have been identified as central goals behind the development of sustainable urban forms (Eizenberg and Jabareen, 2017). For instance, some studies use surveys in which users can express varying levels of well-being related to infrastructure alternatives through expert-defined needs (e.g., safety, comfort, convenience) (Kalyviotis et al., 2018). Other authors use social network analysis to quantify the flow of information and communication of perceptions between infrastructure stakeholders (Doloi, 2018). Assessment matrices that integrate different goals and objectives of social sustainability are also used to integrate different measures of social value into an overall estimate (Reddy et al., 2014; Siew et al., 2013). These studies explore social value as contribution to a goal, acknowledging that the complexity of the social impacts of infrastructure may go beyond what is captured by individual preference. Consequently, they propose or adapt metrics to measure the contribution of infrastructure alternatives to specific goals (e.g., meeting predefined needs, positive public perception). Additional examples may be found in (Cui and Sun, 2019; Edum-Fotwe and Price, 2009; Hertogh and Bakker, 2017; Zeng et al., 2015).

Another perspective of social value are individual and collective priorities and how they relate to public preference over infrastructure projects. The engagement with stakeholder priorities and needs during early-phase planning has been found to influence the perceived usability and the delivery of value during later stages of infrastructure projects (Grum and Kobal Grum, 2020). Some study the relationship between collective value systems and the concept of critical infrastructures, highlighting the importance of the cultural and social perceptions of threat and risk (Burgess, 2007). Others have described how mitigation efforts for negative impacts are dependent on the value systems of the infrastructure developers, which often do not align with the priorities of local communities (Tilt et al., 2009). Consequently, some identify the importance of mapping and understanding the value systems of stakeholders to successfully navigate their expectations and align project performance goals with them (Vallance et al., 2011).

Regarding relational values, some authors discuss the social impacts of infrastructure from a contextual and historical perspective. However, there is little or no literature on large infrastructure that explicitly refers to 'relational value'. This is most likely due to the recent nature of the concept, formally developed in the context of ecosystem services within the last five years (Chan et al., 2016; Tadaki et al., 2017). Rawluk et al. (2019) describe the concept of value-as-relations as a tension between realism and relativism, acknowledging that '... a comprehensive understanding of how people value nature requires multiple ways of knowing (epistemologies)' (Rawluk et al., 2019). Still, some discussions on the social value of infrastructure implicitly explore this concept including contextual or historical analyses, even if they do not formally mention it. Some studies in the domain of infrastructure acknowledge that a challenge in SIA is dealing with the changing cultural and political conditions that shape the perception of impacts that result from infrastructure development (Tilt et al., 2009). Others recommend highly localised assessments of social impacts that shift away from 'universal' metrics of social well-being, highlighting the importance of scale selection in the valuation of infrastructure products (Mulholland et al., 2020). In broader sustainability discussions, the preservation of historical practices within social sustainability is described as 'maintenance sustainability' (Vallance et al., 2011). Additional examples of studies that touch on the concept of value as relations in infrastructure may be found in (Mulholland et al., 2019; Raiden et al., 2018).

2.4.3. Economic Dimension of Value

Infrastructure is closely related to economic development—it enables most economic activities by providing necessary transportation options, energy, and communication platforms. Further, infrastructure itself represents a significant portion of the global economy: estimates show that, in 2013, existing infrastructure accounted for around 70% of GDP in most countries, projecting a global infrastructure investment need between $57 and $67 trillion US dollars through 2030 (Dobbs et al., 2013). Consequently, economies throughout the world depend on the adequate selection, development, operation, and maintenance of infrastructure.

When approaching the economic aspects of infrastructure, it is important to make a distinction between economic impacts and the monetary evaluation of those impacts. The former refers to the positive or negative economic effects that follow the development and operation of infrastructure, while the latter refers to the action of assigning a monetary value on a given impact by a decision maker. While many economic impacts are expressed in monetary terms, these can also relate to non-monetary objectives such as wealth distribution, growth, and economic risk. In this subsection, I review the study of economic value in the domain of infrastructure—both from the perspective of monetary evaluation, and through other notions of value presented in Section 2.3. Table 2.5 summarises the reviewed literature for the economic dimension, classified again into different concepts of value and by domain.

Table 2.5. Reviewed literature for the economic dimension of infrastructure, classified by concept of value and application.

Reference	Concept of value				Type of Infrastructure		
	Value as a magnitude of preference	Value as contribution to a goal	Value as priorities	Value as relations	Water	Transportation	Energy
(Badasyan, 2018)	●				●		
(Badasyan and Alfen, 2018)	●					●	
(Conrad and Seitz, 1994)	●					●	
(Funk et al., 2019)	●					●	
(Jones et al., 2014)	●					●	
(Mousakhani et al., 2017)	●					●	
(Rezvani et al., 2015)	●					●	
(Uddin, 2013)	●					●	
(Bivens, 2014)		●			●	●	●
(Baklanov et al., 2018)			●			●	●
(OECD, 2010)			●		●	●	●
(Wilson, 2012)			●		●	●	●
(Williams et al., 2017)	●				●	●	
(Zhang, 2006)	●				●	●	
(Bujanda and Fullerton, 2017)	●					●	
(Sarkar et al., 2007)	●					●	

Reference	Concept of value				Type of Infrastructure		
	Value as a magnitude of preference	Value as contribution to a goal	Value as priorities	Value as relations	Water	Transportation	Energy
(Martin-Utrillas et al., 2015)	●					●	
(Munnell, 1990)		●			●	●	●
(Straub, 2011)		●			●	●	●
(Leigh & Neill, 2011)		●				●	

Many studies have focused on assessing the economic value of infrastructure as measured by measures of direct preference (Badasyan, 2018; Badasyan and Alfen, 2018; Conrad and Seitz, 1994; Funk et al., 2019; Jones et al., 2014; Mousakhani et al., 2017; Rezvani et al., 2015; Uddin, 2013; Williams et al., 2017; Zhang, 2006). Some have made a clear distinction in the literature between financial performance (which relates to the investors in an infrastructure asset) and economic performance, i.e., whether or not an infrastructure asset has added socioeconomic value (e.g., time savings, increased productivity) (Badasyan and Alfen, 2017). Others measure the economic value of infrastructure through changes in property and land market values, studying revenue mechanisms that capture land value increases that result from infrastructure development (Bujanda and Fullerton, 2017; Mathur and Smith, 2013; Rybeck, 2004). Moreover, some have explored the effect of infrastructure performance in indirect costs such as medical expenses, which are related to air pollution levels that result from different modes of transport (Sarkar et al., 2007).

The integration of several economic factors such as job and social equity, economic growth, and method of financial procurement has been explored through MCM that quantify the relative preference of decision makers between infrastructure alternatives (Martin-Utrillas et al., 2015). These studies seek to aggregate different potential economic benefits such as employment generation and healthcare expense reduction through measures that are directly comparable to construction and operation costs. This provides important insight on how economic goals relate to individual preference, and the willingness of stakeholders to engage in the development of infrastructure products that align with these goals.

Several authors have studied the economic value of infrastructure in terms of its contribution to larger economic goals such as wealth distribution, employment, and equity (Munnell, 1990; Straub, 2011). Some have shown that higher government expenditure on public infrastructure results in a significant reduction in unemployment (Leigh and Neill, 2011). However, others highlight that improvements with respect to these goals are rarely distributed equally among the public (Bivens, 2014). Thus, the distinction between economic growth and economic prosperity becomes key when examining the effects of infrastructure investment. While economic growth is an important motivation for infrastructure investment, ensuring equitable and sustainable productivity in the long-term is also critical to oppose inequalities in income distribution (Samli, 2011).

The concept of value as a framework of priorities has not been extensively studied in the economic dimension of infrastructure. In general, existing studies and collective objectives such as the UN's SDGs call for infrastructure investment itself as a priority (United Nations, 2015). Some draw attention to the tensions between economic and environmental priorities related to infrastructure development (Baklanov et al., 2018; OECD, 2010). Others study the relationship between culture and value systems with respect to economic policy in infrastructure; see, for instance, (Wilson, 2012). However, the existing academic literature lacks an exploration of the economic priorities of stakeholders related to infrastructure development beyond growth itself (e.g., employment quality, wealth distribution, equity). These aspects may hold key insights to improve conflictive dynamics between different groups of stakeholders involved in the infrastructure domain.

Finally, to the best of the author's knowledge, the concept of value as relations has not yet been studied through the economic dimension of infrastructure. This is likely due to the origin of this concept of value, which explores preferences that are not explained by rational measures or motivations such as economic performance. While some communities have specific economic relationships to the development of infrastructure (Wilson, 2012), the concept of relational value highlights the importance of traditions and preferences that stand apart from what are normally labelled as 'rational' motivations (Grubert, 2018; Tadaki et al., 2017).

2.5. Towards an Integrated Notion of Value in Infrastructure

Separating the relevant dimensions of infrastructure performance into different value concepts highlights how these dimensions shape discussions and evaluations of infrastructure systems. Firstly, there is a noticeable tendency to quantify the value of infrastructure through measures of direct preference such as monetary and utility measures. These studies are useful and contribute to very well-studied and widely used methodologies such as cost-benefit analysis and multi-criteria assessments. However, these methods also come with shortcomings, including the lack of consistency in accounting for impacts across projects, aggregation of impacts that are not commensurable, biases towards project development, and implications on external participation and communication (Atkins et al., 2017; Flyvbjerg, 2014; Tadaki et al., 2017).

Since infrastructure systems impact a wide range of stakeholders in ways that go beyond market quantification, it is often challenging to express value as an accurate monetary or utility magnitude, making comparisons across projects difficult and less reliable (Atkins et al., 2017). Moreover, it may overlook the dynamic nature of impacts and the hierarchical nature of some of the potential benefits of infrastructure—an important feature in related fields such as ecosystem services (Fisher, et al., 2009). Even sustainability's most well-known framing, the TBL framework, has been questioned in recent years as it has been used to justify financial assessments, rather than to perform holistic multi-dimensional analyses of the ways in which infrastructure and businesses create or destroy value (Elkington, 2018). In addition, the evaluation of economic value as the contribution to external goals provides valuable insight, showing that even when infrastructure development has been tied to economic growth, this does not necessarily translate to the delivery of economic prosperity.

In terms of impact aggregation and comparison, measures of direct preference may give the illusion of commensurability, distorting the overall view of infrastructure projects for decision makers. Clearly, this limitation biases assessments against impacts that are not readily monetizable, as is the case of many environmental and social impacts (Tadaki et al., 2017). For instance, some of the multi-criteria decision-making methods directly aggregate financial performance (e.g., net present value) with other goals that are not oriented towards direct preference (e.g., impacts on biodiversity). While it may be useful to have an overall view of the preferences of decision makers in some contexts, these methods may also distort both the interpretation and comparison of preferences. Further, they imply that different dimensions impacted by infrastructure products (i.e., social, environmental, economic) can (or should) be balanced through aggregation. In contrast, a broader understanding of the value of infrastructure systems can provide a useful framework that focuses on the trade-offs and alignments across value and sustainability dimensions instead of balancing performance across them. This vision of value can be explored, for instance, through the application of non-compensatory decision-making methodologies (e.g., ELECTRE, PROMETHEE) for the design and management of infrastructure systems (Hassan et al., 2015).

Cost-benefit analyses—usually performed from the perspective of the parties in charge of the development and operation of the infrastructure—often happen in a context where there are already strong incentives to go forward with the implementation of projects, further distorting the value of infrastructure projects for stakeholders (Atkins et al., 2017; Flyvbjerg, 2014). This is exacerbated by the limited and regulatory scope of the assessment of other impacts (e.g., social, environmental), which is often perceived as a hurdle by project developers (Ward and Skayannis, 2019). Recognising the importance of all the notions of value in the context of infrastructure decision-making could result in key improvements to future developments. In order to design and operate successfully sustainable infrastructure, we need to have a clear view of the aspects that are best accounted for through each of the different forms of value (e.g., as magnitude of preference, as contribution to a goal, or as relational values).

Studies that understand value as contribution to goals (particularly for the environmental and social dimensions of infrastructure) have often paid little attention to the ways these goals reflect the priorities of different stakeholders. This may separate their view of high-level collective goal from what is measured as valuable in existing studies. While these goals seek to capture complex preferences that may go beyond individual preference, it is important that they address the priorities of the involved stakeholders (Hienuki et al., 2019). This plays a central role in meeting the service needs at the end user/community level; it also aids in setting appropriate performance thresholds for the infrastructure beyond standard regulations that may not reflect contextual objectives. Thus, it is necessary to study the similarities and tensions in stakeholders' views of socio-economic and environmental performance. In other words, collective goals speak to the varying priorities of communities, and acknowledging these differences is central to a successful management of the trade-offs and the impacts of infrastructure.

Furthermore, it is critical to consider the dynamic nature of value. Infrastructure systems are unique and long-lasting endeavours, and thus the priorities that drive performance goals and the goals themselves will likely evolve throughout its life cycle. Further, infrastructure products face significant deterioration and ageing throughout their life cycle, which often impacts their ability to perform reliably and efficiently (Sánchez-Silva and Klutke, 2016). However, infrastructure is many times designed and analyzed from a static framework of objectives and performance goals (Ward and Skayannis, 2019). This contributes to the obsolescence and underwhelming performance of projects in the long term, where many of the social and environmental impacts of infrastructure become significant. For instance, the motivations behind the development of transportation infrastructure focused on private vehicles have evolved in many societies, where there is now a greater concern for the environmental and social consequences of these systems. The perception of value of the involved parties—as well as the ways that this value is delivered—transformed over time in these infrastructure projects. For example, Greiman and Sclar (2019) describe how shifts in users' mode choices as well as local regulations for environmental assessments led the 'Big Dig' project in Boston, Massachusetts to be outdated from the start of its operation (Greiman and Sclar, 2019). Further, the impacts of infrastructure are also evolving constantly and materialise at different points in time. Rigid definitions of priorities, objectives, and system boundaries may be detrimental to the understanding of the impacts of infrastructure development. For instance, social and environmental impacts often result from long-term processes with fuzzy boundaries that are tied to deep uncertainties and triggered by unexpected circumstances such as extreme natural events that affect a wide range of systems and stakeholders. Consequently, some researchers have called for the development of flexible and adaptable infrastructure systems that embrace change and uncertainty over time, avoiding potential negative technical lock-in; see, for example, (Chester and Allenby, 2018; Sánchez-Silva, 2018). However, existing systems still play a key role in the delivery of value, and improving its management and operation is key to achieving better economic, environmental, and social outcomes (Saxe and MacAskill, 2019). Moreover, end-of-life and legacy considerations are also relevant in the delivery of value given the very significant amounts of materials, logistic effort, and capital embodied in existing infrastructure.

The selection of an appropriate scale for an infrastructure product also plays a central role in the definition of the stakeholders (and their preference), collective objectives, and priorities. Large-scale infrastructure systems, which are the focus of this literature review, usually rely on centralisation and economies of scale that increase efficiency across large populations. However, this can hinder the ability to adjust for individual preferences and priorities of specific communities, impacting the value perceived at the individual and/or community level. In turn, smaller-scale solutions that rely on redundancy and wide distribution may reduce efficiency at large population scales, but in turn, can provide increased flexibility for individuals and communities and reduce vulnerability to failure events compared to centralised systems (Alanne and Saari, 2006; Farmani and Butler, 2014; Makropoulos and Butler, 2010).

Finally, it is critical to recognise the interdependency between the delivery of different dimensions of value in infrastructure. The existing literature clearly reveals a close connection between the social and environmental dimensions of value; for example, improvements in environmental objectives are often associated with better health outcomes and increased well-being (e.g., improvements in air quality or noise pollution) (Coutts and Hahn, 2015). However, little attention has yet been drawn to the modelling of interdependencies nor to the conditional materialisation between different benefits and impacts. Such an awareness could offer greater transparency for decisions related to infrastructure development, better revealing trade-offs and interactions that are often obscured when separate impacts are simply aggregated.

2.6. Conclusions and Recommendations

Infrastructure provides key services and goods that enable a vast array of socio-economic activities. Yet, the development of infrastructure requires significant capital and has long-lasting impacts on societies and their surrounding environments. Thus, not surprisingly, there is a large body of literature that explores the notion of value for different aspects of infrastructure including social, environmental, and economic considerations. However, the way 'value' is understood across the infrastructure literature is shown to be diverse, a reality that results in disparate conversations regarding the impacts and performance of infrastructure projects. The current review of value uses a conceptual framework that separates the different concepts and assumptions of value for infrastructure systems and explores how the concept of value is represented in environmental, social, and economic dimensions, all notably relevant to conversations of sustainability. Ultimately, the notion of value contains—either implicitly or explicitly—key expectations and objectives of all stakeholders relating to infrastructure development, operation, and evolution. Value as direct preference is more prevalent in planning and operation spheres in which infrastructure alternatives are evaluated; value as contribution to goals emerge both in infrastructure regulation and for long-term societal planning; value that articulates priorities reveals that stakeholders have different hierarchies of priorities; value as embedded in relations focuses on the historical bonds between communities and their built environment.

This review illustrates that the notion of value as a magnitude of direct preference is prevalent throughout the different dimensions of sustainability. However, such notion of value is shown to have problematic implications regarding the aggregation and direct comparison of benefits and impacts that are not readily interchangeable. Further, such an approach tends to exclude relevant impacts that are not readily quantifiable. Other studies measure the value of infrastructure projects from the perspective of contribution to collective or external goals, recognising that some aspects of preference go beyond the preference of individual stakeholders, and result from more complex relationships between collectives. Two additional notions of value—namely, as an evaluation of priorities and contextual relations between communities and their environment—are as yet rarely present in existing studies of large infrastructure systems. This has implications on the ways collective preference for infrastructure projects is assessed; namely, it tends to ignore historical relationships between communities and their traditions, and rarely examines the priorities of different groups of stakeholders.

Additional research is needed to integrate the different notions of value of infrastructure studied here. These efforts are critical to successfully address present challenges such as improving the sustainability of infrastructure products. Some of the main research opportunities on the topic of value in infrastructure systems include:

- Addressing the *interdependencies* between different values in the context of system performance. This distinction should lead to a better representation of how impacts materialise throughout an infrastructure system's lifetime. In other words, the aggregation of independent objectives is too coarse, since social, environmental, and economic benefits are often closely coupled and strongly interdependent.

- Exploring the *dynamic* nature of preference towards environmental, social, and economic objectives, so that systems can be transparently and accurately evaluated at different stages of their life cycle. Dynamic decision-making frameworks are critical to successfully achieve long-term objectives, since both the objectives and the metrics used to track infrastructure achievement often transform over time.

Further, some of the recommendations for existing practice of infrastructure decision-making include:

- It is critical that existing frameworks of value integrate *alternative notions of preference*—such as contribution to objectives, or historical relations to the built environment—into the decision-making processes of infrastructure systems, which mostly focus on direct-preference measures of value (e.g., monetary performance, utility metrics).

- Identify and quantify the interdependencies in the delivery of value between infrastructures systems. This could improve the integration between decisions made for interdependent systems, leading to improved performance and less disruptions in their operation.

The ultimate goal is to develop infrastructure that is better equipped to meet broad expectations across different dimensions and at multiple levels, ranging from the direct preference of stakeholders to high-level collective goals and historical relations of communities. Yet, the evaluation process must also seek to avoid being mired by complexity, as infrastructure systems continue to operate and provide essential services. Such a balance is a difficult to achieve.

Chapter 3
Roles of Value in the Evaluation and Modeling of Decision Strategies for Pipe Maintenance in Water Distribution Networks

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3.1. Chapter Overview

Water distribution networks (WDNs) are essential infrastructure systems, providing vital drinking and process water for urban health and economic vitality. The unfolding choices of how and when to maintain these aging networks reflect the values (priorities) invoked by decision makers, and, in turn, these choices determine the value of the service delivered, ranging from adequate water delivery to its alignment with broader environmental, social, and economic objectives. However, the extent to which asset management strategies acknowledge and incorporate diverse values through their priorities, assumptions, and objectives, remains limited both in practice and in modelling research. This chapter proposes a computational model to evaluate the performance of long-term pipe maintenance strategies through Monte Carlo simulations of sequential pipe maintenance activities, capturing the probabilistic nature of pipe failure and its impacts across multidimensional performance metrics. Specifically, the model explores how operator priorities affect the choice of different repair and replacement strategies, and the effects of these value profiles across multiple dimensions including both system-level performance and the perception of different stakeholders such as users and service regulators. An illustrative example of a theoretical distribution network shows how valuing pipe replacement over short-term repair can both reduce pipe failure risk and lead to notable improvements in service, environmental, and monetary outcomes. Through an exploration of stakeholder value perception, this study shows that there is potential for alignment between societal objectives such as water losses and energy use, and between global service outcomes and direct maintenance costs for network operators. This study provides a novel exploration of the relationship between value (i.e., preference, priorities, and objectives) across stakeholders, and proposes methodological improvements in pipe maintenance modelling to better reflect the uncertain nature of WDN operation and a generalised and granular approach to pipe maintenance modelling.

3.2. Introduction

Water distribution networks (WDNs) are an essential infrastructure system, providing vital drinking and process water for urban communities. Indeed, water provision is closely linked to sustainable development because it directly relates to human health, poverty reduction, food security, and ecosystem conservation (UN, 2015). WDNs are long-lived, often operating for many decades. Across their lifetime, WDNs see both significant deterioration of their physical components and important changes in external demand and environmental conditions such as land use change and extreme weather conditions (ASCE, 2017). Consequently, significant effort and investment has been given both in research and practice to the twin challenges of system maintenance and retrofit (AWWA, 2001; ASCE, 2017; Selvakumar and Tafuri, 2012). Despite the clear and numerous connections between WDNs and sustainability, the decision processes motivating maintenance and retrofit decisions have often been based on narrow monetary metrics that can fail to capture the multiple dimensions of value, both in terms of the service delivered and in the consequences of system failure (UN Habitat, 2020).

This chapter explores the relationship between different notions of value and decisions regarding pipe repair and replacement across multiple performance dimensions: logistic, service quality and reliability, monetary, and environmental, using a dynamic computational model for pipe maintenance decisions under uncertainty as an illustrative example. The current study focuses on how value alters the assessment of different maintenance strategies for different stakeholders (e.g., network operators, users, regulators) affected by WDN operations across performance dimensions. Finally, given the predominance of computational modelling in the WDN literature, this chapter discusses the implications of common WDN assumptions and modelling choices on the representation of value in maintenance decisions.

According to the American Society of Civil Engineers (ASCE), there are approximately 155,000 active public drinking water systems in the United States delivering about 160 billion liters of water per day through 1.6 million kilometres of pipes (ASCE, 2017). Renaud et al. (2020) estimated a total pipe length of 875 thousand kilometres in France, whereas in Canada there are approximately 180 thousand kilometres of pipes as of 2019 (CIRC, 2019). With many pipes reaching the end of their expected lifespan of 75–100 years, WDNs face serious aging challenges, with many systems struggling to keep up with asset deterioration (ASCE, 2017). The deterioration of pipes increases the likelihood of leaks and pipe bursts. These failure events are difficult to anticipate and can result in significant volumes of lost drinking water, increased energy use, and monetary costs associated with repair activities, impacting service both in terms of water quality and availability (Giustolisi et al., 2006; Piratla et al., 2015; Selvakumar and Tafuri, 2012). Thus, utilities face complex, impactful decisions about pipe maintenance, which are heavily influenced by financial constraints. In practice, most utilities respond to pipe failures in a reactive manner with immediate repair actions that limit the immediate direct costs and consequences of failure, deferring the opportunity for systematic network retrofit and with it the opportunity to address problems of cumulative aging and broader societal impacts relevant to other stakeholders such as social (e.g., inequalities in access and quality of water delivery resulting from previous designs) and environmental objectives (e.g., upgrading to more efficient components that reduce leakage rates or energy consumption) (Clark et al., 2002; Karney and Gibson, 2021; Selvakumar and Tafuri, 2012). However, the growing importance of sustainability and the prominent role of physical systems in achieving it has led to increasing expectations that infrastructure systems meet multidimensional performance thresholds (Ainger and Fenner, 2013; Atkins et al., 2017; Glasson and Therivel, 2019; Hawkins and Jill, 2006; Purwohedi and Gurd, 2019).

Although all models must simplify reality, the representation and meaning of value in published models of WDN management decisions is often dealt with only implicitly, giving disproportionate priority to traditionally used metrics such as direct costs to utilities (Hernández-Chover et al., 2019; Kerwin and Adey, 2020). Such simplicity can obscure both the priorities and broader impacts upon other stakeholders, aspects key to long-term sustainable objectives (UN Habitat, 2020). Whereas system simplification of complex problems is essential, it is crucial that the influence of choices be shown for how they impact the representation of the expectations, objectives, preferences, and priorities, i.e., the values, of the stakeholders involved. This reality corresponds to the wicked nature of large infrastructure network design and operation, where the criteria selected, methods, and decision alternatives all speak to specific perspectives on value (Chester and Allenby, 2019; Loucks, 2017).

In this light, the next section briefly reviews existing models of pipe maintenance decisions, and the representation of value in WDN operation. Following this, a probabilistic computational model is used to illustrate the relevance of values in WDN modelling and explore how choices of crucial value metrics influence pipe maintenance decisions and outcomes. Results of this model for the Anytown theoretical water network developed by Walski et al. (1987) show how the priorities that inform maintenance activities influence the performance of different maintenance strategies, while also discussing the differences in perceived performance and value across stakeholders. Conclusions are drawn along with suggestions for future research.

3.3. Decision-making Strategies for WDN Asset Management

Asset management and decision-making for WDNs have been topics of interest for decades, with a wide range of methodologies (e.g., cost-benefit analyses, multicriteria methods, decision-making under uncertainty) being published along with advances in decision theory (Kabir et al., 2014). This section briefly reviews the literature on decision strategies for pipe maintenance (i.e., pipe repair and replacement) along with the ties these strategies forge to issues of value and sustainability.

3.3.1. Decision-making for Pipe Maintenance

Maintenance decisions for WDNs are numerous, including whether and when to repair or replace components such as pipes, pumps, and valves. One of the many ways in which maintenance activities are classified is by defining whether they are reactive, preventive, or predictive. Reactive (or corrective) maintenance activities are triggered upon fault detection or failure, whereas preventive and predictive maintenance activities are initiated prior to failure (Sánchez-Silva and Klutke, 2016). Whereas preventive maintenance activities follow regular schedules, predictive maintenance prioritises activities based on the likelihood of component failure (Gorenstein and

Kalech, 2022). Reactive operations tend to have lower immediate costs, but generally lead to higher lifetime costs and greater disruption to interdependent systems, because they do not allow for contingency planning and strategic adaptation over long time periods (Sánchez-Silva and Klutke, 2016). Water utilities are often reactive towards asset management, due both to the challenges of asset monitoring and prediction and to the local cost-centric assessment of maintenance decisions, approaches that can obscure the multidimensional consequences of component- and system-level failure (Selvakumar and Tafuri, 2012). However, predictive maintenance becomes increasingly relevant to research as computational modelling and machine learning algorithms for these systems improve (Li and Wang, 2018).

Maintenance strategies are also classified by their ability to adjust decisions as information on system performance becomes available. Decisions that are defined only by initial parameters and are fixed through the lifetime of a system are known as static strategies, whereas those that adjust over time are usually referred to as dynamic strategies (Giustolisi et al., 2009; Lozano et al., 2020; Zuluaga and Sánchez-Silva, 2020). In engineering practice, maintenance strategies for large infrastructure networks often combine these elements. Moreover, different concepts of value (e.g., stakeholder priorities, societal objectives) are embedded in the reactive, preventive, static, and dynamic elements of maintenance practices, and play a crucial role in the assessment of system performance.

The evaluation of maintenance decisions for WDNs has been studied through several approaches, including cost-benefit analyses (Dandy and Engelhardt, 2001; Ghobadi et al., 2021; Giustolisi et al., 2006; Jenkins, 2014) and multicriteria analyses (Lee and Burian, 2019; Scholten et al., 2014). Recently, a review by Farouk et al. (2021) identified over 20 published approaches for WDN rehabilitation, with most studies focusing on cost-centric optimisation approaches. Existing literature on decision support for pipe maintenance in WDNs has focused heavily on the monetisation of consequences of pipe failure; see, for example, Ghobadi et al. (2021), Giustolisi et al. (2006), Hernández-Chover et al. (2019), Pietrucha-Urbanik and Tchórzewska-Cieślak (2019), Roshani and Filion (2014), Xu et al. (2013), and Yerri et al. (2017). Whereas monetary constraints are clearly of great relevance to the operators responsible for maintenance activities, both the consequences of pipe failures and of maintenance activities affect a much wider set of values for all stakeholders involved such as users, service regulators, and broader society. Thus, reducing maintenance practices to the optimisation of monetary value may undermine the attainment of other valuable objectives such as minimised environmental impacts or an equitable distribution of service levels, which are particularly relevant to the achievement of sustainability goals.

Few studies have focused on decision-making methods that acknowledge the multidimensional impacts of asset management in WDN, a crucial element for assessing timely infrastructure challenges such as meeting sustainability objectives. Existing studies have focused on maintenance strategies informed by a variety of metrics, including the hydraulic performance in the form of efficiency or reliability (Dridi et al., 2009; Scholten et al., 2014); water quality (Cardoso et al., 2012; Shin et al., 2016); environmental impacts such as material use (Hajibabaei et al., 2018; Hernández-Chover et al., 2020); and other sustainability-related measures such as energy efficiency and GHG emission reductions (Lee and Burian, 2019). Most of these studies use compensatory objective functions that weigh and aggregate different goals in the optimisation process, expressing multidimensional solution spaces through a single output. However, the effectiveness of such methods has been questioned because they allow for optimal results where one objective dominates the solution without guaranteeing adequate performance for other objectives (Adshead et al., 2019). Whereas the addition of performance constraints, or the use of partially- or non-compensatory methods for multicriteria evaluation (e.g., ELECTRE), have been identified as solutions to these issues many asset management studies for WDN have focused exclusively on aggregation techniques (Banihabib et al., 2017; Carriço et al., 2021; Figueira et al., 2005). Existing studies also often make significant simplifications when modelling system operation, such as assuming instant replacement of pipes, ignoring cascading effects on the hydraulic performance of the network (both immediate and accumulating throughout the lifetime of the network), or ignoring construction times, all while using deterministic frameworks that may sidestep the uncertain nature of WDN operation. Overall, these simplifications have important implications for the applicability of the results and lend themselves to possibly distorted representations of some stakeholders in the value aggregation process.

3.3.2. Value Scenarios for WDN Management Strategies

Infrastructure provides value in multiple ways across a wide range of stakeholders, including their contribution to collective objectives and their provision of direct utility to users; in turn, value is also used to refer to the priorities of stakeholders in a particular context (Zuluaga et al., 2021). More specifically, WDNs deliver value as: (1) monetary returns for utility stakeholders such as network operators through service provision; (2) service provided to end users who critically depend on these services; and (3) an essential contribution for a more sustainable society. To the latter, WDNs either uphold or neglect collective priorities such as equitable access to water, the promotion of human health, and environmental concerns such as minimised water losses and efficient energy use. Their operation and maintenance ensure the materialisation of the value that the project was designed to deliver and provide opportunities to improve and adjust over original designs as external factors evolve (e.g., demand, environmental conditions). In contrast, short-sighted or mismanaged operations can compromise the value that a system was designed to deliver through service disruptions or increasing both the environmental footprint and the financial costs of the operation, while also leading to further disruption through cascading consequences to physically and functionally interdependent systems.

This study uses three variables to reflect operational priorities. The objective of testing different combinations of these variables is to represent different priorities and attitudes that inform maintenance strategies and the resulting system consequences, as summarised in Table 3.1:

1. the failures threshold for pipe replacement n_f, i.e., the number of failures allowed for a specific pipe before the operator replaces it for a new one;

2. the time to the detection and isolation of a pipe failure t_d, i.e., the time spanned between the first occurrence of failure to the moment where the operator can isolate the pipe segment and re-establish the network's basic hydraulic integrity; and

3. the time to repair t_r, which denotes the time to repair an isolated pipe segment after a failure event has been detected.

Failure is used in this study to refer to pipe breaks or bursts, as opposed to incipient leaks or other, often less sudden, types of failure. Further, the third variable encompasses several activities including site clearing, excavation, the actual pipe repair or replacement (which varies both in our model and in practice with several factors including location and pipe diameter), and posterior site backfill and restoration. For this study, the scenarios test the influence of the time for initial repair activities (i.e., site clearing and excavation), with repair and replacement times based on the trenchless and open-cut intervention times presented in Rehan and Knight (2007). In other words, repair activities are assumed to consist of trenchless cleaning and lining, while replacement is assumed to be full, open-cut replacement.

Table 3.1. Example values related to the input variables tested in maintenance strategy scenarios.

Input variable	Related instrumental values	Related terminal values
Pipe failure repair threshold (n_f)	Minimal maintenance costs Minimal water losses Minimal service disruption	High service standards System reliability & robustness System flexibility
Time to detection (t_d)	Minimal disruption of service Minimal consequences of failure for and around the WDN Minimal operational costs Minimal environmental impact from operation Efficient logistics for WDN operation	High service standards High system resilience Sustainable operation practices
Time for initial repair activities (t_r)	Minimal disruption to surrounding locations Minimal environmental impact from operation Minimal maintenance costs	High system resilience Sustainable operation practices

The priorities and values shown in Table 3.1 are often differentiated in previous literature under diverse concepts such as modes of behaviour, end-states, qualities, instrumental values, terminal values, among others (Badasyan and Alfen, 2017; Brown, 1984; Zuluaga et al., 2021). To avoid conceptual complexity, the priorities discussed here are discussed through the lens of instrumental (means) and terminal (end) values. The latter refer to the ultimate goals or end-states that are preferable, while the former refers to the quality of the ways in which this is achieved (Brown, 1984). For instance, high service standard for all users may be a terminal value for a WDN, while the achievement of these standards while upholding environmental sustainability would reflect an instrumental value, i.e., a desirable way for achieving this goal.

In the context of system operation and maintenance, several values are often invoked. First, satisfying the water needs of a population (both through sufficient coverage and adequate quality) is a fundamental terminal value for the operation of a WDN. However, the instrumental values attached to this objective are both numerous and context dependent. For instance, an operator in a dense portion of a city may prioritise minimising the disruption caused by pipe failure and replacement, particularly in sections where the consequences of intervention may be severe (e.g., disruption of nearby transit routes, structural damage to essential facilities). In contrast, an effective replacement strategy for a residential area may focus on minimising the water quality and delivery impacts of maintenance activities for users in the area. Further, resilience and sustainability have gained importance as critical terminal (as opposed to strictly instrumental) values for infrastructure engineering, being key backbones of long-term objectives such as the United Nations’ Sustainable Development Goals (Castor et al., 2020; Faber et al., 2018; Thacker et al., 2019). Table 3.1 lists example values related to the three variables used for the modelling scenarios of the reactive maintenance model.

A low pipe failure repair threshold indicates that the operator prioritises the reduction of future failure risk through pipe replacement, although this also comes at a higher immediate cost of pipe replacement activities (Christodoulou and Deligianni, 2010). In contrast, higher values of n_f reflect the precedence of minimising short-term costs, even when repair activities may lead to higher risk of failure in the future, with the multi-faceted consequences that stem from these events. In this sense, low pipe failure repair thresholds also prioritise the avoidance of extreme failure events, which significantly reduce the system’s ability to deliver water at an adequate pressure and pose important risks for water contamination (Ghobadi et al., 2021; Gibson et al., 2019).

The time to detection and repair after failure are closely related to a network operator’s ability to contain the event’s disruption on the network and its surroundings. Since pipe bursts result in water losses, a risk of exposure to contaminants, drops in pressure and increased flows throughout the network, minimising the detection times for these events can significantly reduce the consequences of failure and the disruption to interdependent services, improving the resilience of the system (Jung et al., 2015). However, system pressures and flows are inevitably transient, making detection and isolation challenging. Thus, the logistic efforts associated with reduced detection times are significant (Yerri et al., 2017). Further, since repair and replacement activities often require excavation of affected pipe segments, they cause other disruptions such as road closures, noise, air pollution, and greenhouse gas emissions (Osman et al., 2017; Rehan and Knight, 2007). As such, prioritising the reduction of repair times may be an important operator value in context where such disruption critically affects surrounding infrastructure and communities. Moreover, operators with stringent monetary constraints may set their priorities to keep their activities within budget to work towards financial sustainability, since the cost of repair activities is closely linked to their duration, but in turn reducing their ability to limit detection and repair times.

3.4. Developing a Computational Model for Value Exploration in Pipe Maintenance Decisions

This section presents a simulation-based model to explore the connections between maintenance strategies and value. The objective is to incorporate the stochastic nature of pipe failure events and their consequences, while capturing potential differences in performance outcomes (e.g., service, monetary, environmental) under different priority scenarios for maintenance actions (e.g., prioritising repair versus renewal of components, maintaining low detection and/or repair times). Whereas this model does not seek to capture all aspects relevant to WDN operation (e.g., incipient leaks, detailed detection through network monitoring), it is designed to illustrate the impact and resulting variability from input values on multidimensional system performance.

The model is designed to measure performance outcomes for full, time-dependent sequences of maintenance actions over the duration of the system's operation instead of evaluating average outcomes of single, repeated maintenance actions. This approach captures the compounding effect of maintenance actions on overall network performance, both spatially and temporally. Thus, incorporating uncertainty at the component level results in a more realistic range of long-term outcomes, showing cumulative effects that a deterministic model would miss. This is particularly so given the dependency between component failure risk (e.g., the probability of a pipe burst) and the network's hydraulic response (e.g., condition-based hydraulic characteristics such as the pipe roughness). This model was developed in a Python programming environment, with hydraulic simulations performed through the Water Network Tool for Resilience (WNTR) package, an open-source, EPANET-based software tool (Klise et al., 2017; Rossman, 2000).

3.4.1. Model Description

Consider a water distribution network comprising a set of m nodes $\mathcal{N} = \{n_j : j \in 1, \ldots, m\}$ and n pipe segments $\mathcal{P} = \{p_i : i \in 1, \ldots, n\}$ where n_j and p_i represent the j-th node and i-th pipe, respectively. Since this study focuses on the failure and maintenance of pipes, the degradation and operation of control devices such as valves, pumps, and storage units (e.g., tanks, reservoirs) are not considered.

The network's performance is modelled for 100 years in order to capture the evolution of pipe components having average lifetimes of 75-100 years (ASCE, 2017). Hydraulic performance is evaluated upon the occurrence of a pipe failure with a quasi-steady state approach. Rapid transient events are not considered; while transient pressures can be significant for abrupt flow changes, their inclusion comes at a significant computational cost and is not expected to strongly affect network-level hydraulic performance over the long operation window considered here (Ghorbanian et al., 2016; Marsili et al., 2020).

I build on a statistical pipe failure model following the methodology presented in Roshani et al. (2022) to stochastically generate N_s unique sequences of pipe failure events based on a pipe's physical characteristics and its maintenance history. This methodology allows exploration of the long-term effects of pipe failure events across a WDN, as well as to account for the spatial and temporal interaction between maintenance activities in the system. A Monte Carlo simulation framework is used for each realisation of the network operation for a total of N_s simulations, with the annual number of failures for each pipe determined through a zero-inflated, non-homogenous, pseudo-Poisson (ZIP) process. Then, a hydraulic simulation is performed for every failure scenario to capture the hydraulic behaviour of the network during and immediately after failure events. A flow diagram of the overall process is summarised in Figure 3.1.

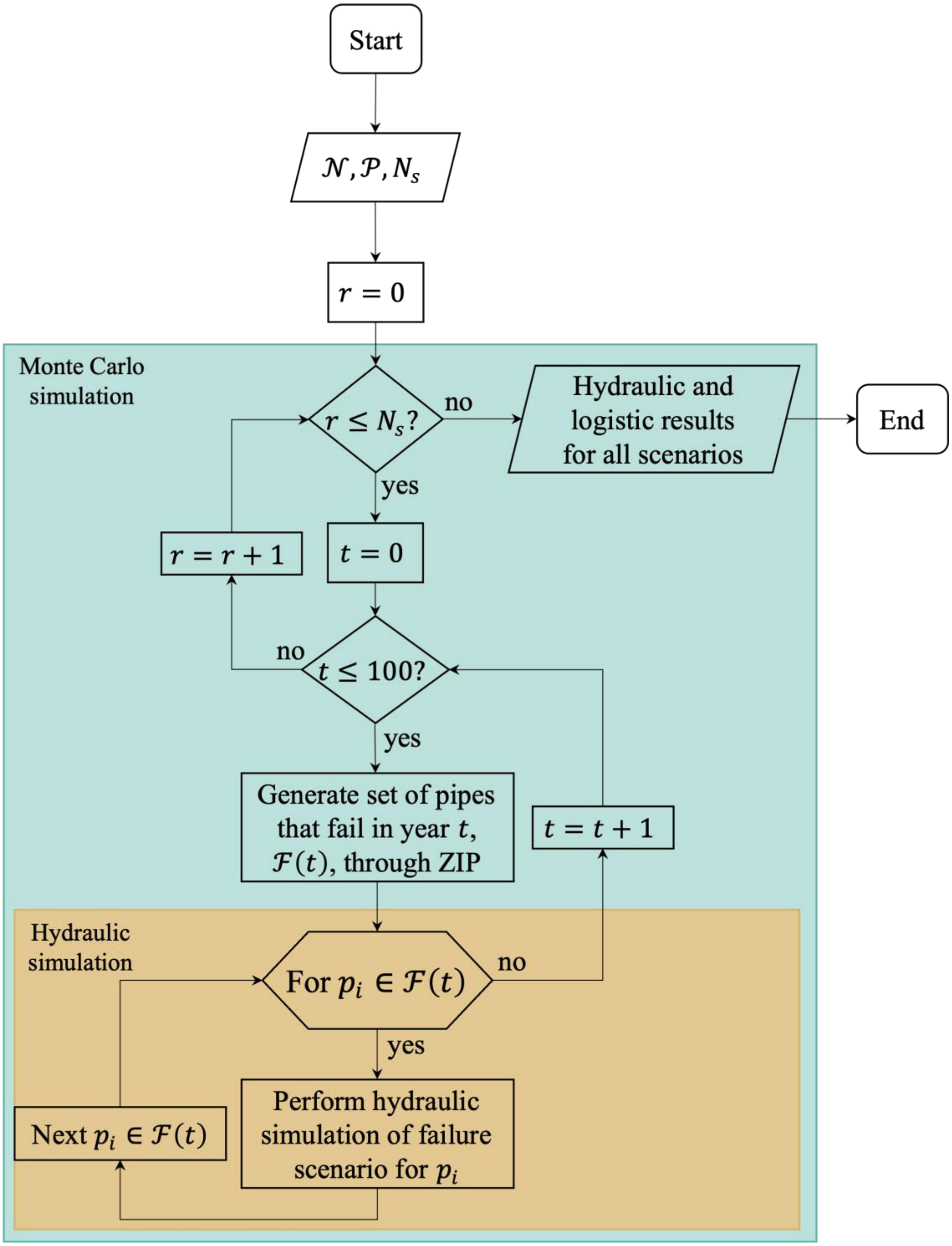

Figure 3.1. Global flow diagram for the Monte Carlo pipe failure model.

The Poisson process is a stochastic counting process used for a wide range of engineering applications (Sánchez-Silva and Klutke, 2016). For pipe failure modelling, Poisson processes estimate the number of failures as a function of time. A ZIP process modifies the traditional Poisson process by adding a zero-generating process, reflecting the natural tendency of a pipe to remain intact or to resist failure. This model overcomes some of the limitations of traditional Poisson models for component deterioration, particularly their known lack of sensitivity for relatively low-frequency events such as pipe breaks (Roshani et al., 2022).

The failure rate (breaks/km/year) under a Poisson process for a pipe is dependent on several physical, environmental, and operational variables. Physical variables of note include the pipe's diameter, age, and length; relevant environmental variables include soil characteristics (e.g., acidity, humidity), precipitation, and external temperature; for operational variables, the number of valves in a pipe and the number of previous failures are often used as a basis for failure rate estimation (Barton et al., 2022; Dawood et al., 2020; Giraldo-González and Rodríguez, 2020). Given that this study focuses on an illustrative example of a theoretical network with no historical failure data, this study adopts the widely used model by Dandy and Engelhardt (2001) in which the time-dependent failure rate is estimated through the diameter, length, and age of each pipe:

$$\boldsymbol{\lambda_{it} = 0.02214 \cdot exp(-8.64 \cdot 10^{-3} \cdot d_i) a_i(t)^{1.337} L_i} \tag{3.1}$$

where λ_{it} is the failure rate for pipe for pipe i in year t [failures/year], d_i is the diameter of pipe i [m], $a_i(t)$ is the age of pipe i [years] which is a function of time t, and L_i is the length of pipe i [km]. Then, the probability of observing k_{it} breaks (in year t for pipe p_i) is given by the following expression (Roshani et al., 2022):

$$\mathbb{P}[\boldsymbol{k_{it}}] = \begin{cases} \boldsymbol{G_{it} + (1 - G_{it}) e^{-\lambda_{it}}} & \boldsymbol{for\ k_{it} = 0} \\ \boldsymbol{\frac{(1-G_{it}) \lambda_{it}^{k_{it}} e^{-\lambda_{it}}}{k_{it}!}} & \boldsymbol{for\ k_{it} > 0} \end{cases} \tag{3.2}$$

where G_{it} is the probability of obtaining zero breaks from the zero-generating mechanism. This probability can also be defined in terms of the failure rate λ_{it}:

$$\boldsymbol{G_{it} = \frac{e^{g_0 - \lambda_{it}}}{1 + e^{g_0 - \lambda_{it}}}} \tag{3.3}$$

where g_0 is a base coefficient for the zero-inflated Poisson process. This definition produces values of G_{it} that approach 1 as λ_{it} decreases, and values of G_{it} that approach 0 as λ_{it} increases (Roshani et al., 2022). For the example presented in this chapter, a constant value of $g_0 = 0.897$ for cast iron pipes was used, based on the results of Roshani et al. (2022).

Once the number of breaks k_{it} is estimated for each pipe p_i in year t, the set of pipes that failed at least once in year t, $\mathcal{F}(t) \in \mathcal{P}$, is defined. This set allows to simulate only the pipes that require maintenance activities for a given year, reducing the computational effort of evaluating the performance of all network components. Then a quasi-steady hydraulic simulation of each pipe with $k_{it} > 0$ is performed sequentially using EPANET to assess the network's performance during the failure events. Note that this study does not consider simultaneous pipe failures for hydraulic modelling. Given the small scale and highly redundant structure of the example network, simultaneous pipe failures are not expected to have an important effect on the hydraulic performance of the network (Gheisi and Naser, 2014). However, the methodology presented here can be used to study the effects of simultaneous component failure on the hydraulic performance of a network where these effects are anticipated to be significant.

Given that events like pipe breaks often lead to low pressure conditions, this model is based on pressure dependent demand simulations (PDD) where the delivered demand depends on the pressure at the nodes. Then, the hydraulic simulation consists in simultaneously determining the flow rates, pressures, and energy losses throughout the network for a series of timesteps denoted as t_s during a simulation period $[0, t_f]$ where t_f is the end time for the simulation. The flow rates are calculated through time-dependent mass balance equations at every node (Klise et al., 2017; Rossman, 2000):

$$\boldsymbol{\sum_{p_i \in \mathcal{P}(n_j)} q_{p_i,n_j}(t_s) - D_{n_j}(t_s) = 0 \quad \forall\, n_j \in \mathcal{N}, 0 \le t_s \le t_f} \tag{3.4}$$

where $\mathcal{P}(n_j) \subseteq \mathcal{P}$ is the subset of pipes connected to node n_j, $q_{p_i,n_j}(t_s)$ is the flow rate of water into node n_j through pipe p_i at time t_s, $D_{n_j}(t_s)$ is the demand at node n_j at time t_s, and t_f is the simulation end time. The Hazen-Williams head loss formula calculates the time-dependent friction losses for each pipe p_i at time t_s (Klise et al., 2017; Rossman, 2000):

$$\boldsymbol{H_{n_e}(t_s) - H_{n_s}(t_s) = h_i(t_s) = 10.667 C_i^{-1.852} d_i^{-4.871} L_i q_i(t_s)^{1.852} \quad \forall\, 0 < t_s < t_f} \tag{3.5}$$

where $h_i(t_s)$ is the headloss in pipe p_i at time t_s, $H_{n_s}(t_s)$ is the head at the start node n_s at time t_s, $H_{n_e}(t_s)$ is the head at the end node n_e at time t_s, C_i is the Hazen-Williams coefficient of pipe p_i, d_i is pipe diameter, L_i is the pipe length, and $q_i(t_s)$ is the flow rate at time t_s. For this model, the Hazen-Williams coefficient was assumed to change over time using the equations presented by Sharp and Walski (1988) with a growth rate of 0.4 mm/year, based on the ranges and values tested by Lee and Burian (2019). Finally, the pressure-demand relationship proposed by Wagner et al. (1988) and implemented in WNTR (Klise et al., 2017) is used:

$$\boldsymbol{D_{n_j}(t_s) = \begin{cases} 0 & p_j(t_s) < P_0 \\ D_{n_j}^{f}(t_s) \left(\frac{p_j(t_s) - P_0}{P_f - P_0}\right)^{0.5} & P_0 \le p_j(t_s) \le P_f \\ D_{n_j}^{f}(t_s) & p_j(t_s) > P_f \end{cases} \quad \forall\, n_j \in \mathcal{N}, 0 < t_s < t_f} \tag{3.6}$$

where $D_{n_j}(t_s)$ is the delivered demand at node n_j at time t_s, $D_{n_j}^{f}(t_s)$ is the desired demand at node n_j at time t_s, $p_j(t_s)$ is the pressure at node n_j at time t_s, P_0 is the minimum pressure below which the node receives no water, and P_f is the required pressure above which the node receives the desired demand.

The chronology of the hydraulic simulation is broken down into three main steps: pipe failure, burst detection and isolation, and pipe repair; this sequence is shown in Figure 3.2. A hydraulic simulation starts at time $t_s = 0$ with the network operating normally until the pipe burst event, which occurs at time $t_s = t_1$, which is a uniformly distributed random time in the first 6 hours of the simulation; at this point, a leak node is added to the pipe that fails, effectively inducing atmospheric pressure and creating an opening for water losses. More specifically, upon failure, the pipe is split into two equal segments, and a node representing a circular hole is added with demand following the flow equations presented by Crowl and Louvar (2011), with a hole diameter of 30% of the diameter of the pipe and a discharge coefficient of 0.75 (Klise et al., 2017).

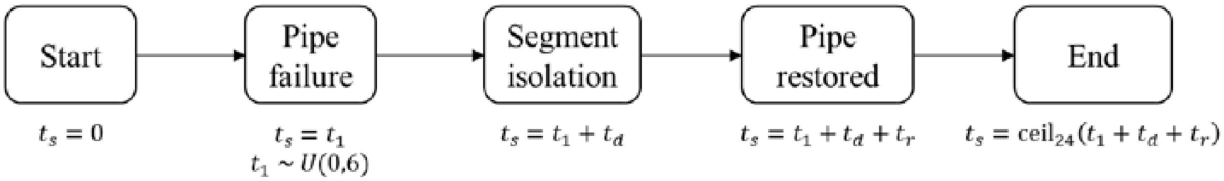

Figure 3.2. Main steps for the quasi-steady hydraulic simulation of pipe failure and maintenance scenarios.

After a detection time t_d, the pipe with the leak is closed and isolated. The network keeps operating under these modified conditions during the repair or replacement time t_r, and then goes back to operating normally after time $t_s = t_1 + t_d + t_r$. The total simulation time for each scenario is obtained by rounding up the finishing of repair activities to the nearest 24 hours (done with a ceiling function as shown in Figure 3.2).

The pipe's condition after maintenance depends on whether it was replaced or repaired. If replaced, the pipe becomes fully operational and both age and roughness are reset, with the C-factor being diameter-dependent as per the parameters of the Anytown network (i.e., a new pipe with lower failure risk is installed). If repaired, the pipe comes back online with partially increased capacitance, but with its age and failure risk unchanged (Walski et al., 1987). This dependence between failure risk and maintenance actions separates the model proposed here from others that use a traditional Poisson process to model failure. While one of the foundational assumptions of a traditional Poisson process is that events occur independently, this model takes a pseudo-Poisson approach where the failure rate λ_{it} for each pipe in the network depends on its maintenance history. In other words, pipe replacement changes the characteristics of the pipe and its failure rate, which will indirectly affect the probability of failure in future years. This dynamic approach to failure risk captures the critical feedback loop between failure risk and maintenance, which is often ignored in WDN maintenance modelling studies. To calculate the intervention times for repair and replacement activities, the model uses the methodology presented by Rehan and Knight (2007) for trenchless repair and open-cut pipe replacement.

The distinction between detection and repair stages is important because the impacts of an undetected failure, such as uncontrolled water losses, water contamination, and failures in surrounding structures, are often significantly greater than the ones that result from a closed pipe segment which has been isolated after failing (Jung et al., 2015). This study focuses on water losses, but the presented model could be used to study other impacts mentioned above. Further, this model allows a separate examination of the effect of repair times, which are frequently ignored in studies of maintenance strategies but play a significant role for system performance even after a failure has been detected (Osman et al., 2017).

3.4.2. Modelling Values Through Priority Scenarios

The different scenarios (i.e., combinations of variables) used here showcase the influence of modelling choices for reactive maintenance strategies. While preventive strategies are also relevant to WDN operation, they imply considering many more maintenance considerations such as network monitoring, budgeting, and logistic capacity; these aspects, in turn, would require modelling choices with underlying values that can distract from the analysis of multidimensional performance and the perceived value of system operation across stakeholders. Thus, this study only considers reactive maintenance to simplify the exploration of complex interactions between maintenance decisions, system performance, and stakeholders. Despite this specific scope, our illustrative example shows a significant impact of values in maintenance actions, and how these beget important differences in system performance.

This study defines a set of input variables that reflect common values as priorities for water network operations, allowing an exploration of common trade-offs. Table 3.2 presents nine scenarios used to highlight different values as priorities reflected on the input parameters for the reactive maintenance strategy. The notation for the scenario names is as follows: the first letter qualitatively describes the repair threshold n_f as Low (L), Medium (M), or High (H) and the second letter describes the speed of the detection and repair activities as Fast (F), Medium (M) or Slow (S).

Table 3.2. Input parameter scenarios assessed for the reactive maintenance strategy model.

Scenario	$\boldsymbol{n_f}$	$\boldsymbol{t_d}$ **(h)**	$\boldsymbol{t_r}$ **(h)**
LF	1	6	12
LM	1	9	24
LS	1	12	48
MF	3	6	12
MM	3	9	24
MS	3	12	48
HF	5	6	12
HM	5	9	24
HS	5	12	48

These nine scenarios are a combination of three possible values for the pipe failure repair threshold (n_f), and three combinations of detection times (t_d) and repair times (t_r). The values for n_f represent a uniform range that captures common choices seen in replacement strategies for WDNs (1-5 failures before replacement), particularly as presented by Christodoulou and Deligianni (2010). For the detection time t_d, different test scenarios are based on the range of average detection time values as presented by Jung et al. (2015); these values were paired with increasing values for initial repair activities based on estimates by Davis and Marlow (2008) and Osman et al. (2017). These scenarios seek to provide an exploratory range of possible input values, and as such are not exhaustive of all the possible combinations for the variables being studied.

3.5. Illustrative Example and Stakeholder Value Perception

An illustrative application of the pipe maintenance model described above is applied to the Anytown network introduced by Walski et al. (1987), a theoretical water network commonly used to benchmark network models (Farmani et al., 2005). The system layout is shown in Figure 3.3; additional details of the network can be found in the original study (Walski et al., 1987). The Anytown water distribution system is meant to reflect the conditions of a small network with few topological and demand changes. It comprises approximately 70 km of pipes with diameters ranging between 20 and 30 cm, with initial ages ranging between 50-100 years (Walski et al., 1987). In terms of demand, the network has 19 junctions with a total average demand of around 0.62 m^3/s; for simplicity, this level of demand has been assumed constant throughout the modelling period. Previous studies show that, while water demand is globally expected to increase, the increase of water use is closely tied to population and economic growth (Boretti and Rosa, 2019). Since this network represents the conditions of a small community in North America, the expected population growth would be low based on current population trends, and any growth might be compensated by a reduction in per capita demand (U.S. Census Bureau, 2021). Further, the results presented below are not expected to change meaningfully under incremental changes in demand.

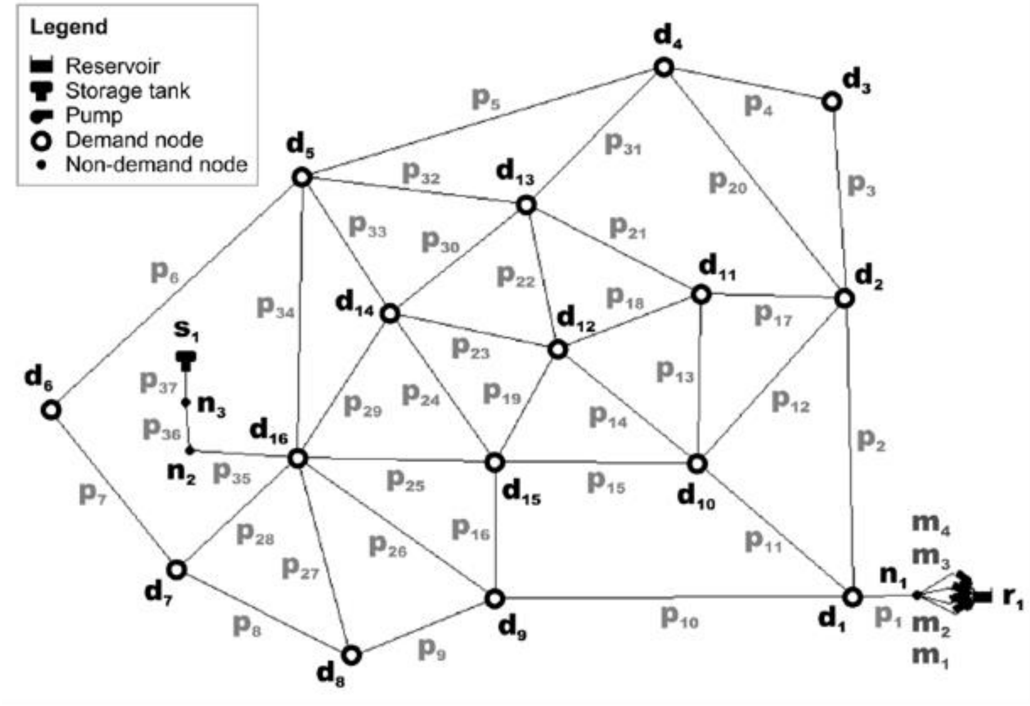

Figure 3.3. Layout of the Anytown network. Reprinted from Mala-Jetmarova et al. (2015) © ASCE.

The value scenarios presented in Table 3.2 are compared through a series of output metrics that measure logistic, service, monetary, and environmental performance. A list of all measured outcomes and their definition is presented in Table 3.3. The selected variables are common output metrics used in WDN modelling studies which makes them useful for comparison with other studies on maintenance strategies. These metrics also provide a broad picture of multidimensional system performance. The value methodology and discussion provided here could be expanded and used to discuss other important performance dimensions such as water quality or disruptions to interdependent systems; the presented results are an illustration of the importance of considering values in operational and modelling choices.

Table 3.3. Output variables used for measuring strategy performance and comparison.

Dimension of performance	Outcome variable	Definition
Logistic	Number of repairs	Average number of repair actions taken, per year and total throughout modelling window
	Number of replacements	Average number of replacement actions taken, per year and total throughout modelling window
Service	Pressure disruption	Average number of people-hours with relative or absolute pressure deficiencies per year
	Hydraulic reliability	Average fraction of delivered volume per year, i.e., yearly average of the delivered volume divided by the requested volume for all failure events
Monetary	Direct maintenance costs	Average yearly cost of maintenance activities, Total discounted cost of maintenance activities (i.e., both repair and replacement)
Environmental	Water losses	Average volume of water lost to pipe bursts, per year and total

These performance outcomes are measured both through their average yearly values, and in aggregate throughout the operation window. This aggregation is done considering the nature of the outcome; for instance, the number of repair and replacement actions can simply be added throughout the operation window, while direct maintenance costs are aggregated considering discounting.

The pressure disruption outcome presented in Table 3.3 is defined as the average number of people-hours—i.e., the product of population affected and the duration of the disruption—with either relative or absolute pressure deficiencies. An absolute pressure deficiency occurs when a node receives water at a pressure that is below a minimum pressure threshold, a value set here as 28 m of head (40 psi) (Walski et al., 1987). For the relative pressure deficiency, disruption at a junction is declared if its pressure is below 75% of its normal operation pressure, which is considered a significant reduction in service quality and water availability (Roshani et al., 2022). The estimation of the population at each junction is calculated based on the demand at each node based on EPA guidelines by assuming a high but constant water consumption per capita (in this case, 200 gallons or around 750 liters per capita per day) and a constant population over time (United States Environmental Protection Agency, 2015). This definition of pressure disruption allows to quantify both the intensity (i.e., number of users affected) and duration of pressure disruptions resulting from pipe failure events. The hydraulic reliability measure at year i (R_i) used for this study is based on the fraction of delivered volume (FDV) metric proposed by Ostfeld et al. (2002). More specifically, the total delivered demand for each hydraulic simulation is divided by the total requested demand, and then averaged over all failure events simulated.

3.5.1. Example Model Results

One hundred simulations were carried out for each of the nine scenarios defined in Table 3.2, with the system being operated and maintained for 100 years. First, the timeline shown in Fig. 3.4 for the average number of replacements for all simulations and scenarios reveals that the network undergoes an initial period of heavy replacement due to the high initial age of its components. Further, because replaced components have a decreased risk of failure, these early actions directly decrease the replacement actions during the first 5–10 years; the subsequent results appropriately emphasise the maintenance actions after this intense initial activity has dissipated. Thus, there is a start-up challenge: the high number of replacements at the outset adjusts for the initially high pipe ages, but given it is dramatically higher than what occurs over the remainder of the operational window, the results for this initial period (i.e., year 0) are omitted from subsequent consideration, allowing for a more balanced view of the value-motivated outcomes that follow.

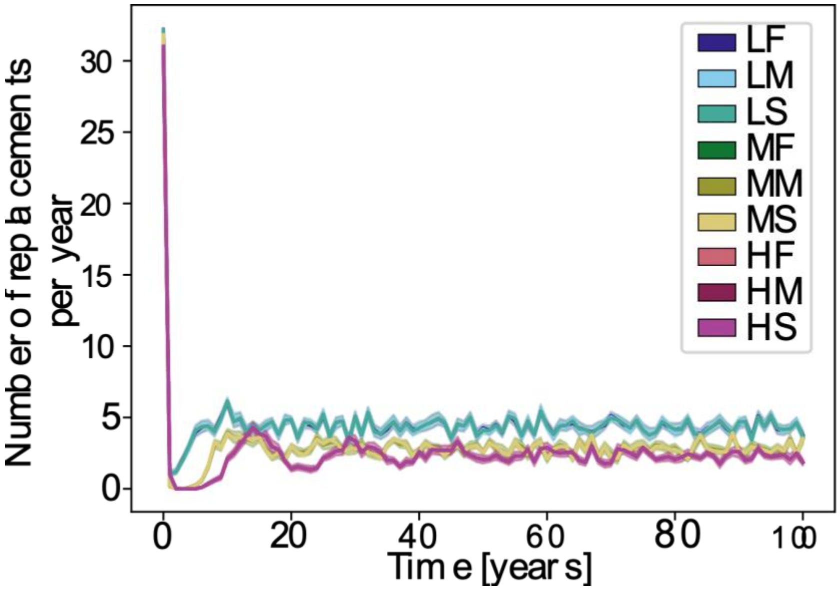

Figure 3.4. Timeline of the number of replaced pipes per year for each value scenario, including the initial simulation period.

Figures 3.5 and 3.6 show the distribution and timeline of the logistic outcomes (number of repair and replacement actions, respectively). These and all subsequent figures follow the same setup: the plot on the left shows a violin plot for the nine different scenarios with the distribution of the average value of each performance metric across simulations; the plot on the right provides a timeline of the average values for the corresponding performance outcomes for each scenario, with 95% confidence intervals shown in a shaded area. As expected, the results indicate that an increasing pipe failure replacement threshold leads to an increase in the average number of repair actions taken per year [shown in Figure 3.5(a)], and a decrease in the average number of replacement actions undertaken [shown in Figure 3.6(a)]. The combined results from these figures indirectly reflect the total rate of failure of the network over time since different pipe failure replacement thresholds result in a different distribution of maintenance actions. For instance, in scenario MM where pipes are replaced upon reaching failure three times (i.e., $n_f = 3$), the average yearly number of repairs is around 7 while the yearly average number of replacements is around 3, for a total of 10 maintenance actions per year on average. For additional discussion on the rate of failure obtained in this study, please refer to Appendix A.

Scenarios with lower pipe failure replacement thresholds lead to a lower average number of maintenance actions per year, which translates to lower levels of service disruption and less impact on interdependent services. Because scenarios with the lowest replacement threshold do not allow for repair activities, the number of total maintenance actions is significantly reduced as increased pipe replacement lowers the overall system age, thus reducing the risk of failure in subsequent years. Additionally, having more replacement actions in theory provides the operator with additional flexibility to adjust the system to possible changes in demand or regulations; however, a detailed study of WDN flexibility and adaptability is beyond the scope of this study.

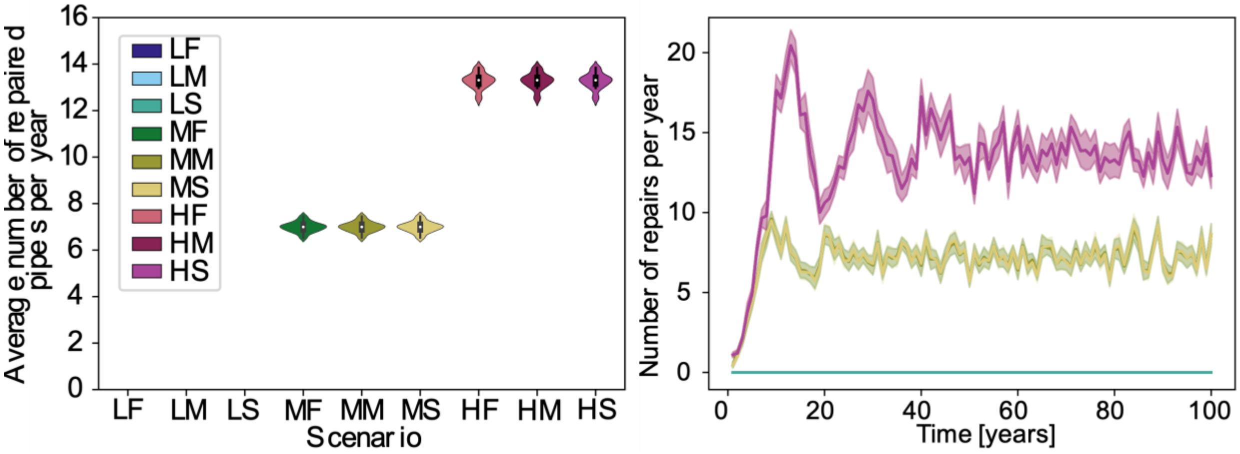

Figure 3.5. (a) Violin plot of the distribution of the average number of repairs per year for each value scenario; (b) Timeline of the number of repaired pipes per year for each value scenario.

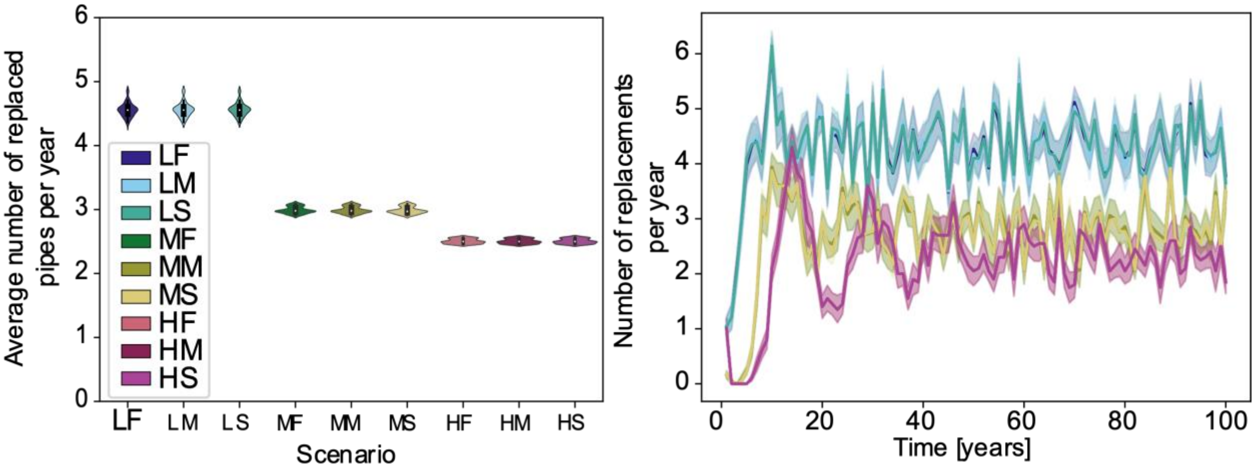

Figure 3.6. (a) Violin plot of the distribution of the average number of replacements per year for each value scenario; (b) Timeline of the number of replaced pipes per year for each value scenario.

Additionally, scenarios with higher replacement thresholds exhibit a cyclic behaviour for maintenance actions, with certain years having as much as double the amount of maintenance activities compared with other years, with replacement peaks approximately 20 years apart for scenarios with high replacement thresholds (i.e., HF, HM, and HS). In contrast, scenarios that focus on replacement actions show a steady amount of activity over the simulation period. Whereas models for asset management strategies in WDN assume a constant rate of intervention across the lifetime of a system, these results show that certain strategies can lead to high variability in terms of logistic effort, which is relevant when designing appropriate planning and scheduling of maintenance activities.

Figures 3.7 and 3.8 show the distributions for the service outcomes defined in Table 3.3, and a timeline of these outcomes. The results for pressure disruptions show that lower pipe failure replacement thresholds (n_f) consistently have lower levels of pressure disruption. Moreover, higher detection and repair times slightly counteract the trend set by the replacement threshold. Scenarios with the highest replacement thresholds show significantly higher levels of pressure disruption, and higher variability over time. Thus, low detection and repair times may not lead to significant reductions in service disruptions compared with medium times, but higher times do lead to significant increases in service disruption.

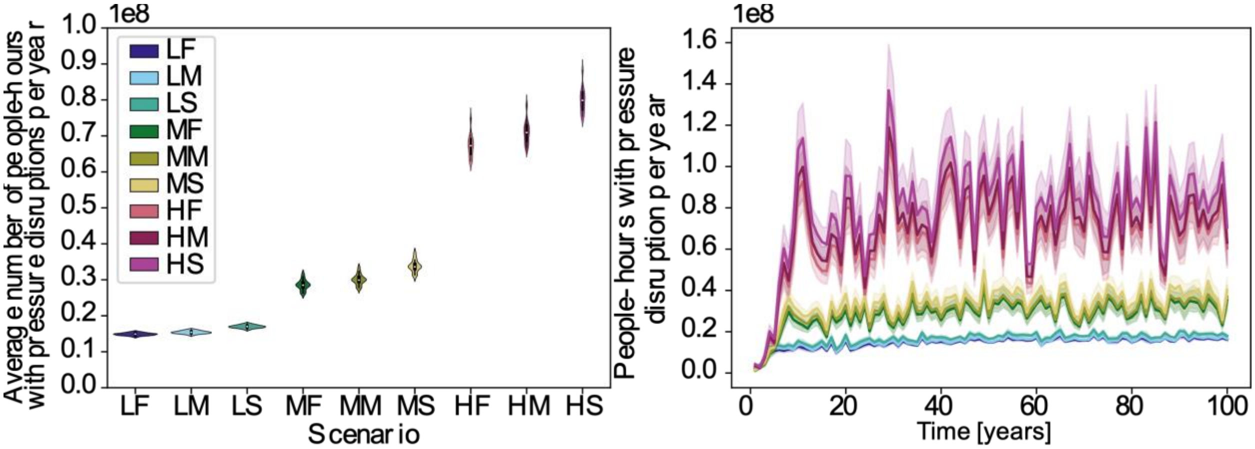

Figure 3.7. (a) Violin plot of the distribution of the average number of people-hours with pressure disruptions per year for each value scenario; (b) Timeline of the total yearly pressure disruption for each value scenario.

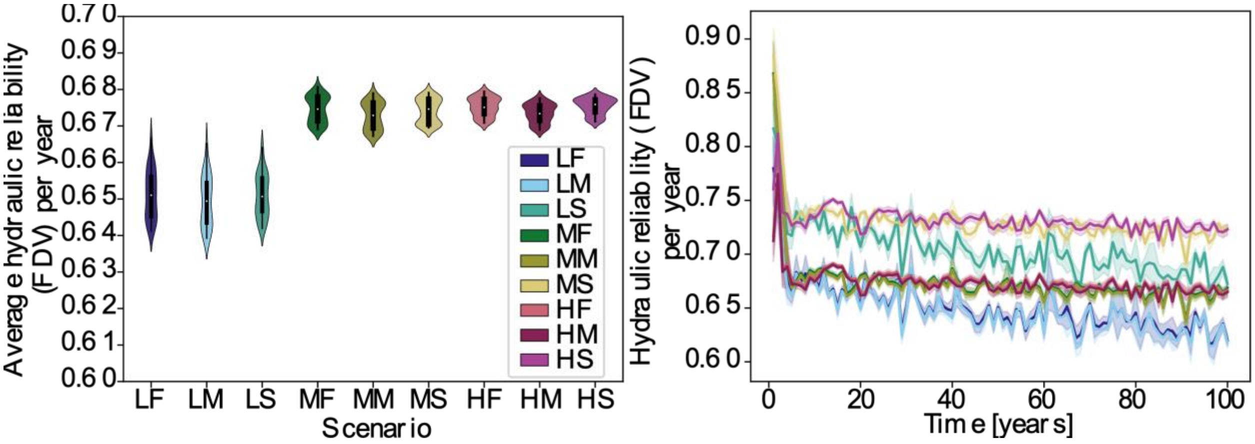

Figure 3.8. (a) Violin plot of the distribution of the average hydraulic reliability (FDV) for the network per year for each value scenario; (b) Timeline of the yearly hydraulic reliability (FDV) for each value scenario.

For the hydraulic reliability measured in terms of the rate of demand satisfaction (FDV), scenarios with no repair (i.e., LF, LM, and LS) show lower delivered volumes than scenarios where repair is allowed. This arises because replacement activities tend to be more time intensive than repairs and therefore lead to greater reductions in delivered volume even with a reduced rate of maintenance activities. Further, replacements more strongly alter failure risks, and thus change the risk profile of the network; as maintenance is performed over time, there is a potential shift towards more disruptive failure events which in turn can increase the uncertainty in the FDV distribution. Additionally, all scenarios show a slight decrease in the FDV over time, with a more noticeable drop in scenarios with low replacement thresholds that explains the higher variability in the distribution per scenario.

Figures 3.9 and 3.10 show the distributions per scenario and timelines for the monetary outcomes defined in Table 3.3. The results are similar both in terms of yearly costs and total discounted costs, showing that higher failure replacement thresholds lead to higher direct costs for pipe maintenance. Whereas repair actions are significantly less costly than replacement actions, the diminished failure risk that results from replacing more often—and consequently, the reduced amount of maintenance activities—leads to a reduction in costs throughout the operation window of the system. For the discounted costs presented in Figure 3.9, a constant discount rate of 4% was used based on commonly used values for previous modelling efforts (Dandy and Engelhardt, 2001; Wu et al., 2010). Higher discount rates would emphasise the higher upfront costs of replacement-focused strategies (LF, LM, and LS), whereas lower rates accentuate the long-term increase in maintenance needs that results from repair-focused strategies (HF, HM, HS). Whereas the selection of a discount rate has important implications on social and environmental sustainability discussions such as debates on intergenerational equity, a closer study of the effect of the discount rate is beyond the scope of this chapter and is found elsewhere (Lee and Ellingwood, 2015; Regan et al., 2011).

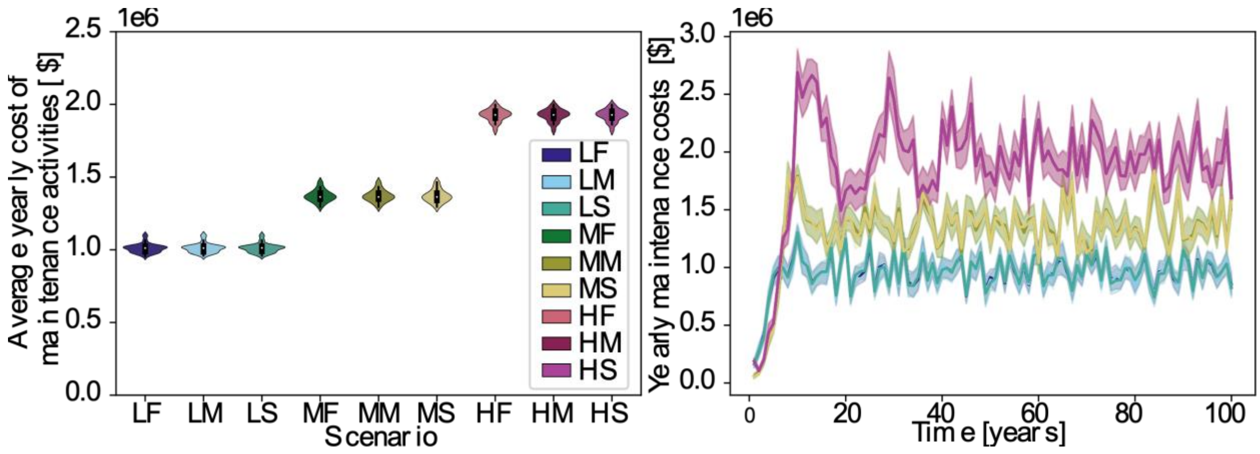

Figure 3.9. (a) Violin plot of the distribution of the average yearly cost of maintenance activities for each value scenario; (b) Timeline of the total yearly maintenance costs for each value scenario.

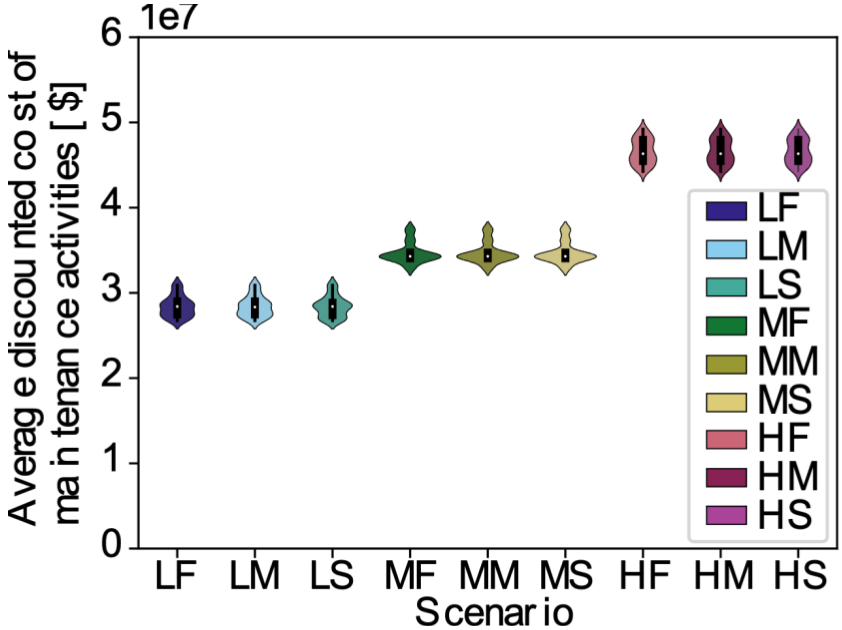

Figure 3.10. Violin plot of the distribution of the average total discounted cost of maintenance activities for each value scenario.

Finally, Figure 3.11 shows the distribution and timeline for the water losses associated with pipe failure events. The results show that higher pipe failure replacement thresholds lead to significantly higher volumes of water lost to failure events. The close relationship between water systems and energy consumption, also known as the water-energy nexus (Helmbrecht et al., 2017; Tsolas et al., 2018; Yang et al., 2018) indicates that high water losses translate into inefficiencies in energy use, which lead to increased water treatment and distribution costs. Delivering drinking water entails important energy expenses that include the operation of most physical components including water treatment plants, pumps, and valves. Conversely, in many cases, energy production relies on water (e.g., through the utilisation of water pressure in turbines), with energy and water networks being highly interdependent (Artioli et al., 2017). Note that this model does not consider water losses due to incipient leaks, although they can lead to significant losses in old networks with maintenance backlogs (Ghorbanian et al., 2016). In this example, however, incipient leakage modelling would be expected to amplify the differences between the studied scenarios, as leakage in scenarios with high replacement thresholds would increase because more pipes are allowed to fail than in replacement-focused scenarios.

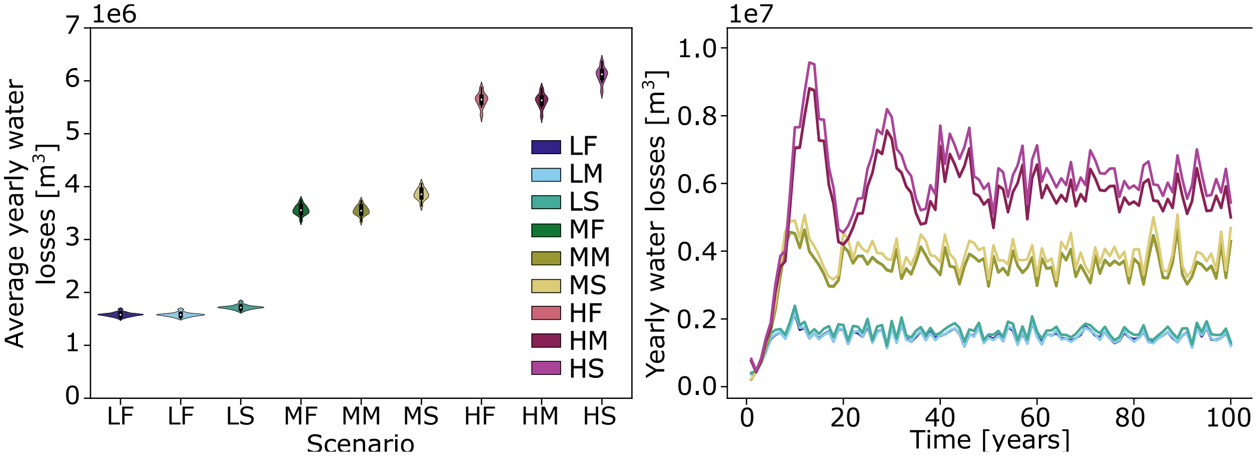

Figure 3.11. (a) Violin plot of the distribution of the average volume of water lost to pipe failures per year for each value scenario; (b) Timeline of the total yearly water losses for each value scenario.

One important similarity across performance outcomes is the minimal differences between scenarios that only vary detection and initial repair times. For all performance metrics used in this example, different values within reported ranges of detection and repair times do not lead to significant changes in performance. This is likely a result of the scale of these times compared with the total duration of a maintenance activity, which is calculated by adding the repair time defined in the proposed scenarios (associated with clearing and excavation) to the time for either repair (trenchless) or replacement (open-cut), which is in turn influenced by the length of the segment being serviced. However, this might be slightly misleading. There is a noted tendency for maintenance activities on infrastructure to incur highly variable delays (Flyvbjerg, 2014); thus, the small observed differences between the current scenarios might underestimate the consequences of potential delays in maintenance operations.

Water losses have also been associated with impacts in the energy use for the network, generally resulting in increased pump energy use and increased head losses associated with higher flow rates (Dziedzic and Karney, 2014). Further, unexpected failure events may lead to changes in energy consumption patterns, which in turn increase operation costs and further amplify the impact of water losses in the system. For instance, a pipe failure event will result in more water being demanded by the network to maintain pressure (particularly prior to segment isolation), which generally leads to higher flow rates and energy use in pumps. Additionally, water losses have knock-on effects on interdependent systems and can create additional damages and costs outside the water network itself, such as structural damage to nearby systems and disruptions due to functional interdependencies between WDN and other infrastructure such as power networks (Wang et al., 2012).

3.5.2. Stakeholder Value Perception

Whereas the outcome metrics studied here represent relevant dimensions for pipe maintenance decisions, they are asymmetric representations of the perceived value for the different stakeholders. For example, pressure disruptions dramatically affect the value users derive and can quickly lead them to search for alternative water sources. In contrast, an operator perceives indirect effects of pressure disruption, such as reduced water consumption and potential deterioration from transient pressures. The perceived value for stakeholders such as users, operators, and regulators clearly varies across scenarios and output metrics. Further, in large networks, there may be important equity considerations related to the experienced performance within groups of stakeholders (e.g., users with different priorities); however, a more detailed discussion of equity in water access and quality is beyond the scope of this chapter and is found elsewhere (Goddard et al., 2021; Pryke and Allen, 2019).

The current example explores a multidimensional performance space given different combinations of operator priorities rather than treating pipe maintenance as a multicriteria optimisation problem. Moreover, an evaluation of stakeholder overall value perception for the proposed scenarios would require providing an aggregation function for the different performance metrics for each identified stakeholder. Further, the illustrative example is based on an artificial network, and thus constructing these objective functions would require numerous, uncertain, and difficult-to-defend assumptions about stakeholder preferences. Consequently, the stakeholder value analysis compares the scale of change between scenarios to identify potentially disproportionate changes across performance metrics, and then links these changes back to the stakeholders that interact with the WDN through the lens of that specific metric.

First, the network operator responsible for maintenance activities does not perceive changes in direct maintenance costs for having higher detection and repair times. However, these higher times lead to increases in pressure disruptions and water losses, which more directly affect the value of service for users and the costs to broader society, because increased water losses significantly impact value delivery within and beyond system boundaries. Water losses increase the need for both source water and water treatment, which may lead to increased energy use for the utility upstream in the service delivery process. Moreover, it can lead to spatially varying impacts such as water damage in nearby structures and services (e.g., structural damage in roads and building foundations, water damage in buildings), with consequences and costs that are not directly borne by the water operator but that do affect both users and nearby services. Reducing detection and repair times, however, comes at a potentially high logistic effort with resource implications, and can lead to additional operational expenses beyond the scope of the direct maintenance costs presented in Figures 3.9 and 3.10. Here, policy and regulation can play a critical role in aligning the operator's incentives with the access of users to adequate service and objectives of broader society such as minimised water withdrawal and emissions; however, there is also a balance for society to consider between the consistent higher logistic effort and higher repair costs.

The outcomes most directly related to the users' value perception are affected in great measure by the management priorities of the network operator. For instance, the amount of pressure disruptions (and repair activities) across scenarios are significantly different, with some scenarios (such as scenarios HF, HM, and HS) showing as high as fivefold differences in average disruption levels, and higher variability over time. Moreover, whereas the network operator might focus on variables with smaller differences across scenarios (e.g., maintenance costs over the analysis period), users may perceive higher variation through pressure disruptions, leading to potential tensions over the management decisions of the system. Another example of a potential tension is the mismatch in the perceived disruption for users and operators resulting from different types of maintenance activities. In this exploratory example, replacement activities show lower levels of disruption, costs, and water losses. However, these activities imply significant levels of maintenance work that involve excavation, and lead to extended road closures, noise, air pollution, and greenhouse gas emissions for longer periods of time than repair activities based on pipe cleaning and lining (Rehan and Knight, 2007). Consequently, users may perceive more value from the system operation and maintenance with a balance of repair and replacement activities (as in scenarios MF, MM, and MS), where the highest levels of pressure disruption are avoided but maintenance activities are not exclusively based on the more disruptive pipe replacement.

The differences in value perception across stakeholders raise a crucial point for studies that focus on optimisation efforts for maintenance strategies in WDN. Whereas the consideration of multiple objectives is critical for achieving more sustainable outcomes, it is important to be mindful of the role values (i.e., priorities, preferences, and objectives) play in the modelling and optimisation efforts for maintenance strategies. The intentions and priorities of different stakeholders shape their preference and perception towards system outcomes, which often have impacts across stakeholders and beyond system boundaries. However, existing multiobjective optimisation efforts for WDN maintenance rarely analyze multiple objective profiles, and consequently propose optimal trade-offs that may poorly correspond to the actual perceived values of relevant affected stakeholders. For instance, optimisation may be used to propose a maintenance strategy that has an optimal trade-off between predicted pressure disruptions and maintenance costs, even though the latter outcome is not directly tied to users' preference, and the former may appear less relevant to the operator based on their priorities. Whereas these trade-offs can provide a global sense of system performance, a serious exploration of the needs, preferences, and priorities of key stakeholders is crucial to finding a balanced and desirable operation for water systems. The outcome scenario exploration performed in this study seeks to provide an alternative analysis framework for this multicriteria problem, challenging the notion of optimality and common assumptions about stakeholder priorities, particularly when it comes to their aggregation into a unique solution.

3.6. Conclusions and Recommendations

Many previous studies have pointed to a backlog in WDN component replacement with an appeal for a significantly increased commitment to maintenance and retrofit. This study provides a novel exploration of the relationship between concepts of value such as preference, priorities, and objectives for users, operators, and regulators in the context of a dynamic computational model for pipe maintenance that accounts for the uncertain nature of WDN operation and its multidimensional impacts. By incorporating relevant operational components such as burst detection, pipe isolation and repair, and allowing for combinations of both repairs and replacements under uncertainty, the modelling approach in this study provides a more realistic assessment of pipe failure than static maintenance models. More specifically, the model provides a generalised and granular modelling approach to pipe maintenance, an approach that is well-suited to component-level risk analysis.

The results from the Anytown network example highlight the significant role of pipe replacement in the reduction of failure risk and show that favoring replacement over repair activities can lead to significant improvements in global service, environmental (as measured through water losses), and monetary outcomes. However, whereas multidimensional performance metrics help improve our understanding of the impacts of maintenance activities, they do not provide a global perception of value across system stakeholders. This can lead to maintenance strategies that prioritise the impacts borne by one stakeholder over another (e.g., the network operator) without considering disruptions on service and interdependent systems that are perceived by users and broader society. Thus, stakeholder value perceptions play an important role in operation modelling, serving to inform choices and as an early identifier of tensions between stakeholder interests. In practice, policy and regulation decisions help align operational incentives with the access of users to adequate service, and to the broader objectives such as minimised water withdrawal, energy use, and carbon emissions.

The connections between value systems and water supply decisions are rich, varied, and still largely unexplored. Certainly, the application of the proposed pipe failure model to larger networks may reveal interesting patterns for more complex, large-scale maintenance operations. Another relevant area for future work is the engagement with real WDN stakeholders, mapping their priorities and preferences related to WDN operation. This could be done through a qualitative exploration of stakeholder value perceptions after the occurrence of highly disruptive pipe failure events to identify challenges and opportunities for improvement in maintenance strategies that effectively include all stakeholders of WDNs. Finally, there is an opportunity to explore the specific mechanisms through which pipe failure events affect value delivery across interdependent systems such as energy grids and surrounding transportation networks.

Chapter 4
Circular economy strategies in cities as a value-driven approach to infrastructure management

This chapter is based on a paper being prepared for publication in a peer-reviewed journal:

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4.1. Chapter overview

The Circular Economy (CE) is increasingly discussed as a promising paradigm to reduce the environmental impact of modern production systems with the key objective of preserving and maximizing the value delivered from human-made products and systems, including the infrastructure sector. However, there is a mismatch between common assumptions in CE thinking, largely developed for consumer products with short lives and simples uses, and large infrastructure products characterised by their interdependency, permanency, and complexity. Focusing on the potential for CE to enhance infrastructure value delivery while reducing environmental burdens, this chapter uses the 10R framework to discuss the applicability of CE strategies to the management of infrastructure systems and to promote higher-order circularity for infrastructure. Natural Language Processing was used to examine urban CE policies for the management of infrastructure in six large cities in the Americas and Europe, studying if and how these cities plan to employ circularity strategies to enhance the value of their infrastructure systems. The analysis reveals that most sampled cities currently focus on closing material loops, envisioning CE for infrastructure as waste management. Nonetheless, London and Amsterdam currently lead the way in the application of life extension strategies, which prioritise narrowing resource loops. For urban infrastructure CE to meaningfully engage with the central goal of value preservation and enhancement, more focus is needed in both research and policy on higher-order CE strategies such as repurposing and intensified use of existing infrastructure.

4.2. Introduction

This chapter discusses the applicability of existing Circular Economy (CE) strategies for infrastructure products, focusing on value preservation and maximisation as key objectives. To do so, I examine current urban CE policies for infrastructure products and the construction sector in six large cities in the Americas and Europe, studying alignment between urban CE policies and value delivery in infrastructure. The chapter investigates which CE strategies are being used and which overlooked in current policy, identifying opportunities to improve circularity in the built environment.

Infrastructure is a key driver of value as it delivers fundamental services and goods that enable a vast array of socio-economic activities such as transportation of people and goods, the provision of drinking water and management of wastewater and stormwater, and the generation and distribution of energy. However, this value comes at a high environmental cost, as infrastructure and the construction sector more broadly cause an estimated 40% of global greenhouse gas (GHG) emissions, a significant portion of which are associated to material extraction and production (International Resource Panel, 2020; United Nations Environment Programme, 2022). Given the essential role of infrastructure in supporting human and societal activities, infrastructure systems such as public transportation, water distribution and sewerage, and power distribution networks are critical drivers of both current and future resource consumption and associated environmental impacts. There is a significant need for new infrastructure to support and enable population growth, improvements in quality of life, and technological transitions across the world (Oxford Economics, 2017). As such, increasing attention is being paid to questions of whether we can avoid development of new infrastructure and reduce the use of primary resources through better management of existing infrastructure and their embodied materials (Pauliuk et al., 2021; Zhong et al., 2021). To maintain current function, let alone adapting to suit the demands of the 21st century, existing infrastructure requires the input of materials and energy in the form of refurbishment activities.

CE is increasingly recognised in both academic literature and policy making as a promising paradigm to reduce the environmental impact of modern production systems, including the construction sector (Kirchherr et al., 2023). Among the main objectives of CE are preserving products at their highest value across their life cycle, reducing the environmental footprint of modern production systems, and promoting regenerative systems that align with natural resource cycles (Ellen MacArthur Foundation, 2023). In terms of the concepts of value discussed in Chapter 2, CE focuses on two concepts of value: value as a magnitude of preference, as it seeks to change production and consumption systems to *preserve* the monetary and functional value of products as long as possible; and value as a contribution to objectives, as it promotes value preservation as a mechanism to reduce the overall consumption of natural resources, and in doing so, achieve environmental sustainability objectives across scales and geographies. While the latter notion of value is often mentioned in foundational CE literature as the motivator, they also highlight the importance of aligning these contributions to environmental sustainability objectives with incentives of direct preference (e.g., monetary benefits) if the objectives of CE are to be materialized (Kirchherr et al., 2017).

Both the beginning- and end-of-life of infrastructure systems are of particular interest for CE interventions. Infrastructure products and buildings depend on high consumption of primary resources, while also generating large amounts of waste (mostly during construction stages, which imply demolition of previous structures, excavation, and material surplus) characterised by its low reuse value and recyclability (Kaza et al., 2018). Existing evidence tends to highlight the linear nature of infrastructure products by focusing on upfront material consumption and waste generation at the end-of-life stages: 40% of natural resource depletion and 25% of global waste are caused by the construction sector, and 35% of all Construction and Demolition (C&D) waste worldwide sent to landfills without proper treatment (United Nations Environment Programme, 2022). These figures ultimately reflect a significant loss of value across the life cycle of infrastructure products, both due to the significant volume of materials disposed without proper management, and the lack of alignment between the use of resources for providing infrastructure products and global environmental objectives and needs.

However, much of the existing discussion around circularity has been centred around the design and production of small-scale consumer products (e.g., electronics, clothing), leaving a mismatch between CE and the infrastructure and construction sectors (Adams et al., 2017; Pomponi and Moncaster, 2017). Thus, there is a need to adapt CE, both conceptually and in practice, to the particular conditions of infrastructure products such as their long and uncertain service lives, unique and integrated designs with highly regulated material specifications, and the tight dependency between adequate performance and maintenance activities (Halpin and Senior, 2011;

Hamilton-Foster, 2014; Gorenstein and Kalech, 2022). These characteristics are key to identifying the most effective strategies for CE implementation for infrastructure products, with the ultimate objective of preserving and enhancing the value provided by infrastructure products at the material, component, and system scales. Indeed, published studies on CE and the built environment, mainly literature reviews, show that existing perspectives on CE for infrastructure focus almost exclusively on circularity understood as waste management (e.g., recycling, recovery), with little to no focus on systemic circularity interventions which have high potential benefits (e.g., lifetime extension, intensification of use) (Joensuu, Edelman and Saari, 2020; Ossio, Salinas and Hernández, 2023). For instance, a systemic circularity intervention in transportation infrastructure is the refurbishment of existing corridors to prioritise modes with more intensive space use such as public transit instead of travel modes with limited capacity for intensification or scaling such as private vehicles (Newman, Beatley and Boyer, 2017). However, this type of intervention is completely overlooked by waste management-focused CE approaches.

The mismatch between the characteristics of infrastructure products and foundational CE frameworks is particularly consequential because of the growing body of policies and regulations to promote CE in the sector (Rios et al., 2022). While circularity is increasingly discussed as a key element of infrastructure management, the study of how it is implemented in policy and practice for infrastructure systems is limited. Based on the existing reviews of the literature and public discussions of CE, there is a risk of CE practice focusing on less effective strategies such as waste management, which could pose challenges and result in missed opportunities for the implementation and operation of new and existing infrastructure products. Academic work on CE policy and strategies for cities across the world currently overlooks the specific context of large infrastructure systems (Petit-Boix and Leipold, 2018; Zhu et al., 2019; Hartley et al., 2023). In parallel, existing work on CE for infrastructure is mostly limited to reviews of academic literature, overlooking CE policy which is increasingly the mechanism through which CE is operationalised for the built environment (Joensuu, Edelman and Saari, 2020; Lei et al., 2021; Yu et al., 2022). Consequently, this chapter investigates urban CE policies to shed light on how circularity concepts are being used in practice for the infrastructure and construction sector, identifying which strategies receive the most attention, and pointing out opportunities for improvement in infrastructure CE practice to align with the baseline goal of value preservation and delivery for these essential systems.

The main objects of interest for this study were large cities in the Americas and Europe, mainly as a result of the author’s language abilities (fluent in English and Spanish) and geographical location, which determine our ability to access and analyze policy documents. Policy reviews indicate that the majority of cities with ongoing public CE initiatives are in Europe and China, due to the long history of sustainability policy and knowledge creation in this region (Petit-Boix and Leipold, 2018; Hartley et al., 2023). In the last 5 years, there has been a growing number of cities in the Americas that are outlining their own CE strategies and policies, presenting a new geography for study. Through the cities selected for this study, I do not seek to provide a complete global landscape of CE efforts. Instead, the objective is to illustrate some of the diverse needs, motivations, resources, and conditions for CE policy and examine which CE strategies are being written into policy for infrastructure products and the construction sector.

4.3. Literature Review

4.3.1. Circular Economy Literature

CE encompasses a broad range of concepts including material efficiency, cradle-to-cradle life cycle assessment, waste reduction and management, and product value retention. The term “circular economy” was coined in 1989 by Pearce and Turner, who pointed out the need to study the economy and its systems not only in terms of the utility or value produced, but the natural resources that are used and disposed in the process (Pearce and Turner, 1989). Others have since discussed related concepts such as the concept of cradle-to-cradle analysis in the field of life cycle assessment (Braungart and McDonough, 2002). More recently, both researchers and policymakers have pointed out the potential of CE as an avenue to achieve sustainability objectives, providing economic prosperity while reducing environmental impacts through reduced resource use and related decarbonisation (Kirchherr, Reike and Hekkert, 2017; Novak et al., 2021; Hartley et al., 2023). Specifically, CE strategies present opportunities for increased material efficiency by: (i) displacing primary material consumption through improved material reuse and recycling (e.g., deconstruction guidelines that facilitate material separation and disposal); (ii) reducing demand by extending the life of existing product stocks, keeping them in use for longer (e.g., refurbishing legacy buildings to avoid their demolition and replacement); (iii) reducing demand for new products through intensified use of existing stock (e.g., ride sharing to reduce overall vehicle demand and production) (Potting et al., 2017).

In a similar way to the concept of sustainability, CE has been defined, interpreted, and implemented in widely different ways, with a recent study identifying 221 definitions of CE that focus on different scales, industries, and operational strategies (Kirchherr et al., 2023). While the definitions are numerous and broad, CE has emerged as an increasingly relevant field in the academic literature, policy, and practice as a promising philosophy to reduce the environmental impact of modern production systems, including the construction sector (Joensuu, Edelman and Saari, 2020).

At its core, the goal of CE is to maximise the value of the goods produced, built, and consumed in society—both in terms of utilisation, and in terms of alignment with broader sustainability efforts. The Ellen MacArthur Foundation describes three principles for CE referred to in both policy and academic literature: (i) eliminate waste and pollution; (ii) circulate products and materials at their highest value; and (iii) regenerate nature (Ellen MacArthur Foundation, 2023). The first principle leans on the closed-system economy concepts of Pearce and Turner, focusing on reducing resource extraction and waste as the main inputs and outputs of societal activity (Pearce and Turner, 1989). The second principle focuses on keeping systems, products, and materials in use for longer, focusing on retaining the value of these products as to avoid the point where resources become “waste”. Finally, the third principle is centred around broadly shifting the focus of economic activity from extraction to regeneration. This encompasses aligning the activities of communities with the natural cycles of their local environment in recognition of the concept of planetary boundaries (Ryberg et al., 2016).

Many frameworks have been proposed to define the core concepts of CE as well as the strategies for its operationalisation. Most existing frameworks refer to strategies that are fundamental for the achievement of CE—usually referred to as “R frameworks” (Kirchherr, Reike and Hekkert, 2017). A well-known example is the 3R framework (i.e., reduce, reuse, recycle), which emerged as part of the North American environmental movement of the 1970s and was later formalised as the integrated waste management hierarchy (El-Haggar, 2007). Others have proposed more granular frameworks, such as: 4R, which adds “recovery” as a strategy to recover energy from waste through composting or incineration (Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives, 2008); 6R, which breaks down “reuse” into different strategies for extending a product life cycle, such as “remanufacture”, “refurbish”, and “repair” (Sihvonen and Ritola, 2015); and 10R, which provides additional strategies for systemic changes in a production process such as “refuse” and “rethink” (Cramer, 2014; Potting et al., 2017). Notably, the 10R framework also classifies CE strategies according to their degree of circularity, with higher circularity strategies generally being associated with less use of natural resources and reduced environmental pressures, all while delivering an equivalent function (Potting et al., 2017). In this chapter, I refer to CE strategies based on the 10R framework, as summarised in Table 1. Note that while Table 1 provides infrastructure examples for all strategies in the 10R framework, the definitions of these strategies do not always match the production systems of construction and infrastructure products. For example, while life extension strategies such as “remanufacture” or “reuse” are well defined and established for consumer products (e.g., by sending a damaged product back to a production facility to be remanufactured), the production processes of infrastructure and construction products can be dramatically different (e.g., with many products constructed and maintained in situ) resulting in a partial alignment at best with the original definitions of the 10R framework.

Table 4.1. Summary of Circular Economy strategy frameworks and principles, with definitions taken from the 10R framework (Cramer, 2014; Potting et al., 2017).

CE principle	3R	6R	10R	Definition	Infrastructure example
Eliminate waste and pollution (i.e., narrow resource flows)	Reduce	Reduce	Refuse (R0)	Make product redundant by abandoning its function or by offering the same function through a radically different product	Refusing development of highways, replacing planned projects with transit expansion (Levinson, 2004)
			Rethink (R1)	Make product use more intensive (e.g., through sharing, or through multi-functional products)	Right-of-way reallocation in streets to promote efficient transit (McCann, 2011)

CE principle	3R	6R	10R	Definition	Infrastructure example
Eliminate waste and pollution (i.e., narrow resource flows)	Reduce	Reduce	Reduce (R2)	Increase efficiency in product manufacture or use, leading to less consumption of natural resources and materials	Best-in-class building design with reduced material requirements (Rankin et al., 2024)
Circulate products and materials at their highest value (i.e., slow resource flows)	Reuse	Repair	Reuse (R3)	Reuse of a discarded product that is still in good condition and fulfils its original function by another consumer	Reusing structural members (e.g., steel beams) from deconstructed buildings in new structures (Fujita and Iwata, 2008)
			Repair (R4)	Repair and maintenance of defective product so it can be used with its original function	Repair water distribution mains that burst or leak (Zuluaga, Saxe and Karney, 2024)
		Refurbish	Refurbish (R5)	Restore an old product and bring it up to date	Refurbishing rail infrastructure including tracks, structure, signals, and stations (Gassner, Lederer and Fellner, 2018)
Eliminate waste and pollution (i.e., close resource loops)	Recycle	Remanufacture	Re-manufacture (R6)	Use parts of discarded product in a new product with the same function	Reusing waste clay bricks recovered during deconstruction or demolition for new projects (Cheng, 2016)
		Recycle	Repurpose (R7)	Use discarded product or its parts in a new product with a different function	Adapt a building set for demolition to be used under a different use (e.g., transform office space into residential units) (Remøy and van der Voordt, 2014)

CE principle	3R	6R	10R	Definition	Infrastructure example
Eliminate waste and pollution (i.e., close resource loops)	Recycle		Recycle (R8)	Process materials to obtain the same (high grade) or lower (low grade) quality	Recycling of ground asphalt for use in new roads (Li et al., 2019)
		Recover	Recover (R9)	Incineration of discarded materials with energy recovery	Incineration unclassified demolition waste for energy recovery or fly ash for use in concrete (Chen et al., 2022)

4.3.2. Circularity for Infrastructure Systems

Common motivations and assumptions in CE literature often fail to capture the nature of infrastructure and construction products (Adams et al., 2017; Pomponi and Moncaster, 2017). Indeed, consumer products have much shorter lifetimes and are often meant to be consumed—a beverage can (a foundational example in LCA and CE literature) is often only “in use” for minutes and has a clear singular function (containing a beverage) with value delivery bounded to its direct use (its storage and dispensing effectiveness) and impact of the product (e.g., consumed material, waste management) (Saxe and Kasraian, 2020). In contrast, infrastructure products deliver value at many levels and scales, ranging from the materials (e.g., by using more efficient materials, or capitalising on locally available resources), energy (e.g., by enabling low-carbon operation or electrification of fossil-fuel based activities), and labour (both for construction and operation) embodied within them to the wide range of activities and services that it enables, with broad spatial, functional, and temporal boundaries (Zuluaga, Karney and Saxe, 2021). For instance, a city-centre road is often integrated with a variety of uses both within (e.g., public transit, active transportation, motor vehicles) and beyond transportation (e.g., commercial and residential land use, integration with green infrastructure, interdependency to surrounding infrastructure such as water and energy distribution). In turn, this variety in use also enables a broad range of value delivered, including accessibility and mobility benefits, both local and global energy and material use with associated

GHG emission, air quality implications, or resilience to climate events (Bart, 2010; Faber et al., 2018).

Published studies rarely explore the overall value delivered by infrastructure, focusing significantly on monetary benefits, and to a lesser extent on the contribution of infrastructure systems towards the achievement of sustainability objectives such as the Sustainable Development Goals (SDGs) (Adshead et al., 2019; Castor, Bacha and Fuso Nerini, 2020). Further, the value delivery of infrastructure extends well beyond individual systems, as it affects the functionality and reliability of interdependent infrastructure systems (Barker et al., 2017; Dong et al., 2020). Thus, there is a need to adapt CE—both conceptually and in practice—to the particular conditions of infrastructure products in order to both promote value preservation and reduce the environmental burdens from these products. Below, I discuss some key characteristics of infrastructure products that challenge dominant approaches to CE: their permanence and ill-defined end of life, the tight relation between infrastructure performance and maintenance, the challenges for material recycling in construction products, and the trade-offs between modularity (a popular design approach promoted in CE literature) and infrastructure durability and resilience.

Infrastructure systems are characterised by their permanence and long operational periods, which often exceed their original design life. While much of the CE literature discusses products that are used, repaired, refurbished, and finally disposed in their entirety (e.g., furniture, clothing), infrastructure systems are often refurbished or replaced slowly and through incremental changes in overall stock (Saxe and Kasraian, 2020). For instance, average replacement rates for pipes in water distribution systems in the United States were estimated as 0.5% of the total pipe stock per year, while transportation infrastructure had a yearly average replacement rate of 1-2% of the overall stock (Wegener, Gnad and Vannahme, 1986; ASCE, 2017). Incremental replacement introduces technological lock-in as new components need to work within the existing system, which can reduce the infrastructure's ability to adapt to changing environmental conditions and functional needs (Markolf et al., 2018). However, extended lifetimes based on incremental replacement also provide opportunities to update components through refurbishment more frequently within the use stage (e.g., replacement of fare systems in public transit that adapt to current technology), as well as opportunities for functionality transformations aimed towards resource use intensification or environmental impact mitigation (e.g., right-of-way reallocation of existing roads). From a CE perspective, the latter is particularly important for the materialisation of significant environmental benefits, as functional changes such as intensification of use (labeled as “reduce” in the 10R framework) are associated with higher circularity and benefits potential than efficiency improvements that do not transform the overall consumption patterns of a product (Potting et al., 2017; Hartley et al., 2023).

The 10R framework also differentiates life extension strategies according to where the intervention happens in the production chain (e.g., repair happens without returning a product to a production facility, whereas refurbishment usually involves a return process and doesn’t guarantee reuse by the same user), which is almost always misaligned with the production processes for infrastructure and construction products which are often constructed, operated and maintained on site. For example, repair and refurbishment of a road both happen on site; thus, distinguishing between the two interventions might be challenging using the definitions of the 10R framework. A more useful distinction could be, for instance, whether there are any functional changes enabled by the maintenance activity (e.g., technological updates, intensified use which implies remanufacturing) or whether the function and technology remain the same after the product has been repaired.

Another key characteristic of infrastructure products is the high importance of maintenance and its relation to adequate system performance. Given the essential nature of infrastructure, and its regular interaction with the open environment, critical systems experience failures and breaks on a regular basis (Gorenstein and Kalech, 2022). In turn, failure events often lead to great resource losses as well as dramatic negative consequences on users and surrounding buildings and infrastructure (Yerri et al., 2017). As such, circularity strategies aimed at “slowing” resource flows (e.g., repair, which restores component functionality without replacing it for a new one) are a key feature of the use phase of infrastructure products. However, because of the scale, complexity, and high resource intensity of maintenance activities in large systems, infrastructure products often face large repair backlogs that compromise the effectiveness of system operation and generate inefficiencies which, in turn, can increase system-level environmental impacts (Rødseth and Schjølberg, 2017). For example, in water distribution networks, lack of regular maintenance activities can lead to serious increases in water losses and energy use associated to incipient leaks (Dziedzic and Karney, 2014). Thus, as shown in Chapter 3, maintenance strategies significantly alter both the risk and consequences of unexpected disruptive events such as pipe breaks for both operators and users (Zuluaga, Saxe and Karney, 2024). Given the high importance of maintenance for adequate infrastructure performance, circularity strategies for infrastructure should explicitly consider high standards of maintenance as a key objective of repair and maintenance interventions and policies.

At the end-of-life stage, the idea of closed loop recycling is one of the best-known CE approaches (e.g., the aluminum from a soda container is reused to make a new soda container). This approach, however, is widely discussed outside considerations of mass balance (e.g. increases or decreases in the quantity of soda manufactured). For construction products, the balance (or lack thereof) between the potential supply of end-of-life materials and the demand for primary materials for new infrastructure is particularly important. On the one hand, there is a continued need for investment in new infrastructure globally due to population growth and gaps in current infrastructure provision. By 2040, yearly global investments in infrastructure are projected to reach between $3.8 and $4.6 trillion USD, beyond current levels of investment and activity (Oxford Economics, 2017). This demand for infrastructure, in turn, implies a large demand for primary materials for new construction (Hertwich et al., 2019; Masanet et al., 2021). On the other hand, infrastructure products have particularly low replacement rates, with many components being used beyond their original design lives. Growing urban settings, where infrastructure and construction activities are deemed to increase in scale to respond to population growth, usually have dramatic imbalances between overall demand for primary materials for new construction and generation of secondary materials from deconstruction or demolition. For instance, the City of Toronto estimated a yearly consumption of 17 million tonnes of materials for construction in 2018, which is over 40 times larger than the estimated 350 thousand tonnes of C&D waste generated that same year (City of Toronto, 2021). In these contexts, there is a limited potential to meaningfully displace material demand through increased secondary material production, even under ideal recycling conditions (Song et al., 2023). Thus, while recycling plays an important role in waste management, it is often severely constrained as a pathway to reduce primary material use by overall growth patterns and material flows, limiting its potential to address key environmental impacts such as embodied GHG emissions (Song et al., 2023).

Some popular CE approaches can break down within the highly integrated nature of infrastructure systems. CE reports generally call for modular design as a key facilitator of life extension strategies (e.g., repair, refurbish, remanufacture) (Kyrö, Jylhä and Peltokorpi, 2019). Modularity is generally associated with easier maintenance, disassembly, and reuse, while also reducing the complexity of material recovery processes which can be complex for products with highly integrated designs

(Baldwin and Clark, 2006). However, there are considerations for modularity in infrastructure networks not often mentioned in CE literature, such as the trade-off between the modularity and the durability of products, or the relation between modularity and system resilience. Recent literature has pointed out that modular design can be at odds with the robustness provided by integrated design, as modularity often comes at the cost of efficiency in component integration (Jaeger-Erben, Proske and Hielscher, 2023). Indeed, existing infrastructure systems are often designed with rigid designs focused on robustness and failure-resistance, features often achieved through unique and integrated designs (Helmrich et al., 2021). Thus, CE interventions for existing systems must pay close attention not to compromise the reliability or efficiency of the system through the addition of modularity in existing systems. Without a careful consideration of these consequences, modularity in infrastructure products could result in increased disruptions and increased physical losses, which would in turn result in more C&D waste after failure events. In contrast, modularity has been identified as a key characteristic to improve the resilience of new infrastructure systems, as it distributes the risk of system failure and increased capabilities for adaptation to unforeseen events when coupled with proper governance and management structures (Helmrich et al., 2021).

Finally, the refusal (R0 in the 10R framework) of inefficient or highly environmentally damaging infrastructure should also be considered as an avenue for achieving sustainability objectives. As previously mentioned, there is a significant need for increased infrastructure spending globally to support and enable population growth, improvements in quality of life, and technological transitions across the world (Oxford Economics, 2017). However, there is a concurrent need to move away from inefficient and resource-intensive infrastructure (e.g., car-centric highways, fossil fuel-based energy production) in cases where there are alternatives that provide a more intensive use of materials and energy (e.g., rail transit, renewable energy production) (Levinson, 2004). In this sense, refusal strategies for infrastructure production should recognize the need for increased investment, but clearly identify the objectives and function provided by the systems so that the most effective solutions can be put in place. Further, it is key to provide enablers for inefficient infrastructure refusal such as improved land use regulation that facilitates increased housing density and prioritization of public transit, or incentives for renewable energy that facilitate their adoption in regions that still rely on fossil fuels for energy production.

4.3.3. Circular Economy Policymaking

CE is increasingly operationalised through government-led policymaking, and there is now a growing body of policies and regulations that promote CE (Kirchherr et al., 2023). Recent studies reviewing CE policies at the national or regional level (e.g., Europe and China) find that most existing CE policies pre-emptively focus on lower levels of circularity (e.g., recycling), designing policies that adapt to current resource use patterns instead of questioning more substantial changes in consumption practices (e.g., demand reductions through more intensive use of existing infrastructure) (Zhu et al., 2019; Hartley et al., 2023). Studies of CE at the city level reveal that while cities are hotspots of resource use, they have a limited ability to regulate whole value chains making foundational transformations difficult at this scale, while also calling for studies on sector-specific (e.g., construction) policies (Petit-Boix and Leipold, 2018; Prendeville, Cherim and Bocken, 2018; Campbell-Johnston et al., 2019).

Existing literature on CE for the built environment and the construction sector is recent and mainly comprised by literature reviews and theoretical frameworks that provide a conceptual base for CE thinking in the sector and have not yet analyzed existing CE policies being proposed and used for construction and infrastructure products. Emerging studies on CE for the built environment echo the findings of broader CE literature reviews, that most of the existing academic literature has focused on low-level circularity strategies such as recycling and waste management improvements, as well as noting a gap in studies of CE policy for the built environment (Joensuu, Edelman and Saari, 2020; Rios et al., 2022; Ossio, Salinas and Hernández, 2023). A recent review by Yu et al. (2022) studies the implementation of CE concepts in the construction industry from a policy-making perspective, providing a framework of CE policy-making stages for the construction industry and highlighting the importance of integrating different CE policies to overcome sectoral barriers (Yu et al., 2022). However, while the study by Yu et al. provides a policy-oriented framework for literature classification, it does not review existing CE policies being put in place for the construction sector, instead providing a framing for CE policy (Yu et al., 2022). This is the gap this chapter seeks to fill by analyzing current urban CE policies for the infrastructure and construction sector, examining which CE strategies are being used or overlooked in current policy and identifying opportunities for improvement given the value implications and features of infrastructure products discussed above.

4.4. Methods

To examine infrastructure current urban CE policies, I performed a documentary analysis of CE policy documents for construction and infrastructure products (e.g., CE strategy documents, regulatory guidance for developers) from 6 large cities in the Americas and Europe. The policy documents were analyzed for the main motivations, strategies, and objectives of the municipal governments for the sampled cities regarding CE for infrastructure systems and the built environment.

4.4.1. City Selection

Based on population rankings published by the United Nations for urban agglomerations, I selected the cities with highest population as of 2020 in Europe and the Americas from an initial list of 622 cities across 56 countries (United Nations, 2019). From these 622 cities, the list was further narrowed by selecting cities with a publicly published CE strategy or policy framework. Ultimately, I selected the top three cities for each region in the population rankings with publicly available CE policy documents (New York City, Toronto and Santiago in the Americas, and Paris, London, and Amsterdam from Europe). Amsterdam, Netherlands was also added to the list as it is a world leader in CE where most of the existing frameworks have been developed and can provide a perspective of current “best” practices, as it was regularly referenced in the policy documents of the other cities. The final list of 6 cities, their population, and reviewed policy documents are shown in Table 2.

Although the city selection process was done based on population rankings at the urban agglomeration level, which is a functional definition of urban boundaries (i.e., based on density thresholds), the CE policy documents referenced in Table 1 are often produced based on administrative boundaries, and thus rely on administrative definitions of ‘city’ (e.g., city proper, greater metropolitan area). While urban agglomerations are recommended as an ideal scope for population comparison, policy documents are inevitably a result of administrative arrangements. In ranking cities by their population at the urban agglomeration level, I sought to identify large cities since they tend to have the most administrative capacity to tackle and develop a variety of CE policy motivations, priorities, and currently envisioned strategies. This study does not seek to compare the selected cities through specific boundary-dependent metrics, since this would require a consistent spatial scope and the selected cities have different approaches to governance and administrative boundaries. For example, while the City of Toronto bases its CE documents based on administrative boundaries which exclude many conjoining suburbs of the Greater Metropolitan Area, the City of Paris proposes a CE approach at the metropolitan level, with different municipalities collaborating towards the region’s CE efforts.

Table 4.2. Final selection of cities and policy documents used for this study.

City	Country	Population of urban agglomeration in 2020, in thousands (United Nations, 2019)	CE policy document references
Amsterdam	Netherlands	1,149	(City of Amsterdam, 2020)
London	United Kingdom	9,304	(Greater London Authority, 2022)
New York City	United States	18,804	(van Heel et al., 2022; New York City Economic Development Corporation, 2024)
Paris	France	11,017	(Mairie de Paris, 2017; CitéSource et al., 2022)
Santiago	Chile	6,767	(Gobierno de Chile, 2020)
Toronto	Canada	6,197	(City of Toronto, 2021)

4.4.2. Policy Content Analysis

This study assessed CE policies for the selected cities listed in Table 1 through a complementary approach to documentary coding analysis: qualitative coding was used to analyze the content of the policy documents, and quantitative metrics of term frequency were calculated using Natural Language Processing (NLP).

The qualitative coding of CE policy documents investigated and classified CE initiatives proposed in each of the policy documents based on the 10R framework of circularity strategies (Cramer, 2014; Potting et al., 2017). The qualitative documentary analysis consists of four key steps:

1. **City characterisation:** First, I coded attributes related to the local context as explained in each of the analyzed policy documents. Some examples include population trends, the current regulatory environment around CE initiatives, as well as context on current infrastructure stock and needs.

2. **Motivation for CE implementation:** I coded each document for explicit uses of the term "objective", as well as related terms (e.g., "goals", "purpose", "ambitions") and implicit objectives mentioned in each document. This coding provides information about the key priorities behind the development of CE policy in each city, while also providing context on related sustainability objectives such as decarbonisation or waste reduction goals.

3. **Definition and scope of value and circularity**: I coded each document for explicit uses of the term "value", as well as related terminology (e.g., "benefits", "utility", "worth"). The goal of this step is to examine the definition and assumptions of value (both as an outcome and as strategies) for each city's CE policy documents. Additionally, I coded the definitions of circularity for each document and associated criteria for measurement, if any.

4. **Classification of CE strategies:** For this step of the coding process, I classified all of the proposed CE policies related to the construction sector and infrastructure products based on the 10R framework (Cramer, 2014; Potting et al., 2017). This coding is used to calculate the distribution and proportion of proposed strategies that fall in each of the 10R strategies.

For the quantitative term frequency analysis, the plain text for all policy documents was extracted and coded in a Python environment using the Natural Language Toolkit package (Bird, Klein and Loper, 2009). All analyzed policy documents underwent word- and sentence-level tokenisation and stemming to obtain word and sentence sets for each document. Then, the relative term frequencies of each of the 10R framework strategy terms within the token sets for each document and city was calculated.

Given that the policy documents were written in three different languages (English, French, and Spanish), all the terms in the 10R strategy had to be translated to quantify the term frequency in non-English documents. To do so, the English terms were translated into Spanish and French as shown in Table 4.3. Further, synonyms were checked in Spanish and French to ensure the inclusion of related terms that might not fall under the original translation. For instance, the term "remanufacture" is translated into French as "reconditionner"; however, the term "réusinage" is also used in Paris's policy documents to refer to remanufacture activities, and so was also counted for the term frequency. Further, through the process of stemming, related conjugations such as "reconditionnement" in the previous example were also included in the term frequency calculations.

Table 4.3. Translation of 10R Framework strategy terms from English into Spanish and French.

10R framework strategies	**Spanish translation**	**French translation**
Refuse	Rechazar	Refuser
Rethink	Repensar	Repenser
Reduce	Reducir	Réduire
Reuse	Reusar	Réutiliser
Repair	Reparar	Réparer
Refurbish	Restaurar	Restaurer
Remanufacture	Remanufacturar	Reconditionner
Repurpose	Reutilizar	Réutiliser
Recycle	Reciclar	Recycler
Recover	Recuperar	Récupérer

4.5. Results and Discussion

The documentary analysis revealed a variety of motivations, perspectives on value and circularity, and proposed CE strategies to tackle the particular challenges in each of the selected cities; a summary of the main results is presented in Table 3.

Table 4.4. Summary of value and circularity perspectives of CE policy for the built environment in selected cities.

City	Value perspectives	Circularity perspectives
Amsterdam	Opportunity for monetary value capture through recovery and recycling of C&D waste	Building with fewer materials
	Promote assessment of total cost of ownership and use throughout the product's life cycle (LCC)	Building with reused materials
	Promote reuse and repurposing of existing buildings and infrastructure where possible to preserve value as embodied carbon, energy, and labour	Adaptive and modular construction
London	Opportunity for monetary value capture through recovery and recycling of C&D waste	Building in layers Designing out waste Designing for longevity
	Promote reuse and repurposing of existing buildings and infrastructure where possible to preserve value as embodied carbon, energy, and labour	Designing for adaptability and/or flexibility Designing for disassembly Using components or materials that can be recycled
New York City	Opportunity for monetary value capture through recovery and recycling of C&D waste Promote reuse and repurposing of existing buildings and infrastructure where possible to preserve value as embodied carbon, energy, and labour	Build only what is necessary Build with recyclable, low-carbon materials Build efficiently (in design and process) Build for long-term value (longevity, adaptability)
Paris	Opportunity for monetary value capture through recovery and recycling of C&D waste	Promote recovery of materials in buildings and linear infrastructure Develop an inter-departmental material exchange platform

City	Value perspectives	Circularity perspectives
Santiago	Opportunity for monetary value capture through recovery and recycling of C&D waste	Promote modularity in building construction and use
		Promote reversible and dismantling-ready design
	Promote assessment of total cost of ownership and use throughout the product’s life cycle (LCC)	Extend the lifetime of existing buildings through maintenance, repair, retrofit, etc.
		Promote better material data practices to facilitate material reuse and recycling
Toronto	Opportunity for monetary value capture through recovery and recycling of C&D waste	Design for longevity
		Design for adaptability and modularity
		Design for simple, standardised maintenance
		Design for simple repurposing

Firstly, the cities report high volumes of consumed materials and C&D waste as a motivation for CE efforts. For instance, Paris reports a yearly material consumption for construction activities of approximately 13 million tonnes, around 7 million tonnes of waste, and 13 million tonnes of excavated soil (Mairie de Paris, 2017). While the magnitude of material consumption and waste generation is similar in dense, established cities like Paris, cities with lower levels of density but subject to significant growth such as Toronto exhibit a significantly higher imbalance between the mass of materials consumed (around 17 million tonnes per year) and generated C&D waste (around 350 thousand tonnes per year) (City of Toronto, 2021). Regardless of their different material balances, all six cities in the present sample explicitly tied their CE objectives to their ambitions for reduced material consumption and waste generation.

Targets associated with material consumption and waste generation reductions vary across the sampled cities. One on end of the spectrum, there are overall demand reduction targets in

Amsterdam’s CE policy reports, which call for the city to achieve “100% circularity” by 2050, with an intermediate target of 50% by 2030 (City of Amsterdam, 2020). Here, “circularity” is measured as the share of primary raw materials out of the total material consumed in the city. In contrast, other cities in the sample define targets based on current levels of generated C&D waste by setting minimum rates of waste diversion, which are not explicitly tied to primary material consumption. For instance, Paris has set the goal to recycle 70% of C&D waste by 2020; New York City has a goal of diverting 75% of C&D waste sent to landfill by 2030; and London has a goal of achieving 95% recycling rates for C&D waste by 2020 (Mairie de Paris, 2017; New York City Economic Development Corporation, 2024). Finally, the CE policy guidance documents for Santiago define its circularity objectives in terms of CE policy and criteria inclusion in construction projects, by setting a goal of having 50% of new buildings and infrastructure projects be accredited for inclusion of circularity criteria or attributes, or 80% of transportation infrastructure having some percentage of secondary material use (Gobierno de Chile, 2020).

Another notable objective is the implementation of proper accounting and reporting of material use and C&D waste generation, with most cities citing a major gap in the availability and quality of data. For instance, CE policy for the City of Santiago highlights the challenge of implementing circular strategies given the existence of illegal disposal facilities for C&D waste, which lead to a low share (20-30%) of C&D waste in the city being reported and accounted for (Gobierno de Chile, 2020). Other cities such as Toronto also explicitly included data transparency as part of their goals for CE in the sector, noting that better tracking of consumed and disposed materials facilitates reuse and recycling markets, as well as allowing for more accurate estimates on embodied GHG emissions from the construction sector (City of Toronto, 2021).

The analyzed CE policies also presented a variety of circularity perspectives, ranging in focus from waste management (low circularity) to refusal of construction products where possible (high circularity). For example, Paris focuses its circularity efforts on recycling, with all of its circularity objectives for the construction sector focused on the recycling and recovery of materials (R8 and R9 in the 10Rs) (Mairie de Paris, 2017; CitéSource et al., 2022). Further, the city has created a digital platform for material exchange to facilitate the redistribution and resulting recycling and recovery of C&D materials and waste, based on a detailed spatial investigation of projected locations for new developments and existing buildings that are expected to undergo retrofitting or major refurbishments (Mairie de Paris, 2017; CitéSource et al., 2022). In contrast, London refuses building demolition in cases where it is technically feasible to retain or retrofit (R0 and R5 in the 10Rs) an existing development, requiring developers to consider refurbishment of existing buildings before proposing new construction activities (Greater London Authority, 2022). For new buildings and infrastructure, London requires proposals to justify and consider future changes in use for the product and to incorporate adaptability by "design[ing] with thought of how it might be easily altered to prolong its life, for instance by alteration, addition, or contraction, to suit new uses or patterns of use" (with change of use considerations being elements of R1 and R7 in the 10Rs) (Greater London Authority, 2022). While other cities like New York City and Amsterdam also mention prioritising retrofit and refurbishment activities, they do not provide explicit requirements such as those developed by the City of London. Finally, Toronto and London were the only cities to highlight maintenance and repurposing (R4 and R7 in the 10Rs) as key CE objectives in their respective policies, with Toronto promoting modular designs as a key feature of new buildings and infrastructure to facilitate component replacement and life extension efforts (City of Toronto, 2021; Greater London Authority, 2022).

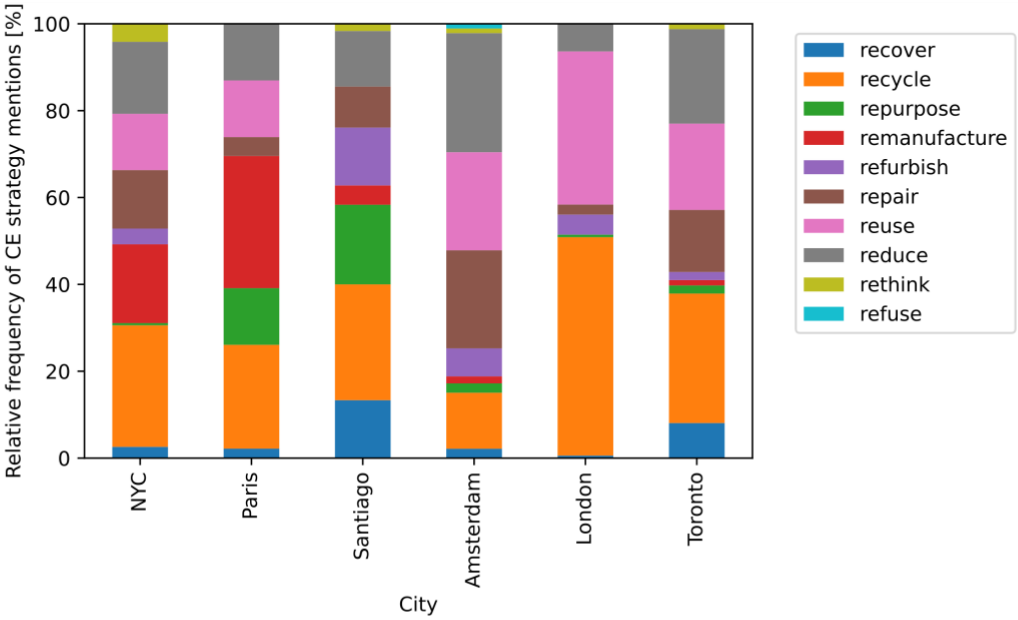

Figure 4.1. Relative frequency of identified mentions for each of the 10 strategies in the 10R framework (Cramer, 2014; Potting et al., 2017) in the policy documents for all sampled cities.

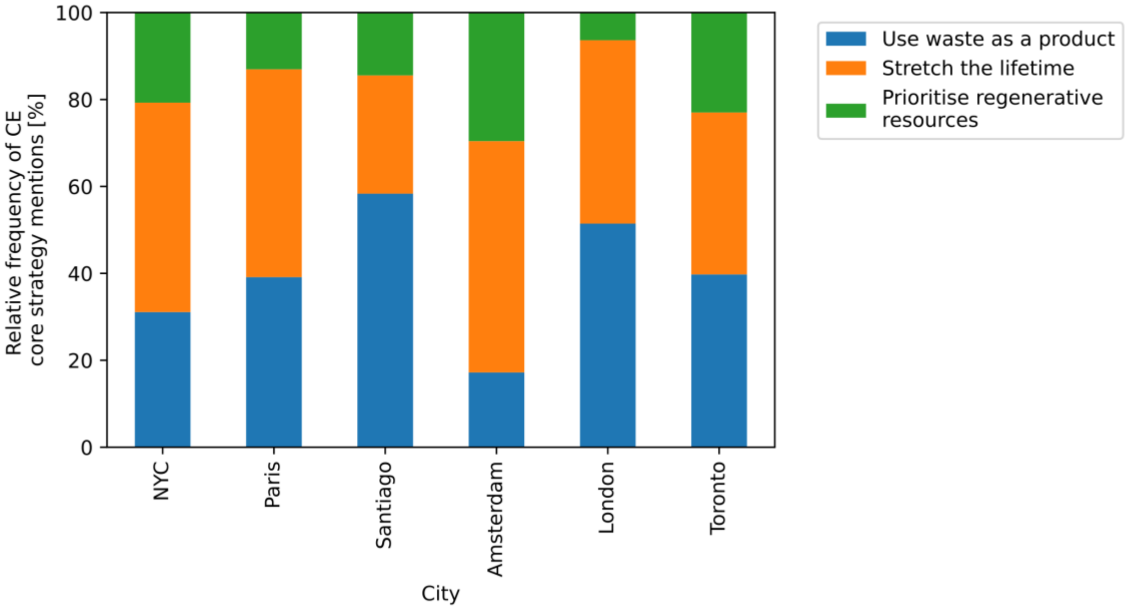

Figure 4.2. Relative frequency of identified mentions for each of the core CE principles for all sampled cities as defined by the Ellen MacArthur Foundation and classified in the 10R framework (Cramer, 2014; Potting et al., 2017; Ellen MacArthur Foundation, 2023).

Figures 4.1 and 4.2 show the relative frequencies of mentioned circularity strategies from the 10R in each of the selected cities' CE policy documents, as well as the distribution of mentions across the three CE principles stated by the Ellen MacArthur Foundation (Cramer, 2014; Potting et al., 2017; Ellen MacArthur Foundation, 2023). The distribution of mentions reveals a consistent and frequent use of recycling (R8) across the sampled city policies, with London being the city that most frequently mentioned this strategy. Interestingly, an analysis of the "recycle" mentions coded for London's CE policy reveals that the strategy's frequent mentions result from a detailed description of the steps developers should follow to demonstrate recycling planning for their proposed activities, as well as a step-by-step methodology with examples for calculating recycled contents by mass and monetary value (Greater London Authority, 2022). Even though less than 10% of mentions for 10R strategies in London's CE policy focus on the principle of "prioritising regenerative resources", London's CE policies set ambitious and strong regulations for refusing new construction and maximising the retention of materials and components from existing buildings with an explicit focus on avoiding the replacement of carbon-intensive components such as building substructures (Greater London Authority, 2022).

Figure 2 also reveals that Amsterdam and Toronto are the cities in the sample with the highest proportion of mentions for high-circularity strategies based on the principle of “prioritising regenerative “resources". Within this group of strategies, “reduce” (R2) is the most frequent term, with “rethink” (R1) and “refuse” (R0) having almost no mentions in any of the analyzed policy documents. Upon closer inspection, “reduce” mentions in both cities’ CE policy is mostly a result of reiterating the objective of reducing the environmental impact of buildings and infrastructure products by reducing the amount of primary materials that are consumed for their production and maintenance (City of Amsterdam, 2020; City of Toronto, 2021). However, most of the objectives these cities have set out for primary material reduction are based on increasing the use of recycled materials in the sector, which does not necessarily guarantee reductions in primary material consumption, particularly for cities like Toronto which face pressures to increase its supply of buildings and infrastructure as a result of its rapid growth. As mentioned previously, Toronto reports a consumption of around 17 million tonnes of materials for construction annually, compared to 350,000 tonnes of C&D waste generated per year (City of Toronto, 2021). Even under ideal conditions for recycling, this strategy would displace less than 5% of the total mass of primary material demanded for construction activities in the city. In contrast, policy aimed at refusing new construction products where possible (e.g., promoting retrofitting for intensification of use in existing buildings) could be used to reduce the demand for new buildings and infrastructure, which translates into reduced material consumption and embodied carbon needs. Consequently, future CE policy should account for the overall balance and patterns of their building and infrastructure stocks, as they are key determinants of overall demand for new construction and replacement, and thus strongly influence the effectiveness of different strategies for CE implementation.

4.5.1. Current Value Perspectives in CE Policy for Buildings and Infrastructure

The documentary analysis also revealed different definitions and perspectives on value preservation and generation across the selected cities. The most frequent scope of value was the recognition of the economic value of C&D waste, which could be captured through low-level circularity strategies like recycling. While this perspective is clearly identified throughout the analyzed CE policies, some of them have pointed out limitations in this perspective—for instance, Toronto’s CE roadmap highlights that markets for secondary materials have historically resulted in higher prices for recycled materials compared to raw primary materials, which also benefit from more structured and robust supply (City of Toronto, 2021). Two of the analyzed cities (Santiago and Amsterdam) explicitly set goals for value assessments beyond material recovery in their CE policy, mentioning the need for new value assessments for infrastructure and buildings that consider the total cost of ownership and use throughout the product’s life cycle, as well as highlighting the importance of considering monetary value preservation not only at the end-of-life stage, but also at the design, construction, and operating stages (City of Amsterdam, 2020; Gobierno de Chile, 2020). However, current CE policy documents for these cities do not provide more detail about the importance of maintenance in infrastructure operation, which also plays a key role in preventing inefficient performance and increased resource use (e.g., energy inefficiencies, water losses), or failure events, which can induce significant infrastructure repair and replacement activities and associated material consumption.

Half of the selected cities (New York, London, and Amsterdam) included perspectives on value beyond the monetary. For instance, the City of New York highlights the importance of reusing and adapting existing buildings and infrastructure as much as possible to meet future needs given the loss in embodied carbon, energy, and labour associated to demolition and replacement activities, which also increases the need for primary materials (New York City Economic Development Corporation, 2024). As a result, CE policy in New York City has set minimum a minimum share of 25% of “low carbon” materials in all of their capital projects in addition to minimum recycling standards (New York City Economic Development Corporation, 2024). However, only Amsterdam and London translated these needs into specific policy objectives, with both cities prioritising the reuse or adaptation of existing buildings and infrastructure to meet future demand before resorting to new products (City of Amsterdam, 2020; Greater London Authority, 2022). In its CE statements, the Greater London Authority further highlights the need to consider “environmental value” preservation by requiring that all new developments be designed with considerations for adaptability at their end-of-life, which could facilitate the preservation of materials with high carbon intensity, or other associated environmental impacts such as intensive water use, water contamination, or highly constrained waste management requirements that make recycling or disposal challenging (Greater London Authority, 2022). The CE policy in London puts decarbonisation at the forefront of their CE initiatives for construction products, specifying that “the promotion of CE outcomes should also reduce the [Whole Life Carbon, or WLC] of the development, or provide additional benefits beyond the development’s life” (Greater London Authority, 2022).

Interestingly, the CE policies analyzed were heavily focused on improving the design characteristics (e.g., modularity, recycled content) and construction processes for new systems rather than evaluating the potential for existing systems to satisfy building and infrastructure demand. While including circular criteria in future construction activities is certainly beneficial and important to reducing the negative impacts of the sector, currently proposed CE policy would be insufficient if other drivers of development are not accounted for, as is the case of growth and the current supply of buildings and infrastructure in the region. For instance, while Paris provides a detailed examination of the necessary logistics for secondary material exchange using future projections of expected construction activity, it does not explore whether the existing housing and infrastructure stocks are able to satisfy demand, which would potentially inform policy centred around life extension of existing stock or call for repurposing that allows for more intensive use of existing structures. For example, refurbishment of existing rail infrastructure has been estimated to preserve up to 75% of the material stock of the system, while providing lifetime extension of most materials well beyond their original intended life and keeping the use of raw primary materials below 40% of the total material requirements (Gassner, Lederer and Fellner, 2018).

4.5.2. Towards Higher-Order Circularity and Value Delivery in Infrastructure

Indeed, effective circularity interventions for existing infrastructure and construction products are often different than those for new products. While reductions in primary material use (e.g., through recycling or more efficient designs) are more relevant in the context of new construction which is highly material intensive, these strategies do not tackle the challenges of preserving the value of existing buildings and infrastructure. In contrast, life extension strategies such as refurbishment (e.g., retrofitting buildings to improve operational performance) and rethinking (e.g., subdividing an existing residential dwelling to increase housing supply, reallocating right-of-way in roads and streets) can help preserve the value delivery of existing systems. While this distinction is not yet made clearly in the CE policy objectives of most sampled cities, it will play a key role in the successful implementation of CE efforts for the sector.

Infrastructure products do not only hold value at the material level but are enablers of broader patterns of consumption and development. Transportation infrastructure, for instance, has been shown to affect land use and consumption patterns (e.g., housing density, accessibility to services and employment) which in turn lead to different environmental outcomes (Burchfield et al., 2006; Kasraian et al., 2016). Consequently, CE policy for infrastructure products should pay particular attention to the indirect and induced impacts associated to its use, unlike other products (e.g., consumer goods) with more bounded direct impacts during their use phase, thinking which is currently entirely absent in the examined policies. The enabling and essential nature of infrastructure systems implies that these systems have a strong, profound influence on the consumption patterns and choices of users, and thus could be used as essential enablers of higher order circularity in the products and activities that depend on them by rethinking, reducing, and refusing activities that rely on linear consumption patterns with significant impacts on the environment.

Finally, it is critical to note that circularity interventions and policies need to be tailored depending on the scale and the context of the region for which they are being developed. As mentioned previously, cities facing significant or sustained growth will likely have a growing material and infrastructure stock with many new buildings and systems being constructed, which increases the relevance and potential of high-order circularity interventions (e.g., rethink to increase intensity of use in new products, refuse to avoid the development and lock-in of inefficient systems) but also reduces the potential effectiveness of end-of-life interventions (e.g., recycling, material recovery). Further, cities with significant amounts of legacy buildings and infrastructure (e.g., Paris, London) have particular potential for interventions to existing stock, both in terms of life extension which can reduce overall demand for new systems, and of technological and functional updating through refurbishment, which can help increase the value delivered by existing systems while reducing their environmental footprint compared to product replacement (e.g., insulation improvements in old buildings to enhance thermal performance) (Schwartz et al., 2022). In contrast, life extension policies will have a more limited impact in developing cities where buildings and infrastructure have not operated for long periods. In developing cities, CE policies centered around efficient and intensive design and land use are likely to have a much more significant effect on reducing the overall environmental burden of infrastructure and building provision.

4.6. Conclusions and Recommendations

Construction products such as buildings and infrastructure systems will continue to be main drivers of resource consumption across the world, and consequently play a key role in the achievement (or not) of a Circular Economy. However, most foundational literature on circularity has been centred around the design and production of goods that do not match key characteristics of infrastructure and construction products. This study helps to bridge this gap by providing a novel discussion of CE strategies for infrastructure products, using value preservation as a lens to explore the implications of key infrastructure characteristics such as their long operating lives, lack of a defined end-of-life, and dependence on maintenance for proper performance. Additionally, this chapter examines current urban CE policies for infrastructure products and the construction sector in six large cities in the Americas and Europe, studying how cities are using circularity strategies to preserve the value of their existing infrastructure and enhance the value of new buildings and infrastructure. This exploration of existing CE policy for cities in different regions advances the understanding of the ways CE concepts are being operationalised and helps to identify opportunities for improvement that could aid in the delivery of value from the built environment through circularity.

The results from the documentary analysis of CE policy show that the sampled cities, which were selected as examples of large cities in their corresponding regions, predominantly centre their CE policy for buildings and infrastructure on the recycling of C&D waste and formation of markets for secondary construction materials, implicitly focusing on value capture at the material level. However, our analysis reveals that only a few cities in the sample set policy aimed at higher levels of circularity and such as refusal of new construction and focusing on the life extension of existing infrastructure, which delivers significant systemic value. Further, there is a disconnect between the urban metabolism of some cities and current CE policy goals. For instance, Toronto's CE policy is shown to be primarily focused on waste management strategies, even though the yearly primary material consumption is estimated to be over 40 times higher than the mass of C&D waste generated the rapid growth of the city. This imbalance in overall material flows severely limits the potential impact of recycling for reducing primary material consumption and associated GHG emissions and environmental impacts.

The connections between the value of infrastructure and the circular economy are still mostly unexplored and limited to the monetary recovery of construction materials, instead of adopting a more holistic view of the broader sustainability benefits of implementing CE principles in the built environment such as overall demand reduction. Some of the main research opportunities on the topic of circularity and value preservation for infrastructure systems include:

- Studying the effect of circularity strategies in the sector for particular environmental outcomes (e.g., GHG emission reductions, water withdrawal), as they could become useful evidence to guide policy adjustments for CE in the built environment.
- An evaluation of the effects of current policy on overall consumption patterns, which would provide a useful evidence base to evaluate current CE policies and determine whether they are leading to the desired improvements in terms of overall material consumption, waste management, and their associated environmental impacts.
- While this study focuses on the materiality of infrastructure and construction products (e.g., product lifetimes, durability, resource intensity), it is critical to study the social and governance structures that shape infrastructure performance (i.e., infrastructure as socio-technical systems), since they add internal complexity and consequently play a significant role in facilitating or inhibiting CE implementation in different regions.

Further, some of the recommendations for existing CE policy for infrastructure and construction products include:

- Consider the role and potential of existing systems to address overall service demand. This study shows that current urban CE policies are heavily focused on improving the design characteristics (e.g., modularity, recycled content) and construction processes for new systems, which leaves out the considerable stock of buildings and infrastructure that is already in place. Existing systems hold high potential for overall demand reduction through life extension and intensified use and will inevitably play a role in the future urban metabolism of cities.

- Consider the specific metabolism of cities when prioritizing the implementation of CE strategies. While the magnitude of material consumption and waste generation is similar in dense, established cities providing potential to low-level CE strategies (e.g., recycling), municipalities facing significant growth exhibit imbalances between the mass of materials consumed and generated C&D waste that call for higher-level strategies (e.g., infrastructure lifetime extension, design improvements for new systems).

- Integrate CE policy with sectoral infrastructure strategies (e.g., transit planning) to leverage the indirect and induced value associated to infrastructure use that goes beyond the product level (e.g., induced demand, impact on travel patterns, impacts on overall durability of materials and components) key to unlocking high-level circularity for these products.

Infrastructure systems are essential technological systems and a key enabler of value, providing essential services ranging from shelter and clean water to key economic drivers such as energy and transportation of people and goods. As such, they play a defining role in achieving the ultimate goal of CE: to preserve and maximise the value of produced, built, and consumed goods, and to align economic activity with planetary boundaries and broader sustainability objectives. In turn, effective policymaking must leverage the potential of infrastructure systems to enable a transition towards CE, or we risk undermining the fundamental goal of transitioning to a more sustainable, circular society.

Chapter 5
Overall Conclusions and Recommendations for Future Work

5.1. Research Contributions and Key Conclusions

This dissertation bridges several gaps in the literature of value and multi-criteria sustainability assessment for infrastructure systems through three main research avenues: (i) providing a conceptual framework for value in *academic literature*; (ii) exploring how value is integrated in long-term *computational modelling* and multi-criteria decision-making for water distribution networks; and (iii) exploring the value challenges, opportunities, and perspectives embedded in current *urban infrastructure policy,* namely, Circular Economy strategies for large cities. The main contributions and conclusions of these three avenues of work are:

- **The way 'value' is understood across the infrastructure literature is diverse, a reality that results in disparate conversations regarding the impacts and performance of infrastructure projects**. Chapter 2 illustrates that the notion of value as a magnitude of direct preference is the most prevalent throughout the different dimensions of sustainability. However, such notion of value has problematic implications regarding the aggregation and direct comparison of benefits and impacts that are not readily interchangeable. Further, such an approach tends to exclude relevant impacts that are not readily quantifiable. Other studies measure the value of infrastructure projects from the perspective of contribution to collective or external goals, recognising that some aspects of preference go beyond the preference of individual stakeholders, and result from more complex relationships between collectives. Two additional notions of value—namely, as an evaluation of priorities and contextual relations between communities and their environment—are rarely present in existing studies of large infrastructure systems. This has implications on the ways collective preference for infrastructure projects is assessed; namely, it tends to ignore historical relationships between communities and their traditions, and rarely examines the priorities of different groups of stakeholders.

- **Chapter 3 provides a novel methodology to assess multidimensional values for long-term maintenance decisions for infrastructure networks.** More specifically, this research introduces a dynamic computational model for pipe maintenance that accounts for the uncertain nature of WDN operation and its multidimensional impacts. By incorporating relevant operational components such as burst detection, pipe isolation and repair, and allowing for combinations of both repairs and replacements under uncertainty, the modelling approach in this study provides an improved assessment methodology of pipe failure compared to static maintenance models. This approach provides an alternative analysis framework for this multicriteria problem, challenging the notion of optimality and common assumptions about stakeholder values (i.e., priorities), overcoming the drawbacks of value aggregation and fungibility.

- **The results from the WDN example in Chapter 3 highlight the significant role of pipe replacement in the reduction of failure and disruption risk**. This research shows that favoring replacement over repair activities can lead to significant improvements in global service, environmental (as measured through water losses), and monetary outcomes. However, whereas multidimensional performance metrics help improve our understanding of the impacts of maintenance activities, they do not provide a global perception of value across system stakeholders. Chapter 3 shows how different perspectives on the results of the illustrative example can lead to maintenance strategies that prioritise the impacts borne by one stakeholder over another (e.g., the network operator) without considering disruptions on service and interdependent systems that are perceived by users and broader society.

- **Chapter 4 provides a novel discussion of Circular Economy strategies for the conditions of infrastructure products, using value preservation as a lens to explore the implications of key infrastructure characteristics.** This research explores several challenges for circularity in infrastructure products: (i) the long and ill-defined lives of infrastructure products; (ii) the dependency between infrastructure maintenance, safety, and adequate performance; (iii) the balance (or lack thereof) between the potential supply of end-of-life materials and the demand for primary materials for new infrastructure; (iv) and the trade-off between modularity and durability at the system level.

- **Chapter 4 performs a novel documentary analysis to examine value perspectives in Circular Economy policy in cities across the Americas and Europe.** This research shows that Circular Economy policies in the sampled cities are largely centred around the recycling of C&D waste and formation of markets for secondary construction materials, which implies current value capture efforts are mostly focused on the value embodied in construction materials (i.e., low-level circularity). However, only a few cities in the sample aim their policy objectives at higher levels of circularity such as refusal of new construction and prioritising life extension of existing infrastructure, which has significant amounts of embodied energy, labor, and already sustains essential activities. Finally, this research highlights the disconnect between the urban metabolism of some cities and their current CE policy goals. For instance, Toronto's primary material consumption—largely driven by the rapid growth of the city—is over 40 times higher than the mass of C&D waste generated every year, severely limiting the potential impact of recycling (one of the city's main strategies for fostering circularity in the construction and infrastructure sector) for reducing primary material consumption and associated GHG emissions and environmental impacts.

5.2. Limitations and Recommendations for Future Work

While this dissertation has improved the understanding of value assessment for infrastructure products, there are limitations associated to the methods and scope chosen for the different research outputs of this work. Further, the connections between values and infrastructure decisions are rich and still largely unexplored, thus holding significant potential for future research. This section discusses some of these key limitations and avenues for future work.

5.2.1. Infrastructure Value Interdependency

One of the key limitations of this dissertation is the assessment of infrastructure value at an individual system level. Indeed, the literature reviewed and discussed in Chapter 2, the model for value assessment of pipe maintenance strategies in Chapter 3, or the CE policies examined in Chapter 4, are all centred around the objectives, performance, and priorities for singular infrastructure systems. Nonetheless, infrastructure interdependency is a key aspect of value delivery.

Almost every aspect of an infrastructure network (e.g., physical layout, performance, reliability) is constrained and affected by the presence of other infrastructure networks; this is known as an interdependency between the infrastructures. For example, water and power distribution networks have a functional interdependency, where the control of water pumps and valves requires electricity supplied by the power network. An example of physical interdependency is the overlap between transportation, water, and power networks, which are usually built in corridors, and thus in proximity to one another. There are several types of interdependencies that have been identified in published works, such as functional, physical/geographic, policy, and informational interdependencies (Ouyang, 2014).

Existing quantitative studies focus heavily on reliability and express consequences of interdependent failure as monetary outcomes, ‘optimising’ decision strategies around objective functions of minimum cost (Dueñas-Osorio et al., 2007; Lee et al., 2007; Liu et al., 2018). This leaves many issues unaddressed, including the study of the role of interdependency in the delivery of benefits and valuable services, and its effect in the environmental and social performance of infrastructure (Ersoy et al., 2020). Relevant aspects of infrastructure value, sustainability, and interdependency include the material and energy footprint of networks, where operation and maintenance activities on one network may disrupt and induce the need to repair an interdependent network, or the allocation of carbon budgets across infrastructure sectors (Lee et al., 2007; Müller et al., 2013).

For the literature review in Chapter 2 and policy analysis in Chapter 4, the focus lies on infrastructure products as discrete products, although their value delivered (particularly towards broad sustainability objectives) depends considerably on their coordination with surrounding infrastructure systems. Additionally, while the model developed in Chapter 3 considers maintenance activity durations and disruptions for a single WDN, it could be adapted to study the effect of spatially or functionally interdependent infrastructure maintenance activities on system performance.

5.2.2. Infrastructure Stakeholder Engagement

Throughout this dissertation, it is highlighted that the perception of value by different stakeholders is an important feature of more sustainable infrastructure systems. In Chapter 3, stakeholder perception is one of the key lenses of analysis for the proposed computational model, as the different performance metrics included in this chapter are assumed to have different impacts on the perception of value for users, network operators, and regulators. However, this is not confirmed through a systematic inquiry of stakeholder priorities and preferences. Thus, another relevant area for future work is the engagement with real infrastructure stakeholders, mapping their priorities and preferences related to infrastructure design and operation. This could be done through a qualitative exploration of stakeholder value perceptions at several levels: (i) on an ex-ante basis, to assess the needs and priorities for infrastructure development across stakeholder groups; and (ii) after the occurrence of significant disruptions on service, to identify challenges and opportunities for improvement in infrastructure operation strategies that consider more effectively the needs and expectations of all stakeholders.

5.2.3. Integrated Value Assessment Towards Regional Sustainability Objectives

Value delivery as contribution to collective objectives is one of the main concepts of value discussed throughout this dissertation. Indeed, the link between infrastructure systems and numerous sustainability objectives such as the SDGs has been well documented in literature (Adshead et al., 2019; Thacker et al., 2019). However, the contribution of infrastructure is often discussed at the individual system level, leaving important questions behind, including whether total infrastructure stocks are collectively achieving desired objectives, or what the allocation of a given objective should be across infrastructure sectors (e.g., energy, transportation, water).

While the computational model developed for Chapter 3 assesses scenarios for a singular WDN, an integrated assessment of multidimensional performance at different spatial scales is important for evaluating tipping points such as specific climate goals for GHG emissions, overall water withdrawal for different water use and efficiency metrics, and monetary budgets for sectoral infrastructure assessments. Although regional, national, or global objectives such as cumulative GHG emission budgets for specific climate targets are highly uncertain due to model and scope choices (Visser et al., 2000; MacDougall et al., 2015; Lontzek et al., 2015), they present an important avenue for future work on infrastructure value assessment as contribution to objectives are one of the main avenues of value delivery by infrastructure systems. Finally, Chapter 4 highlights the value of future work on the evaluation of the effects of policy on overall consumption patterns, which would be key to assess whether current CE policies as the ones analyzed in this study are leading to the desired outcomes in terms of overall material consumption, waste management, and their associated environmental impacts.

5.3. Closing Statement

Infrastructure systems shape many critical aspects of our lives: the mobility of people and goods; access to essential services such as drinking water, food, and electricity; or our capacity to withstand and recover from increasingly intense and frequent extreme weather events. In this sense, infrastructure systems are the most valuable technological systems in modern society. However, these systems also impose significant burdens on societies across environmental, social, and economic dimensions, and are often at the forefront of public discussion. Moreover, infrastructure plays a defining role in how we interact with both natural and built environments, is a key enabler of social prosperity, and holds immense potential for transformation in the face of crucial societal sustainability challenges such as decarbonisation and climate adaptation. However, the value of infrastructure systems to date has had a narrow focus on monetary implications and has lacked recognition of the key objectives and outcomes for society and diverse groups of stakeholders.

Overall, this dissertation advances our understanding of the ways value is used to articulate aspects of preference, achievement of collective objectives, and to reflect diverse perspectives from infrastructure stakeholders. This work explores in detail the value trade-offs that are implicit in decision-making models commonly used in infrastructure studies, providing a model for long-term maintenance decisions that grapples with the uncertain, dynamic nature of large network operation. Lastly, this dissertation provides a base for integrating infrastructure value perspectives in a promising new field of urban policy (the Circular Economy), pointing out the diversity of priorities across large cities and highlighting opportunities for improved value preservation and enhancement.

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Appendix A:
Additional discussion on pipe failure modelling and break rates

Given that the results of the example presented in Chapter 3 heavily depend on the modelling of the pipe failure rates, this appendix provides additional context on how the proposed model compares to other published studies and to observed rates of pipe failure. Figure A.1 below shows the failure rate λ_{it} for a 30 cm pipe [breaks/km/year] against the age of the pipe according to different failure rate models. Firstly, the figure shows the failure rate used for the model developed in Chapter 3 in blue, taken from (Dandy and Engelhardt, 2001). The light green line shows the failure rate over a range of pipe ages after including the Zero-inflated Poisson coefficient G_{it}. The failure rate as proposed in (Roshani and Filion, 2014) is shown in yellow. Finally, the two dashed lines correspond to pipe failure surveys performed for water distribution networks in the United States and Canada for 2012 and 2018, as published in (Folkman, 2018).

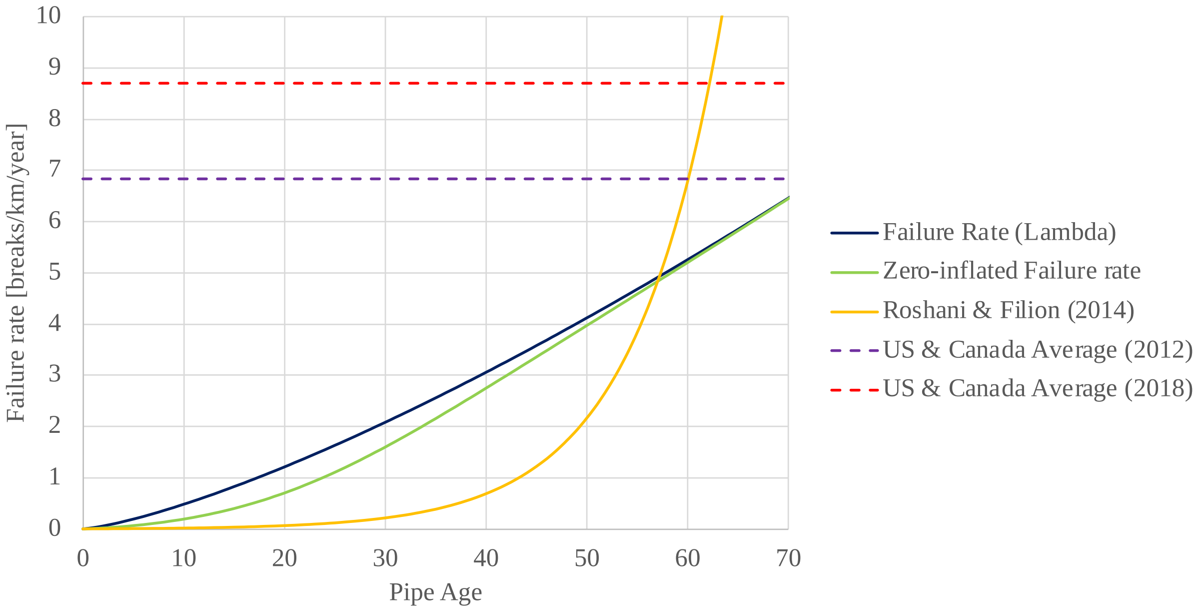

Figure A.1. Comparison of failure rate used in Chapter 3 with alternative studies and empirical values.

The figure above shows that the failure rate model used in Chapter 3 follows a similar trend and has a similar magnitude as both alternative models published in the literature, as well as with observed failure rates in real water distribution networks. However, it is worth noting that the failure rate equation proposed by Dandy and Engelhardt (2001) results in higher expected failure rates earlier in the lifespan of pipes, which may result in lower average pipe lifetimes given the thresholds proposed for the maintenance model in Chapter 3.

However, an important distinction with alternative models such as the one proposed by Roshani and Filion (2014) is the fact that the model proposed in Chapter 3 is not a traditional Poisson model, but a dynamic, non-homogenous stochastic process. Given that the model of Roshani and Filion is used under a static modelling framework (i.e., no effect of maintenance on future failure risk), the failure rate shape is chosen to keep failure rates low early in the lifespan of pipes. In contrast, the model proposed in Chapter 3 takes a dynamic approach, where failure rates dynamically adjust upon actual failure and posterior maintenance of the pipe. For example, while the values in Figure A.1 show that a 40-year-old pipe has a failure rate of about 3 breaks/km/year under the model of Dandy and Engelhardt (2001) as opposed to around 1 break/km/year according to Roshani and Filion (2014), the latter failure rate is used to estimate future failure probabilities regardless of whether a particular pipe has been maintained or not—even though repair and replacement actions will presumably improve the physical and functional conditions of the pipe and thus change the future risk of failure.

Finally, it is important to mention that the example provided in Chapter 3 is meant to showcase the range of results that can be obtained from the proposed model, while also pointing out the limitations of assuming stakeholder priorities by showing significant differences across scenarios of operational priorities. Future work could integrate the dynamic modelling approach from Chapter 3 into more detailed studies of failure rate, either through statistical approaches based on collected failure data from real networks (Folkman, 2018; Snider and McBean, 2020) or in future modelling exercises such as (Lee and Burian, 2019; Roshani, 2022).