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A Framework for Value-Integrated Infrastructure Business Models

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Abstract

There is ongoing debate about the value of infrastructure systems—energy, water, transport, waste, and communications—and how infrastructure investments should be prioritized to account for social, economic, and environmental wellbeing. The concept of an infrastructure system is inherently linked to interdependencies. Although infrastructure systems differ across countries and cities, they are all closely connected to transport, as movement involves both cost and utility. These systems ultimately exist to serve individuals, who assign value to them. To explore the full spectrum of value creation, which underpins business models, the relationship between individuals and transport infrastructure must be understood. This research tests the hypothesis that integrating economic, environmental, and social value dimensions within a unified business model provides a more comprehensive representation of infrastructure interdependencies than conventional economically focused approaches. Economic value was analyzed using principal component analysis of input–output tables, social value through structured interviews and statistical analysis, and environmental value using secondary data linked to economic demand in the infrastructure context of England, Scotland, Wales, and Northern Ireland. The proposed business model integrates social, economic, and environmental values, giving policymakers a clearer understanding of infrastructure system interactions and supporting more informed investment decisions that maximize societal value.

Keywords: business models; communications infrastructure; economic value; energy infrastructure; environmental value; infrastructure business models; social value; transport infrastructure; waste infrastructure; water infrastructure

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1. Introduction

There is an ongoing debate concerning the significance of the non-economic benefits of infrastructure and the challenge of prioritizing infrastructure investments across England, Scotland, Wales, and Northern Ireland while accounting for environmental and social value [1]. Environmental and social value "are sufficiently difficult to observe or measure

quantitatively, much less capture in economic transactions, and the benefits may be diffuse and sufficiently small in magnitude to escape the attention of individual beneficiaries" [2] (p. 6). Infrastructure is commonly defined as "a large-scale physical resource made by humans for public consumption" [2] (p. 3). Infrastructure is inherently connected to economic interdependencies. Building on general interdependency theory, economists refer to interdependencies as synergies [3], whereas engineers describe them as interconnections [4]. The divergent terminology used by the social sciences and engineering disciplines highlights the need for interdisciplinary research. In what follows, the term interdependencies will be used to encompass both dependencies and interdependencies. Interdependencies refer to the relationships among components and processes within the same infrastructure sector, where each element influences the operation and performance of the overall system. Dependencies refer to the reliance of one infrastructure sector on another infrastructure sector for the provision of resources, services, or operational support necessary for its functioning. Efforts to better understand the influence of infrastructure interdependencies on transport infrastructure system performance have led to the development of a new infrastructure business model that integrates economic, social, and environmental value, including the value arising from these interdependencies.

Existing literature predominantly concentrates on economic value and interdependencies [1,4]. Economic interdependencies can be mapped using data derived from economic input–output tables across sectors [1]. Furthermore, the environmental impacts of various infrastructures and sectors—such as pollutant emissions—are well documented in previous research [5], enabling their incorporation as one dimension of environmental value [6]. This illustrates how connections between infrastructure systems and environmental consequences—such as pollutants—can be examined and modelled [6]. Social value, however, is more challenging to identify through such methods and instead requires engagement with societal needs, often through direct consultation with communities, such as interviews and surveys [7].

Business models, by definition, focus on value creation (and thus value identification) and value capture for key stakeholders or end users [8,9]. This immediately underscores the multiplicity of stakeholders who derive value from infrastructure systems. The evolution of business models is driven by innovation [10,11], globality [12], public policy [13], and corporate social responsibility [14].

Internal value creation is achieved through value chain analysis, while external value emerges from the value network [15]. External value can be identified by deconstructing the value chain to map the elements that support the business model [16]. Marketing imperatives can be categorized into three value propositions: low-cost leadership [17], mass customization [18], and solutions [19], with the latter being most prevalent in innovation-driven industries. When a traditional market such as transport infrastructure requires an innovative approach, the marketing imperative may combine mass customization with solution-oriented strategies. The growth engine illustrates how firms expand, demonstrating the relationship between inputs and outputs within a business model under specific market opportunities or targets [20]. These elements should be considered in the development of any new business model.

Co-creation has recently gained scholarly attention as a means of understanding how stakeholders' needs and expectations—their interdependencies with the system—shape value creation and capture [21,22]. Value co-creation identifies the conditions under which customers are willing to engage without economic constraints [23]. Co-creation may enhance infrastructure system performance by influencing outcome delivery through the integration of knowledge capital and resources from diverse stakeholders. This approach requires alternative organizational structures that foster creativity and enable outcome

management within the dynamic environments generated by stakeholder interactions [24]. Such structures rely on "incentives rooted in the supply and demand for interaction and transactions for which prices or explicit market based value may be determined" [24] (p. 28). The question then arises: how can such a structure be designed to capture the value thus determined? Analysis of empirical data in the research of George & Bock [25] (pp. 91–94) conceptualizes a business model as the design of an organizational structure for capturing value, which they term a "value structure" [25] (p. 107). Within the adaptive organizational framework required by co-creation, it becomes evident that the business model is the central mechanism for designing this "value structure." Co-creation can therefore be examined within this framework without the need for separate analysis. The required alternative structure also incorporates relational structures [24] (p. 28), reflecting the interdependencies inherent in the systemic analysis underpinning this research.

The Research Question and Hypothesis

The infrastructure business models and infrastructure interdependencies delineate an under-researched domain and constitute the research gap that motivated the selection of the topic, the formulation of the research question, and the overall purpose and structure of the study. Although numerous studies examine critical infrastructure interdependencies, the majority focus on periods of crisis. Research addressing routine, day-to-day infrastructure interdependencies remains notably limited.

Regarding infrastructure, Steinmueller [3] (p. 117) observed that "Both traditional and modern uses of the term infrastructure are related to 'synergies', what economists call positive externalities that are incompletely appropriated by the suppliers of goods and services within an economic system." Historically, the concept of infrastructure emerged from the recognition that private gains from constructing and expanding transportation and communication networks, while substantial, were accompanied by even greater social gains. Hall et al. [4] (p. 6) defined infrastructure as "the collection and interconnection of all physical facilities and human systems that are operated in a coordinated way to provide (a service)." For the purposes of this research, interdependencies refer to the synergies described by Steinmueller [3] or the interconnections described by Hall et al. [4], as both terms capture the same underlying phenomenon. The prevailing value model for infrastructure interdependencies remains rooted in an economic perspective that evaluates each infrastructure in isolation, thereby reinforcing siloed thinking. An alternative approach would integrate energy, water, communication, and waste infrastructures into the appraisal of transport infrastructure system performance. Such integration would provide a more comprehensive understanding of transport system attractiveness and support the development of informed investment recommendations. This research aims to highlight findings relevant to the value interdependencies of infrastructure.

Furthermore, "infrastructure investment has always been considered key for economic growth" [26] (p. 555). In the context of urban development, the final users are the individuals residing in the urban area and experiencing its economic trajectory. Moreover, "the development of transport infrastructure is most economic" within urban development [27] (p. 275). These individuals may be regarded as "key stakeholders," as their needs and expectations shape governmental responsibilities. Previous studies indicate that "infrastructure investment alone is not significantly linked with regional GDP change," whereas transport infrastructure investment "is more strongly linked to economic growth in regions with better government quality" [26] (p. 577). This "strong and highly significant connection with regional economic performance," when transport infrastructure investment "is interacted with government quality" [26] (p. 577), underscores the importance of the individuals who elect or influence government. For these reasons, this study focuses

on economic value through growth, which both affects and is affected by citizens, who constitute key stakeholders.

The system of infrastructure networks (energy, water, transport, waste, communication) examined by this research has been studied internationally [5,27], as these networks are significant not solely because of their economic value. The dominant value model of infrastructure interdependencies continues to emphasize economic value from a siloed perspective, neglecting interdependencies and the essential requirements of sustainability, resilience, and liveability [28]. The process of identifying the research gap—'gap spotting'—used here is neglect spotting [29] (p. 30), which involves identifying under-researched areas in existing literature. This study aims to address the identified research gap and highlight findings relevant to value interdependencies of infrastructure in developed countries.

The development of infrastructure business models requires a clear distinction between infrastructure sectors and infrastructure systems, as value creation, resource allocation, and stakeholder interactions occur at different levels of analysis. Infrastructure system refers to an interconnected network of physical assets, operational processes, organizations, and supporting technologies that function together to deliver a specific infrastructure service within a sector. Infrastructure sector refers to a broad functional category of infrastructure that provides a specific public or economic service. Examples include the transport, energy, water, waste, and telecommunications sectors. Each sector comprises one or more infrastructure systems that collectively support the delivery of sector-specific services.

Interactions among infrastructure systems generate interdependencies, which must be examined through a new business model. Consequently, the business model requires the involvement of end users, or "key-stakeholders," as value co-creators. This research aims to fill this research gap and identify findings relevant to infrastructure business models and infrastructure interdependencies management. The theoretical contribution of this research lies within civil engineering and infrastructure management, particularly in the domain of infrastructure business model theory.

The preceding arguments lead to the following hypothesis:

"Infrastructure business models that integrate economic, environmental, and social value dimensions provide a more comprehensive representation of infrastructure interdependencies than conventional economically focused business models."

This hypothesis will be examined against the literature and, assuming it holds, the aim of this research will be to develop a new approach to constructing a business model. The aim will be achieved by addressing the following research question:

"How can economic, environmental, and social value dimensions be integrated into an infrastructure business model that supports the management of infrastructure interdependencies and improves infrastructure decision-making?"

This research question assumes two primary interdependencies: those between key stakeholders and infrastructure systems, and those between transport infrastructure systems and the four 'economic infrastructures' (water, waste, energy, and ICT). The main objectives of this research, which define its scope, are:

Objective 1: Develop a framework that integrates economic, environmental, and social value dimensions into infrastructure business models.

Objective 2: Examine representative interdependencies between transport infrastructure and other critical infrastructure systems.

Objective 3: Design and demonstrate an integrated infrastructure business model that supports value-informed infrastructure planning and management.

Figure 1 distinguishes between the previously published research stages and the novel contribution of this study. The three value dimensions (economic, environmental

and social), corresponding to Sections 3.1–3.3, were developed and published previously as independent studies [1,6,7]. These studies provide the empirical foundations for the present research and are incorporated here only as inputs to the integrated framework. The remainder of the research—including the integration of the three value dimensions, the development of the infrastructure business model, the analysis of infrastructure interdependencies, the empirical validation of the integrated framework, and the discussion of its theoretical and practical implications—is presented here for the first time and constitutes the original contribution of this manuscript. Figure 1 is an original conceptual illustration of the overall research program, while any concepts derived from previous studies are appropriately cited. Selected figures, tables, and equations presented in Sections 3.1–3.3 are adapted from the authors' previously published studies [1,6,7] and are fully cited in the manuscript.

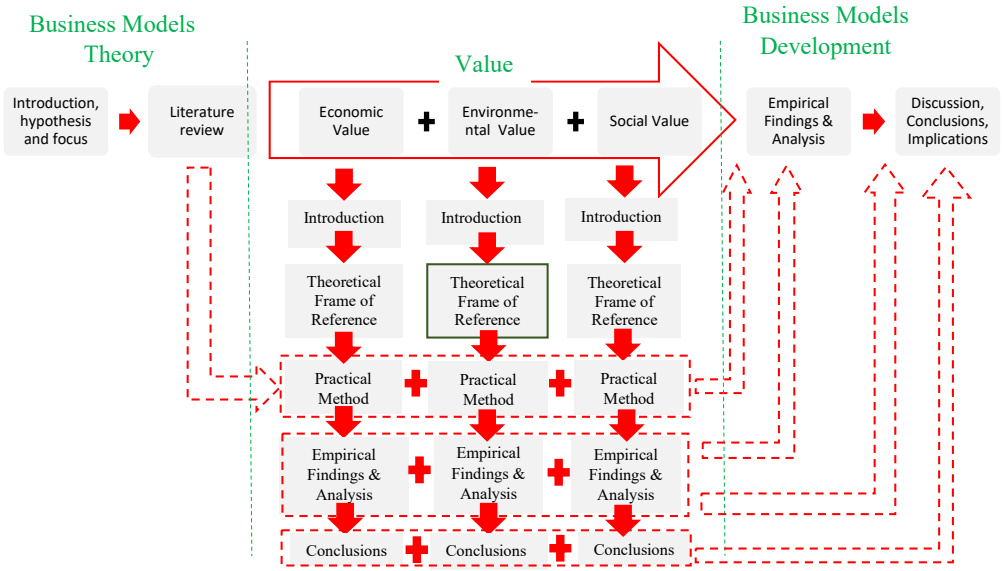


Figure 1. Research methodology flowchart [30].

The three value dimensions considered in this study—economic, environmental, and social—are measured using different empirical constructs and analytical methods and therefore are not combined into a single mathematical objective function. Instead, their integration is achieved through a unified infrastructure business-model framework that represents their complementary relationships and interdependencies. This approach recognizes that the three dimensions capture different forms of value that cannot be directly aggregated without introducing additional assumptions regarding their comparability, weighting, and trade-offs. The framework therefore integrates these dimensions structurally, linking them to infrastructure interdependencies, stakeholders, value creation and capture mechanisms, and the broader business-model architecture.

The geographical scope of this study encompasses the four constituent nations of England, Scotland, Wales, and Northern Ireland. The quantitative empirical analysis, however, is conducted using internationally harmonized datasets that report economic and environmental information at the aggregate national level. In particular, the World Input–Output Database (WIOD) and EXIOBASE 3 do not provide the disaggregated national accounts required to construct equivalent input–output and environmental accounts separately for England, Scotland, Wales, and Northern Ireland within the analytical framework adopted in this study. Consequently, the quantitative results should be interpreted as a four-nation geographical scope represented through an aggregated national dataset, rather than as four independent national estimates.

This distinction is important because infrastructure governance, transport delivery, public expenditure, planning responsibilities, and policy frameworks differ across England, Scotland, Wales, and Northern Ireland. The aggregation of the quantitative evidence therefore does not imply institutional homogeneity. Instead, the proposed business model is intended as a common analytical structure whose practical implementation can be adapted to the governance, funding, regulatory, and policy conditions of each of the four nations. Accordingly, nation-specific institutional differences are considered in interpreting the applicability of the proposed business model, while the underlying economic and environmental evidence remains constrained by the resolution of the available international databases.

The four-nation context is particularly relevant to infrastructure business models because the same underlying value-creation logic may operate through different institutional arrangements. Thus, policy instruments, transport authorities, funding mechanisms, planning procedures, and stakeholder responsibilities may vary between England, Scotland, Wales, and Northern Ireland. These differences do not invalidate the proposed business model; rather, they determine how its components—particularly governance, ownership, funding, financing, stakeholder engagement, and value capture—are configured in practice. The model should therefore be interpreted as a transferable structural framework rather than as a uniform governance or financing arrangement applicable identically across all four nations.

2. Theoretical Framework

This study adopts a primarily deductive research approach, progressing from general theoretical concepts to specific empirical observations in line with the positivist paradigm [31] (pp. 261–262), while also incorporating inductive elements where empirical findings are generalized to extend theoretical understanding [32]. The conceptualization of value is shaped by the study's scope and its aim to develop a delimited theoretical perspective, consistent with Huang and Gao's [33] (pp. 156–157) argument that delimited theories require continuous empirical validation; their illustration of Einstein's treatment of the dual nature of light as a "paradigm revolution" [33] (pp. 152–154) informs the study's analogous treatment of value as possessing both an economic and a broader sustainability-oriented nature. Accordingly, the study employs this "paradigm revolution" methodology to examine value from both perspectives, strengthening its conceptual validity if supported by empirical evidence. This methodological stance resembles Bryman and Bell's [32] (p. 14) description of "weaving back and forth between data and theory," combining deductive hypothesis testing with inductive theory development; thus, research propositions are derived from existing theory and subsequently interpreted through empirical findings to generate broader theoretical insights. Overall, the research is exploratory because the full extent of relationships and findings cannot be predetermined [34] (p. 11), and in seeking to investigate emerging phenomena [35], it explores the economic, social, and environmental opportunities associated with value-oriented business models.

2.1. Business Models

Business models explain how organizations create, deliver, and capture value, while also identifying the associated costs and mechanisms through which stakeholders benefit [36]. As such, they provide an essential framework for understanding organizational sustainability and long-term performance [36]. This section reviews the concept of the business model, examines its principal components, and discusses the mechanisms through which business models achieve value creation. Unlike an analytical framework, which primarily provides a structure for examining relationships among concepts or variables,

the proposed infrastructure business model explains how infrastructure systems create, deliver, and capture value through the interaction of stakeholders, governance arrangements, financial mechanisms, lifecycle processes, and infrastructure dependencies. Accordingly, the framework presented in this study is conceptualized as a business model because its purpose extends beyond analysis to describe the mechanisms through which infrastructure value is generated and sustained.

2.1.1. The Nature of Business Models

The concept of the business model is fundamentally rooted in value creation. Despite its widespread use, no universally accepted definition of a business model exists. Osterwalder [37] (p. 15) defines a business model as "an abstract conceptual model that represents the business and money earning logic of a company," whereas Afuah and Tucci [38] describe it as the organization's underlying logic for creating value. Since organizations compete for customers and resources, business models should also explain "how it wins customers, woos investors, and earns profits" [39] (p. 84).

Similarly, Magretta [8] (p. 43) defines a business model as "a set of assumptions about how an organization will perform by creating value for all the players on which it depends." She further argues that effective management begins with a theory of how the entire system operates to generate value [8] (pp. 43–44). Expanding on this perspective, Magretta [40] (pp. 3–8) characterizes business models as practical applications of systems thinking within management. According to this view, successful business models should communicate a coherent and easily understandable narrative that can be shared among all stakeholders.

From a conceptual perspective, business models function as analytical models that transform specified inputs into desired outputs. A model represents the researcher's understanding of a phenomenon and serves to simplify reality by illustrating the relationships among its principal elements [41,42]. Consequently, business models provide a structured representation of how organizations generate and capture value within a defined set of assumptions and operating conditions [43].

Traditional business and economic literature generally conceptualizes business models as mechanisms that transform technical inputs into economic outputs by creating and capturing financial value through organizational resources and infrastructure. Consistent with this perspective, Casadesus-Masanell and Ricart [9] (p. 197) define a business model as the way an organization creates and captures value while generating revenue. However, a broader definition is offered by Aho [44] (p. 287), who describes a business model as "the rationale of how an organization creates, delivers, and captures value—economic, social, or other forms of value." Across these definitions, two common elements consistently emerge: value and the final user.

The broader conceptualization adopted by Aho [44] acknowledges that value extends beyond purely financial outcomes and may include social and environmental dimensions. This study adopts this multidimensional interpretation of value, recognizing that economic, social, and environmental value are closely interconnected and cannot always be considered independently. Achieving an appropriate balance among these dimensions ultimately reflects societal priorities and policy choices. Consequently, while acknowledging the relevance of the neoclassical economic perspective, this research primarily adopts a sustainability-oriented interpretation of value.

Because business models are conceptual representations rather than exact descriptions of reality, they necessarily operate under conditions of incomplete environmental knowledge. Their explanatory power depends on a series of assumptions, limitations, and delimitations. Assumptions may arise through the generalization of empirical findings, limitations may result from constraints such as restricted data availability, and delimitations

reflect the intentional boundaries established by the research, such as focusing on particular forms of value. Within this context, business models are fundamentally concerned with explaining how value is created, delivered, and captured. Accordingly, this study defines business models as the organizational structures and management arrangements through which value is delivered to selected stakeholder groups by implementing specific value propositions.

The effectiveness of a value proposition depends not only on the value itself but also on the design of the business model through which that value is created. Amit and Zott [45] (p. 493) argue that the architecture of the business model is fundamental to value creation and propose a framework that explains organizational success through four principal sources of value creation. These include efficiency, whereby value is generated through improved processes [45] (pp. 503–504, 221–222); complementarities, whereby value is enhanced by combining products or services with complementary offerings from other organizations [45] (pp. 504–505, 221); lock-in, which increases customer retention by raising switching costs [45] (pp. 505–507, 221); and novelty, which creates value through innovation and new ways of conducting business [45] (pp. 508–509, 221). These four mechanisms subsequently became the principal business model design themes proposed by Amit and Zott [45] (p. 222).

Although the literature differs slightly regarding the core components of business models, considerable agreement exists concerning their underlying principles. The conceptual foundation of the present study builds upon the alternative infrastructure business model framework developed by Bryson et al. [46], which is closely aligned with the business model design themes proposed by Amit and Zott [45]. Existing research consistently suggests that value is generated through the selection and implementation of an appropriate business model. Value may arise from reorganizing organizational activities to reduce transaction costs [45] (p. 222), attracting and retaining customers [39], or implementing organizational strategies effectively [38]. Bryson et al. [46] further demonstrate how infrastructure business models integrate these design principles while emphasizing value flows that facilitate the selection and combination of financing mechanisms according to project-specific requirements (see Table 1).

Table 1. Business models in the literature.

Approach	Marketing Imperative	Internal Value Creation	External Value Creation	Growth Engine	Linked to Each Other
Afuah & Tucci [38]	scope, implementation			revenue, capabilities, sustainability	Yes
Amit & Zott [45]	transaction content & structure	efficiency, lock-in, novelty, complementarities transaction governance			Yes
Linder [39]	how it wins customers	how it earns profits	how it woos investors		Yes
Bryson [46]		Government guarantee schemes & charges of actors	finance development		Yes
	inputs, activities and outcomes that aim to create and capture economic, social and environmental values over the whole infrastructure life cycle				
This research	Evaluation and use by the key stakeholders/final users (social value)	Economic value (Demand) Social & Environmental value creation (welling, emission reduction)		Growth through value integration	Yes

Within the infrastructure sector, iBUILD [47] defines infrastructure business models as "the system of physical artefacts, agents, inputs, activities and outcomes that aim to create, deliver and capture economic, social and environmental values over the whole infrastructure life cycle." This broader definition extends conventional business model theory by

recognizing that social and environmental outcomes should be evaluated alongside economic performance. Similarly, Casadesus-Masanell and Heilbron [48] argue that consumers derive value from the use of the completed product, while simultaneously acknowledging that business activity itself is inherently complex and dynamic [48]. Consequently, the primary beneficiary of a business model remains the final user. Furthermore, not all studies explicitly recognize the economic foundations of business models. As argued by Casadesus-Masanell and Heilbron [48], adopting alternative approaches to value capture represents an important step toward understanding the strategic advantages of business models. From this perspective, shifting from an exclusively economic orientation toward a broader benefit-oriented model enables organizations to recognize and capture forms of non-economic value that conventional approaches often overlook.

2.1.2. The Marketing Imperative of Business Models

Marketing constitutes an essential component of business models because it represents the primary interface through which final users encounter the value proposition embedded in a product or service. Since value emerges through transactions, marketing plays a critical role in value creation and in the overall functioning of business models [49] (p. 53). Business models not only describe potential value but also rely on marketing activities to generate the resources necessary for value capture [49] (pp. 47–49). Moreover, marketing communicates the value proposition to the final user and enables stakeholders to understand the benefits associated with a particular service or product [50] (pp. 215–216). The value proposition therefore targets those users for whom the organization seeks to create value [50] (pp. 215–216). In broad terms, value propositions may be categorized into three principal types according to the relationship between the price paid by the user and the value received: low-cost leadership, mass customization, and solutions (see Figure 2).

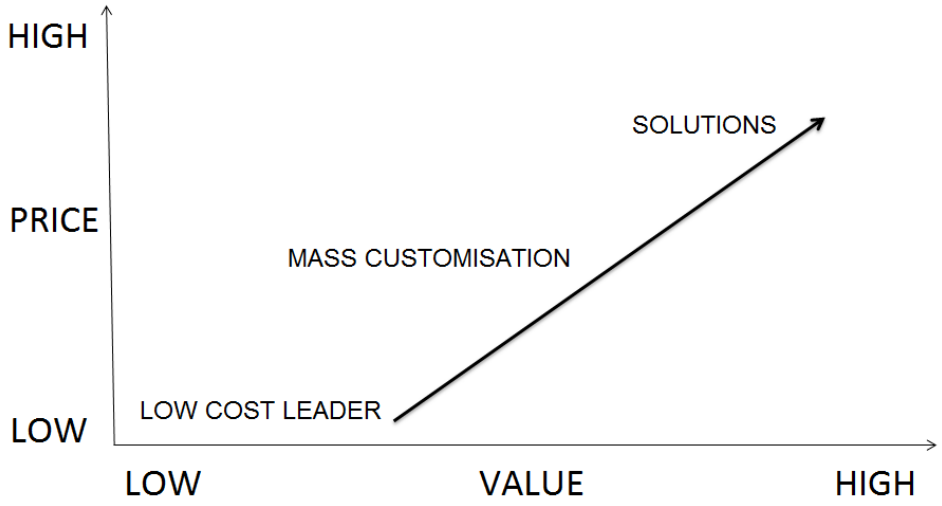


Figure 2. Value propositions [30,36].

The low-cost leadership proposition is most common in markets characterized by high price sensitivity. Under this approach, products and services tend to become commoditized because they are largely undifferentiated [17] (pp. 502–503). As a result, competition occurs primarily through price rather than through product distinction. Such a proposition depends heavily on economies of scale, which arise when unit costs decline as greater quantities of an identical product or service are produced or delivered [51] (p. 29). The standardization associated with low-cost leadership corresponds closely to the production of the same product or the provision of an identical service at increasing scale. Conse-

quently, external value creation becomes particularly important through mechanisms such as outsourcing, offshoring, and global sourcing strategies.

Mass customization, by contrast, seeks to provide individualized offerings while maintaining the efficiency and affordability associated with mass production. Pine [18] (p. 44) defines mass customization as the development, production, marketing, and delivery of affordable goods and services with sufficient variety and customization to satisfy nearly every customer. Similarly, Mooney et al. [52] (p. 504) describe it as the provision of variety and customization through flexibility and rapid responsiveness. The literature consistently emphasizes that mass customization aims to deliver to final users what they want, at the desired price and time, while allowing customized products to be offered at costs comparable to mass-produced alternatives [18,52,53]. Importantly, customization refers to the adaptation of a product or service to the requirements of an individual user rather than merely offering a wider product range. This implies that final users become active stakeholders within the business model because they participate directly in the value creation process.

Gilmore and Pine [54] (pp. 91–101) identify four forms of mass customization based on whether the product or service itself changes and whether the customization is visible to the user (see Figure 3). Transparent customization provides individually tailored offerings without explicitly informing users that customization has occurred [54,55]. Collaborative customization involves users directly in specifying their needs and co-designing the customized offering [54,55]. Adaptive customization delivers a standard product that users can subsequently modify themselves [54,55]. Cosmetic customization maintains a standard product while adapting its presentation or supporting services to individual users [54,55].

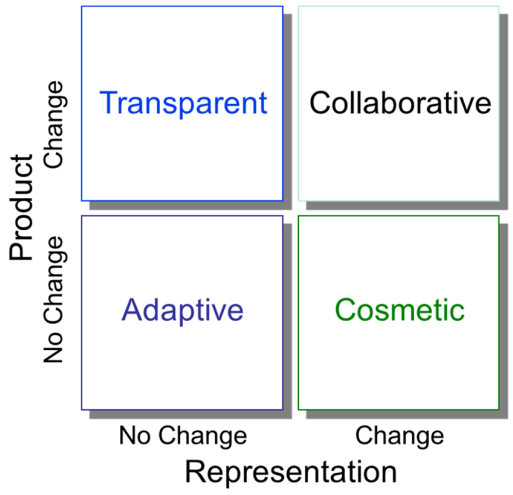


Figure 3. The four faces of mass customization [54] (p. 95).

The advantages of mass customization are substantial. Customized offerings better satisfy the unique needs of individual users [56,57], while lower inventory requirements can improve efficiency throughout the distribution channel [56,57]. In addition, products perceived as unique may justify premium pricing [56,57]. Continuous interaction with customers also creates opportunities for organizations to identify evolving market needs and adapt accordingly [56,57]. Nevertheless, the implementation of mass customization requires a significant shift in business model design. Although operational, labor, and supply chain challenges are important, the decisive question remains whether the customized offering will generate sufficient appeal among final users.

The third value proposition category is the solutions approach, which seeks to create exceptional value through highly tailored offerings. This model depends on the develop-

ment of mutually reinforcing value networks and close relationships between providers and users. Miller et al. [19] (p. 3) define solutions as "integrated combinations of products and/or services that are unusually tailored to create outcomes desired by specific clients or types of clients." Under this approach, the offering is designed to address a specific problem or need faced by the final user [19,58]. Value creation often involves collaboration between the provider, the user, and potentially additional third parties [19,58].

In the context of transport infrastructure, the proposition examined in this study lies between mass customization and solutions. Transport infrastructure must serve the diverse needs of a broad user base, consistent with the logic of mass customization, while simultaneously recognizing that individual users are key stakeholders who face specific mobility problems and should therefore participate in shaping the service outcome, consistent with the solutions perspective.

2.1.3. Value Creation and the Value Network

Value creation can be distinguished into two complementary forms: internal and external value creation. Internal value creation occurs within the boundaries of the organization and is closely associated with its organizational structure and business context [15,59]. The principal mechanism through which internal value is generated is the value chain.

The value chain (Figure 4) provides a framework for identifying where value is created within an organization by addressing key questions regarding the location of core value, the activities and competencies responsible for value creation, the appropriate distribution channels, and the governance of those channels [15]. Consequently, the value chain defines the organization's principal relationships, including customer relationships, together with its value and cost structures.

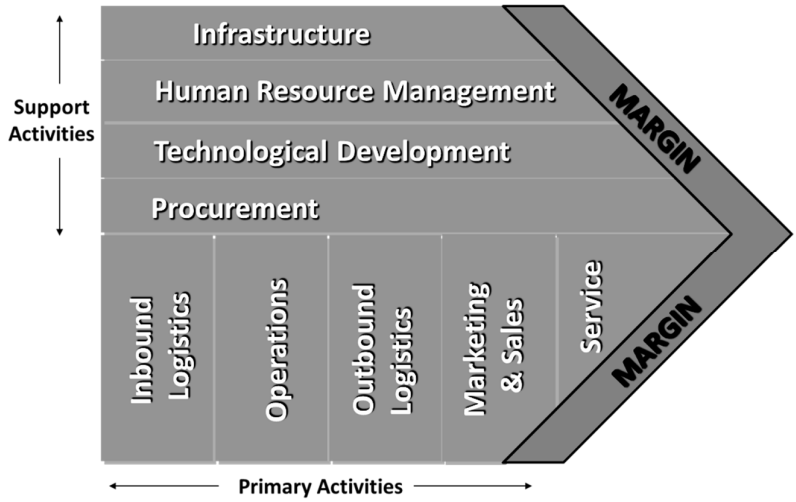


Figure 4. Michael Porter's value chain [15] (p. 37).

External value creation extends beyond organizational boundaries through the deconstruction of the value chain and the integration of upstream suppliers, downstream distribution channels, and complementary service providers that collectively support the business model [16]. Within a value network, value propositions may be classified as virtual, integrated, or hybrid according to the extent of third-party involvement. A virtual value proposition exists when the majority of value is created by external organizations and delivered to the customer through an intermediary firm, as illustrated by digital platform businesses such as Uber Technologies. In contrast, an integrated value proposition occurs when value is created and delivered entirely by a single organization, although such arrangements are increasingly uncommon in contemporary markets. Hybrid value

propositions represent the most prevalent configuration, combining internal and external value creation through collaboration with one or more third parties. Examples include co-creation between firms and customers, outsourcing of specialized services, and offshoring of manufacturing activities.

Based on this distinction, a comprehensive definition of value should encompass both internal and external value creation together with the associated value proposition. Among the alternative approaches, co-creation is particularly relevant for contemporary infrastructure business models because it explicitly recognizes the final user as a key stakeholder in the value creation process.

As discussed previously, business models are fundamentally rooted in value creation. Across the literature, the concepts of value and the final user consistently emerge as the defining characteristics of business models. Value reflects the importance, usefulness, or worth of a given phenomenon. However, assessing value becomes increasingly challenging when multiple forms of value coexist within the same system. Although exchange provides a quantitative measure of value, perceptions of value frequently remain qualitative and cannot always be represented through market transactions alone.

Historically, the concept of value has been closely associated with monetary exchange. In The Wealth of Nations, Adam Smith [60] (p. 48) argued that "the real price of everything, what everything costs to the man who wants to acquire it, is the toil and trouble of acquiring it. What everything is really worth to the man who has acquired it, and who want to dispose of it or exchange it for something else, is the toil and trouble which it can save to himself, and which it can impose upon other people." Despite emphasizing labor as the source of value, Smith also recognized that market prices represent only a nominal expression of value because they are shaped primarily by exchange rather than by the intrinsic worth of goods.

John Stuart Mill, in Principles of Political Economy [61], challenged this interpretation by arguing that value should not be equated solely with monetary worth. Instead, he distinguished economic value from broader forms of value embodied in goods and services. These broader forms include qualitative dimensions that cannot be adequately measured in monetary terms. Mill's interpretation anticipated later environmental and anti-consumerist perspectives by recognizing the existence of non-market values.

Environmental value entered mainstream academic debate through the work of the Club of Rome [62], which highlighted that environmental degradation, including air pollution and deforestation, is not reflected in conventional measures of economic value. Although this work represented a significant advance in environmental economics, it proposed translating environmental value into monetary terms. Such an approach remains controversial because it implies that environmental degradation may be justified provided an appropriate economic compensation is offered. This exchange-value perspective overlooks ecological limits beyond which environmental losses become irreversible and threaten long-term societal wellbeing.

These contrasting perspectives have contributed to an ongoing debate between the neoclassical economic paradigm and the strong sustainability paradigm. The neoclassical perspective assumes that individuals create value through rational economic exchange and market-based decision-making [63]. In contrast, strong sustainability emphasizes human dependence on ecosystem services [64] and evaluates coupled human–environment systems through vulnerability-based frameworks [65]. Consequently, conventional business and economic theories prioritize economic value, whereas sustainability perspectives emphasize the interdependence of economic, social, and environmental values. These differing interpretations largely reflect the distinct ethical foundations of the respective disciplines.

Bonnedahl and Eriksson [66] provide a comprehensive comparison of these alternative perspectives on economic organization. They argue that conventional business and economic approaches primarily prioritize shareholder wealth and short-term organizational viability, whereas sustainability-oriented organizations emphasize resilience and the long-term viability of both present and future generations. Accordingly, mainstream organizations focus on profit, consumption, economic growth, and operational efficiency, while organizations founded on principles of strong sustainability seek stakeholder satisfaction through multi-value effectiveness and intra- and intergenerational justice [66] (p. 168). This perspective explicitly recognizes the multidimensional nature of value.

Within this framework, value should be understood as a balanced combination of economic, social, and environmental dimensions. Achieving an appropriate balance among these dimensions ultimately represents a societal and political choice that depends on the priorities, capacities, and developmental objectives of each society.

The multidimensional nature of value becomes particularly important in the context of infrastructure systems. A fundamental question is how infrastructure value should be assessed and for whose benefit it is created. Infrastructure constitutes a shared-resource system collectively used by individuals pursuing their own objectives. Individual decisions may therefore conflict with collective interests when users maximize private benefits without considering broader societal consequences. This phenomenon is commonly described as the "Tragedy of the Commons" [67].

According to Hardin [67], when individuals seek to maximize personal benefits from resources that are both rivalrous and non-excludable, overexploitation and eventual resource depletion become likely. This principle is directly applicable to infrastructure systems, particularly from a sustainability perspective. Water infrastructure, for example, is affected by water pollution, groundwater depletion, and excessive abstraction for irrigation [68]. Energy infrastructure generates significant environmental impacts through the combustion of non-renewable energy sources [69]. Transport infrastructure produces externalities including air pollution, greenhouse gas emissions, and traffic accidents [70]. Communication infrastructure may generate health-related externalities associated with radio-frequency and microwave radiation [71], while waste management infrastructure is intrinsically linked to public health risks arising from exposure to hazardous waste [72]. These interdependencies and externalities demonstrate that infrastructure systems cannot be evaluated solely according to their economic performance.

Hardin [67] proposed privatization and government regulation as two principal solutions to the tragedy of the commons. Privatization assumes that private ownership encourages rational, long-term management of resources, whereas government regulation seeks to limit resource use through institutional controls. Although these approaches may be appropriate in some contexts, they are difficult to apply to critical infrastructure systems such as water, transport, and communications because restricting access may compromise essential public services. Moreover, excessive privatization may increase societal vulnerability by reducing equitable access to critical infrastructure.

Rather than relying exclusively on privatization or regulatory restrictions, a more appropriate approach for critical infrastructure is to strengthen collective ownership and governance while actively involving users in the value creation process. This requires reconceptualizing individual users as key stakeholders rather than passive recipients of services. Mechanisms such as infrastructure sharing and value co-creation provide opportunities to achieve this objective by encouraging collaborative decision-making while maintaining accountability for individual actions. Such an approach also requires governance mechanisms capable of guiding individual decision-making toward collectively beneficial outcomes.

Within transport infrastructure management, value therefore extends beyond economic performance to include environmental and social outcomes. Consequently, the core relationships embedded within the business model should reflect the interactions among these three dimensions and the stakeholders who collectively contribute to value creation.

2.1.4. The Growth Engine

Infrastructure managers continually seek opportunities to achieve sustainable growth. Since value creation generates the resources required to sustain organizational activities, the long-term viability of a business model depends on its ability to secure and continuously generate such resources [20]. Business models operate within a broader external environment, and resource generation is therefore determined not only by internal organizational capabilities but also by the interaction between the organization and its external stakeholders. Examining these interactions reveals that a proportion of the value generated does not arise directly from organizational activities but instead emerges indirectly through infrastructure interdependencies. Consequently, a fundamental objective of the business model is to generate or access resources from all available sources by enhancing value creation across the wider stakeholder network.

Within the context of this study, value creation in transport infrastructure extends beyond purely economic outcomes. Accordingly, the growth engine should target resource providers—including investors, strategic partners, and other stakeholders—that recognize the importance of social and environmental value alongside financial returns. The stakeholder groups considered in this research are adapted from Bryson [46] and are classified according to the extent to which they prioritize economic, social, and environmental value (see Table 2).

Table 2. Infrastructure business models ownership typology [30,46].

Name	Description	Forms of Stakeholders	Type of Value Interests Them:
Public–Private Partnership	Service funded and operated through a partnership between government and private business	• Public subsidy to private-led management • Publicly owned asset—SPV management • Public/private development and management of new asset • Private Finance Initiative • Public subsidy, private ownership and management • Performance based partnership • Public Special Purpose Vehicle	Environmental Social Economic
Public	Public finance and management of asset/service	• Publicly managed and owned infrastructure (tax) • Public management of community purchase • Funds of funds leverage • National subsidy • User pays charge • Collective management • Fiscal decentralisation • Social equity bonds	Environmental Social Economic

Table 2. *Cont.*

Name	Description	Forms of Stakeholders	Type of Value Interests Them:
Private	Privately financed and operated asset/service	• Toll • Service rental and usage fee • Privately operated with public subsidy	Economic
Co-operative/Community Ownership	Organisation owned and managed by its members. Profits shared with members	• Community share scheme • Community ownership • Community asset transfer	Economic
Third Sector	Third sector ownership of asset	• Voluntary • Public-third sector partnership • Third sector asset managed by public sector	Economic
Trust	Independent local group of statutes (no ownership or shareholders) and surplus revenues reinvested in the trust	• Trust ports	Economic

Public-sector organizations, public–private partnerships, and third-sector (voluntary) organizations are generally characterized by a strong commitment to social and environmental objectives in addition to economic performance. Their organizational missions typically emphasize the delivery of public value and societal benefits, making them particularly relevant for infrastructure projects that pursue broader sustainability objectives.

By contrast, private-sector organizations, trusts, and cooperative or community ownership structures are considered to place greater emphasis on economic value creation. Although cooperative and community ownership models may also pursue social objectives, their establishment generally involves the generation of financial returns for their members. Similarly, private organizations frequently undertake activities associated with corporate social responsibility; however, it is often difficult to distinguish whether such initiatives are motivated primarily by commitments to social value or by broader commercial objectives, including reputation management and marketing. Furthermore, the implementation of socially oriented initiatives within private organizations remains largely discretionary and may be subordinated to the interests of shareholders or members.

A similar distinction applies to environmental value. While private organizations may invest in environmentally responsible practices, these actions may be driven by regulatory compliance, financial incentives, or the avoidance of penalties rather than by an intrinsic commitment to environmental sustainability. In contrast, public-sector organizations are generally expected to pursue social and environmental objectives as part of their institutional responsibility to serve the broader public interest. Consequently, this study classifies stakeholder groups according to their primary organizational objectives while recognizing that, in practice, economic, social, and environmental motivations frequently overlap.

In line with this stakeholder configuration, the growth engine must also be supported by a diversified and strategically aligned resource base. Transport infrastructure projects increasingly depend on blended funding structures that combine public allocations, private

capital, and mission-driven financial contributions from third-sector organizations. As shown inductively in Table 3, funding sources emerge from a wide spectrum of actors whose motivations reflect the economic, social, and environmental priorities discussed above. Inductively means beginning by identifying the actors and the source, and only afterwards turning to the literature to interpret what was observed.

Table 3. Funding sources.

Funding Source	Explanation	Illustrative Examples
User charges	Direct fees paid by the public or consumers who actively use the infrastructure, such as highway tolls, public transit tickets, or utility bills [73].	Used by Transport for London (TfL) via the Oyster/Contactless fare system, water company utility bills, and the M6 Toll road [74,75]
National taxation (revenue)	Long-term operational budgets allocated directly from centralized government tax revenues collected across the country [76].	Managed by HM Treasury, which assigns revenue directly to central services like the NHS budget and national highway operations [77].
Local development levy	One-time or recurring fees charged to private property developers to offset the infrastructure costs and impacts of their new developments [78].	Codified under the Community Infrastructure Levy (CIL) via the Planning Act 2008, allowing UK local authorities to charge flat square-metre fees [79].
Tax increment financing	A method that funds public improvements by capturing and borrowing against the predicted future increases in local property tax revenues [80].	Utilised as TIF schemes in Scotland and England (e.g., the Battersea Power Station Northern Line subway extension, borrowing against future Business Rates) [81].
Subsidized user charges	Lowered costs or discounted fees for specific user groups, with the financial gap covered by government or organizational subsidies [82].	Department for Transport initiatives such as the National Railcard system, Freedom Passes, and regional £2 cap on bus fares [83].
Pay-as-you-save	A framework where energy or utility upgrades are implemented upfront, and repayments are funded entirely by the proven savings generated by the upgrade [84].	Implemented via the UK government's historical Green Deal framework and modern local council energy efficiency retrofitting initiatives [85].
Performance-based partnership	Service agreements where payments to the operating partner scale up or down based on meeting specific quality, safety, and efficiency benchmarks [86].	Found in National Rail Passenger Service Contracts (PSCs), where train operating companies receive bonuses/penalties based on punctuality [87].
Land value capture	A mechanism to recover the increase in private land value that is triggered directly by public infrastructure investments, like a new subway line [88].	Debated in UK Parliament Committees and historically extracted partially via the Mayoral CIL used to help fund London's Crossrail (Elizabeth Line) [89].
Sponsorship	Commercial partnerships where private corporations pay for naming rights, branding, or marketing space on the asset to generate revenue [90].	High-profile London examples include Santander Cycles (the "Boris Bikes") and IFS Cloud Cable Car sponsorship agreements with TfL [91].

Table 3. *Cont.*

Funding Source	Explanation	Illustrative Examples
Philanthropic donations	Capital gifted by charitable foundations, non-profit organizations, or wealthy individuals without any expectation of a financial return [92].	Funding heavily utilized by major UK heritage and environment caretakers like The National Trust and the National Lottery Heritage Fund [93].
Debentures	Long-term, fixed-income debt instruments issued by corporations or authorities to raise revenue, backed solely by the general creditworthiness of the issuer [94].	Frequently issued by privatized UK utility providers (e.g., Thames Water or National Grid) to fund major network assets [95].

The practical examples presented in Tables 3 and 4 are illustrative applications of funding and financing mechanisms identified within the national infrastructure context. They are intended to demonstrate how the identified mechanisms may operate in practice and do not constitute a systematic or proportionally balanced representation across the four nations.

Table 4. Financing sources.

Financing Source	Explanation	Illustrative Examples
National taxation capital	Direct upfront cash reserves drawn from the central government's savings and explicitly earmarked for building infrastructure [96].	Administered via capital allocation programs like the UK Government Capital Spending Review or the Levelling Up Fund [97,98].
National debt financing	Upfront capital raised by the federal government through the issuance of sovereign bonds on the global financial markets [99].	Managed by the UK Debt Management Office (DMO), which raises billions upfront by selling UK Gilts to institutional investors [100].
Debt financing: municipal bonds	Capital raised by individual city governments by selling bonds directly to investors to fund localized public works [101].	Issued via the UK Municipal Bonds Agency (UKMBA) or individual councils (e.g., Aberdeen City Council issuing listed bonds) [102].
Debt financing: collective municipal bonds	Shared debt structures where multiple local authorities pool their credit to issue a joint bond, reducing borrowing costs [103].	Issued collectively through the Public Works Loan Board (PWLB), which pools central government lending rates for local councils [104].
Debt financing: tax increment financing	Upfront loans or bonds secured against the future projected tax revenue gains generated by the new development [80].	Enabled through localized legislation allowing UK councils to borrow upfront capital specifically against retained Business Rates [105].
Borrowing through a special purpose vehicle	Creating a legally isolated subsidiary company specifically to hold the project assets, isolate financial risk, and secure targeted loans [106].	Standard practice in UK infrastructure; for example, Tideway (Bazalgette Tunnel Limited) was set up as an SPV to build London's Super Sewer [107].
Public investment bodies	State-backed development banks or national investment funds that inject upfront capital into public-interest projects [108].	Championed by the National Wealth Fund (formerly the UK Infrastructure Bank), which provides targeted equity and loans [109].

Table 4. *Cont.*

Financing Source	Explanation	Illustrative Examples
Private finance initiative	A public–private partnership structure where private consortiums take on the upfront burden to design, build, and finance the asset [106].	Historically massive in the UK as PFI/PF2 projects used to build dozens of NHS hospitals, police stations, and schools since the 1990s [110].
Private investment	Traditional upfront capital injections in the form of commercial bank equity, loans, or corporate developer financing [111].	Sourced from major institutional investors like pension funds, private equity firms, or global infrastructure investment funds [112].
Community share scheme	A mechanism allowing local citizens to buy equity or shares in a community-owned asset to raise localized upfront capital [113].	Regulated by the Financial Conduct Authority (FCA) and utilized by community-benefit societies to fund local solar farms or pubs [114].
Planning obligation	Legal agreements where private developers are forced to provide upfront funding or physical infrastructure as a condition for planning permission [115].	Legally designated as Section 106 Agreements (S106) under the Town and Country Planning Act 1990 [116,117].
Crowdfunding	Gathering small chunks of upfront capital from a massive pool of everyday individual internet users and investors [118].	Facilitated via platforms like Crowdfunder UK or Spacehive, often used by local councils to co-fund civic/park upgrades [119].
Lottery	Non-repayable capital injections drawn from national or regional lottery proceeds designated for public-good and culture projects [120].	Distributed via The National Lottery Community Fund to finance local community halls, sports fields, and arts facilities [121].
Grants	Non-repayable financial awards provided by central governments, international bodies, or institutions for specific project types [122].	Provided via schemes like the Homes England Strategic Partnership Grants to accelerate affordable housing builds [123].
Government guarantee schemes	An underwriting system where the state promises to repay lenders if the project defaults, lowering borrowing risks and interest rates [111].	Managed by the Infrastructure and Projects Authority via the UK Guarantees Scheme (UKGS), which has backed projects like the Hinkley Point C nuclear site [124].

Complementing this, Table 4 presents the corresponding financial sources generated through organizational activities and stakeholder interactions, illustrating how direct and indirect value streams collectively sustain long-term viability. Mobilizing these resources is therefore not merely a transactional exercise but a relational and strategic process: infrastructure managers must articulate value propositions that resonate with different stakeholder groups, leverage interdependencies to unlock indirect financial flows, and design funding arrangements that reinforce sustainability objectives rather than narrowly optimizing short-term returns. This integrated approach ensures that the growth engine remains financially resilient while advancing the broader societal and environmental commitments embedded in the business model.

2.1.5. Forces Driving the Evolution of Business Models

Sections 2.1.1–2.1.4 introduced the principal components of business models. However, business models are dynamic and continuously evolve in response to changes in their external environment. Four principal forces are identified in the literature as drivers of

business model evolution: innovation, global reach, public policy, and corporate social responsibility (CSR).

Innovation refers to the application of new knowledge to existing products, processes, marketing practices, or organizational structures [11]. It may take either an incremental or a radical form [11]. Consequently, innovation may involve the introduction of an entirely new business model or the adaptation of existing organizational processes and structures while maintaining the same core product or service, such as transport infrastructure.

Globalization also influences business model evolution by extending organizational activities beyond national boundaries and exposing firms to new competitive conditions [12]. While global reach may expand the geographical scope of business activities, its influence depends on the context of the study. For geographically bounded infrastructure systems, such as transport networks within the United Kingdom, globalization primarily affects organizational resources, capabilities, and assets rather than the fundamental structure and relationships that define the business model itself.

Public policy represents another significant driver of business model evolution. It has been defined as "a course of action adopted and pursued by a government" [125] (p. 124) or other public authority in response to identified societal challenges [126]. Harrington and Estes [13] further argue that public policy is closely associated with citizenship and civic participation. Given that this study conceptualizes individuals as key stakeholders, public policy is viewed as emerging, at least in part, from the collective behavior and preferences of citizens.

Corporate social responsibility (CSR) has also become an increasingly important influence on business model development. The European Commission [14] defines CSR as the integration of social, environmental, ethical, and human considerations into organizational activities with the objectives of maximizing value creation for stakeholders while identifying, preventing, and mitigating the adverse impacts of organizational actions on society and the environment.

The present study focuses on the development of a business model describing infrastructure interdependencies within a specific operating environment. Consequently, the external forces discussed above are acknowledged as contextual influences but are not explicitly incorporated as variables driving the proposed model.

2.1.6. Business Model Design

The preceding discussion demonstrates that the principal elements of business models are interconnected through continuous value flows across the organization (see Table 1). Within this framework, value creation emerges from the interaction between the growth engine and marketing activities (Figure 5).

Tables 3 and 4 operationalize the Growth Engine by identifying the stakeholders and mechanisms through which resources for infrastructure development and long-term operation are mobilized. Table 3 presents funding mechanisms—the revenue streams that sustain infrastructure services over time—while Table 4 presents financing mechanisms—the instruments used to raise upfront capital. This functional distinction highlights how financing informs the initial capital structure, while funding supports ongoing operations. Rather than serving as descriptive inventories, the tables provide the mechanism set from which an appropriate Growth Engine configuration can be assembled for a given project. They also map the stakeholders associated with each mechanism, thereby defining the actors that constitute the Growth Engine and linking these mechanisms to the Marketing Imperative, particularly where value is communicated or exchanged through user charges, subsidies, sponsorship, partnerships, or community participation. In doing so, the tables

offer the practical means through which stakeholder relationships within the business model can be operationalized.

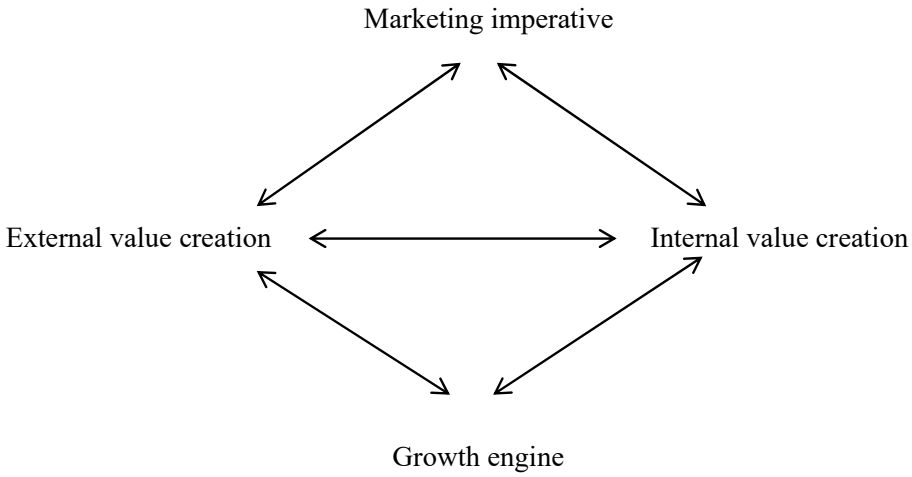


Figure 5. Business model components and relations.

In the transport sector, value may be created both internally through transport-related activities and externally through interactions with other infrastructure sectors, including water, energy, waste, communications, and other interconnected systems. Resource providers and investors, represented by the growth engine, contribute to value creation alongside successful marketing activities that attract and retain sufficient numbers of transport users. Together, these mechanisms determine the capacity of the business model to generate value.

A key challenge in developing an infrastructure business model is identifying and representing the dependencies among interconnected infrastructure systems. While business models are inherently qualitative representations of organizational relationships, value is often measured quantitatively. To bridge this gap, infrastructure interdependencies are conceptualized as functions composed of multiple value variables. Furthermore, individuals are treated as key stakeholders who actively participate in value creation rather than as passive end users.

The proposed framework distinguishes three dimensions of value: economic, social, and environmental. Each dimension is initially examined independently before its interactions are investigated using appropriate analytical methods to establish quantitative relationships. Infrastructure interdependencies are explored inductively by examining the correlations between corresponding value dimensions across different infrastructure sectors. However, as correlation alone does not imply causation [127], statistical relationships are interpreted cautiously and are evaluated against established theoretical knowledge.

Different methodological approaches were adopted to investigate each value dimension. Economic value was examined using network and cohort methodologies applied to input–output tables together with linear analytical techniques [1]. Social value was investigated through structured interviews, with the resulting primary data analyzed using appropriate statistical and geometric methods [7]. Environmental value was derived from existing studies that linked environmental impacts to the economic demand represented in input–output tables [6,128]. Finally, the interdependencies between economic and environmental value were examined using Pearson's correlation coefficient applied to secondary data, whereas social value interdependencies were analyzed using statistical methods applied to primary data.

3. Empirical Foundation of the Integrated Framework

The integrated infrastructure business model developed in this paper is founded on three complementary empirical studies addressing the economic, environmental, and social dimensions of infrastructure value. Sections 3.1–3.3 summarize these previously published studies, which are incorporated as secondary empirical evidence rather than presented as original empirical findings of the current research. Their purpose is to establish the three value dimensions that form the inputs to the integrated framework developed in the subsequent sections. The novel contribution of the present study lies in the synthesis of these independent value dimensions into a unified infrastructure business model and the development and validation of the associated interdependency framework.

Economic value in infrastructure aligns closely with the principles of the linear economy and shareholder capitalism. It is commonly defined as the increase in economic prosperity generated through infrastructure investment, whether aimed at improving existing systems or constructing new ones [129]. Transport infrastructure, in particular, contributes to economic growth by facilitating networks for trade between societies [130]. Such investments are long-lived, require substantial capital, and deliver their benefits over extended periods [130]. Within shareholder capitalism and the linear economy, short-term profitability is often prioritized over long-term societal benefit, leaving limited incentive for infrastructure to retain value over time. In contrast, circular economy principles capture the long-term sustainable benefits of infrastructure, while stakeholder capitalism emphasizes societal goals such as resilience, which align more closely with the long-term nature of infrastructure systems.

Environmental value refers to the importance and wellness of nature [131]. Infrastructure construction and maintenance inevitably impose environmental costs, yet these actions simultaneously fulfil essential human needs. Applying environmental value to infrastructure therefore requires recognizing that infrastructures are built to support human life and quality of life [128]. Andersen [132] examined environmental value in relation to human activity and categorized it into amenity value, natural resource base, a sink for residual economic activity, and a fundamental life support system. Environmental amenity value represents the inherent value individuals derive from the environment without additional interference [132]. It is highly subjective, shaped by personal experiences, preferences, and cultural factors [133], and is therefore examined in this research as part of social value.

The next two categories—environment as a resource base and as a sink for residual flows—reflect an economic perspective. As previously discussed, the environment provides renewable and non-renewable inputs into economic production and absorbs waste from human activity [132]. These categories align with the input-output circular economy models and can be studied using environmental input-output tools [134] such as EXIOBASE. The final category, environment as a life support system, is considered but not adopted in its original form, as Andersen's approach [132] is purely economic and does not fully align with sustainability principles. It nevertheless informed the division of economic, social, and environmental values in this research.

Infrastructure projects affect ecosystems by altering or destroying habitats [135]. Such impacts are typically addressed at the project scale through tools like Habitat Conservation Plans, which focus on construction-related effects rather than systemic interactions [135]. At a broader scale, new infrastructure may interact with other infrastructures or environments, amplifying environmental impacts. Natural resources are required to construct and operate infrastructure systems, and many natural resources have a reciprocal relationship with infrastructure, as their extraction often depends on significant infrastructural support [136]. Economists study natural resource scarcity as a factor influencing economic growth [137], and when analyzing natural resource consumption they consider development patterns,

noting, for example, that low-density regional development consumes more resources per capita and per linear meter than dense urban development [138,139].

These perspectives reveal how deeply shareholder linear economy thinking is embedded in economic analysis. Economists often conceptualize the environment as a sink for economic residuals, including waste and emissions [132], and view human-built infrastructure as a mechanism for metabolizing pollution that exceeds natural absorption capacity. This approach becomes problematic because environmental limits are undefined. Global climate change exemplifies this issue: scientific evidence indicates that the environment's capacity to absorb carbon is reaching its limit, yet there is no clear societal pathway for reducing emissions. Moreover, it is unclear how emissions generated by one sector interact with those generated by others. This research examines these interactions across sectors. Since no technology exists to expand environmental capacity, the study explores ways to limit residuals through changes in individual behavior. Although defining environmental limits lies outside the scope of this research, its findings can inform future studies on sectoral interactions and behavioral influences on environmental thresholds.

Infrastructure also extends the environment's life support function by providing access to water, energy, and shelter [140]. Pollution accumulation affects the final form of environmental value, and if infrastructure fails to support or adversely impacts human life, it generates economic consequences in addition to environmental ones [140]. The discussion above illustrates the difficulty of disentangling environmental value from economic value within current socio-political contexts. This interdependence underscores the need for an interdisciplinary approach capable of capturing the full spectrum of value associated with infrastructure systems.

The discussion of infrastructure and environmental value reveals a pattern that connects directly to themes in the social sciences. Policy- and decision-makers are often influenced by tangible short-term economic gains and political considerations, particularly when environmental value becomes less certain or more difficult to quantify [141]. In the context of this research, which examines business models, the value proposition plays a central role in implementation. A value proposition articulates the essence of a business model, defining how products and services are assembled and delivered to final users in order to meet their needs [142]. To understand how infrastructure meets human needs, it is necessary to draw on established social science frameworks. Three main approaches dominate the literature: the theory of human needs [143,144], the capability approach [145,146], and Maslow's hierarchy of needs [147].

Both the theory of human needs and the capability approach conceptualize needs as non-hierarchical and non-substitutable. However, the theory of human needs is highly abstract and therefore unsuitable for tactical and pragmatic questions, such as those encountered in engineering. The capability approach, while influential, has been criticized for overlooking the needs of the most vulnerable people. This research aims to develop a new business model without ignoring vulnerable populations, and therefore requires a framework that is both pragmatic and inclusive. For these reasons, Maslow's hierarchy of needs is adopted as the most appropriate tool for determining the social value of infrastructure projects. In Maslow's hierarchy, value is linked to the satisfaction of individual needs rather than productivity or income. To address the productivity/income gap, the analysis incorporates not only Maslow's hierarchy but also expected utility theory, which is grounded in income-based decision-making. The central challenge of Maslow's approach lies in determining the satisfaction of a need both quantitatively and qualitatively.

Maslow's hierarchy acknowledges that value is subjective, but it does not account for the broader impacts of individual decisions when the scope of those decisions affects diverse stakeholders, including those from different temporal scales (such as future generations) or

spatial scales (such as stakeholders in different regions). Infrastructure may be extremely valuable to some individuals and meaningless to others [133]. Consequently, achieving an optimal level of social value is inherently complex because stakeholders possess different needs and priorities [148]. A second source of ambiguity arises from the spatial scale of infrastructure decisions. When decisions affect stakeholders with varying priorities in their hierarchy of needs, determining the genuine social value of a project becomes even more challenging [148].

Stakeholder theory defines a stakeholder broadly as anyone who can affect or be affected by a decision [149]. As the number of stakeholders increases, conflicts over values and value uncertainty also increase [148]. Furthermore, when more subjective stakeholder needs are impacted, the likelihood of conflict rises [148]. Under such circumstances, determining the true environmental or economic value of infrastructure using Maslow's hierarchy becomes difficult. This reinforces the methodological decision in this research to study environmental and economic values independently from social value. To address stakeholder conflict and value uncertainty, the results are generalized using statistical tools based on the responses of the vast majority of stakeholders.

This approach ensures a clear and consistent narrative throughout the disciplinary context, underpinning the assumptions and methods used and demonstrating that these are sufficiently coherent and robust to justify the conclusions drawn in the subsequent sections.

There is ongoing debate about the value of the benefits generated by infrastructure systems—specifically those of energy, water and wastewater, transport, waste, and communications—and about how infrastructure investments should be prioritized to incorporate social, economic, and environmental wellbeing. The use of the term 'infrastructure system' is inherently related to interdependencies. Although infrastructure systems operate differently across countries and cities, they all maintain a strong relationship with transport, since movement entails both cost and utility. Infrastructure systems are ultimately created to serve individuals, who place value on them. To explore all forms of value realization—commonly conceptualized as a business model—it is necessary to establish the relationship between individuals and the transport system. The hypothesis being tested in this research is that it is possible to identify multiple value dimensions relevant to infrastructure decision-making associated with transport infrastructure, including social, economic, and environmental wellbeing, and to establish the interdependencies with the other four infrastructure sectors across England, Scotland, Wales, and Northern Ireland, thereby enabling the development of robust alternative business models for transport infrastructure interdependencies management.

Sections 3.1–3.3 do not present new empirical analyses. They summarize the methodologies and principal findings of three previously published studies [1,6,7], which constitute the empirical inputs to the integrated framework developed in this paper. Consequently, the statistical analyses reported in those studies, including the economic regression modelling and the environmental correlation analysis, are not reproduced or extended here. Only the findings relevant to the integrated framework are presented.

3.1. The Economic Value of Transport Infrastructure

Input–output tables are used in this research because they provide a consistent, transparent, and ideologically neutral way to analyze how economic sectors depend on one another. Input–output tables rely on a globally standardized system of equations developed originally by Leontief. They trace value flows across an economy by linking each sector's demand to the inputs it requires from other sectors, thereby revealing structural interdependencies. Their matrix structure—where rows represent sectoral outputs and

columns represent sectoral inputs—allows researchers to observe how changes in one sector propagate through the rest of the economy [150,151].

Another reason for using input–output tables is their capacity to quantify both direct and indirect economic effects. They are widely used to model large-scale phenomena such as infrastructure systems, because they capture how shocks—recessions, expansions, emergencies, or infrastructure changes—affect the wider economy [152,153]. Their transparency, low data requirements, and accessibility make them cost-effective tools for analyzing sectoral relationships [150,154]. Although they are often used to study shocks, they can also describe routine, steady-state conditions, which is the focus of this research. A well-calibrated input–output model can reveal systematic economic benefits that may not be visible through traditional appraisal methods such as CBA [155].

Finally, input–output tables are appropriate for this study because they allow the modelling of infrastructure interdependencies at the system level, rather than at the level of individual projects—where the method is less suitable [156]. While they have limitations, such as assuming fixed prices, homogeneous sector outputs, and a demand-driven economy [157,158], these constraints do not hinder this research. The required tables are already provided by the World Input–Output Database, and the study focuses on infrastructure as a whole rather than specific projects. For these reasons, input–output tables offer a robust, transparent, and internationally recognized foundation for analyzing economic value interdependencies in transport infrastructure.

This research adopts a top-down analytical framework based on the World Input–Output Database (WIOD) aggregate national accounts for the United Kingdom, using the 2016 release covering the period 2000–2014 [1]. The analysis follows the International Standard Industrial Classification (ISIC) structure provided by WIOD and employs product-by-product input–output tables balanced using the RAS method [159]. The transport sector was modelled as the dependent variable, with the energy, water, communication, waste, and other economic sectors serving as explanatory variables in the regression analysis. Several alternative combinations of regression specifications were also tested; however, these models are not presented here because they did not yield statistically reliable or interpretable results due to persistent multicollinearity.

Given the extent of multicollinearity observed among the predictors, Principal Component Analysis (PCA) was applied to reduce dimensionality and eliminate linear dependencies [127]. PCA transforms correlated variables into a smaller set of orthogonal components, ensuring stable and interpretable regression coefficients. This step was necessary because the original regression structure exhibited unstable behavior due to strong interdependencies among infrastructure sectors.

PCA was conducted on the value-added data of WIOD, including the four infrastructure sectors of interest (energy, waste, water, and communication) together with the remaining economic sectors. The sector Activities of extraterritorial organizations and bodies was excluded because it contained zero values throughout the study period. After standardization, PCA was performed on 46 variables, generating 46 principal components that capture the underlying variance structure of the economy while resolving multicollinearity prior to regression modelling.

PCA transforms correlated variables into a smaller number of uncorrelated components through linear combinations that maximize the explained variance [127]. This procedure reduces multicollinearity while preserving most of the information contained in the original variables [127]. Eigenvalues were used to determine the number of components to retain, following the Kaiser criterion (eigenvalues > 1) [127], supported by visual inspection of the scree plot (Figure 6).

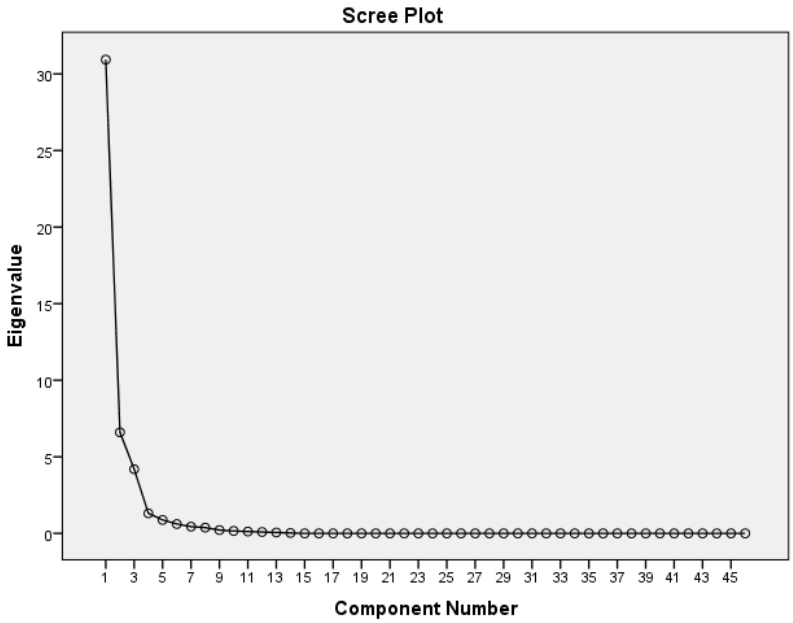


Figure 6. Eigenvalues of the correlated variables.

As illustrated in Figure 6, the first four components have eigenvalues greater than one, while the remaining components contribute only marginally to the explained variance. The first four retained components explain 93.54% of the total variance, with the first component accounting for 67.24%, the second for 14.35%, the third for 9.11%, and the fourth for 2.84%. These four components were therefore retained for further analysis. The eigenvalues decrease sharply after the fourth component, supporting the retention of four principal components.

The component matrix (Table 5) and the rotated component matrix (Table 6) were subsequently examined to identify the variables most strongly associated with each retained component. Rather than using the component scores directly in the regression model, the variables with the highest loadings were selected to preserve their original economic interpretation and measurement units. This approach enabled the development of an interpretable regression model while substantially reducing multicollinearity among the explanatory variables.

Table 5. Principal component analysis factors—Component Matrix (4 components extracted).

Components	1	2	3	4
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	0.984			
Administrative and support service activities	0.984			
Computer programming, consultancy and related activities; information service activities	0.984			
Accommodation and food service activities	0.981			
Architectural and engineering activities; technical testing and analysis	0.979			
Telecommunications (Communication)	0.975			
Legal and accounting activities; activities of head offices; management consultancy activities	0.975	−0.205		
Public administration and defence; compulsory social security	0.967			

Table 5. *Cont.*

Components	1	2	3	4
Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	0.966			
Human health and social work activities	0.960	−0.224		
Advertising and market research	0.959			
Education	0.958	−0.250		
Other professional, scientific and technical activities; veterinary activities	0.957			
Other service activities	0.956	−0.258		
Construction	0.955	0.206		
Manufacture of furniture; other manufacturing	0.954		−0.214	
Water collection, treatment and supply (Water)	0.946	−0.200		
Scientific research and development	0.932			
Fishing and aquaculture	0.925			
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services (Waste)	0.917		0.303	
Postal and courier activities	0.914		0.282	
Insurance, reinsurance and pension funding, except compulsory social security	0.908		−0.247	
Manufacture of fabricated metal products, except machinery and equipment	0.906	0.339		
Real estate activities	0.894	−0.344	−0.210	
Manufacture of paper and paper products	0.892			
Financial service activities, except insurance and pension funding	0.890		0.352	
Activities auxiliary to financial services and insurance activities	0.881	−0.438		
Manufacture of food products, beverages and tobacco products	0.859			−0.438
Manufacture of basic pharmaceutical products and pharmaceutical preparations	0.820	−0.500		
Mining and quarrying	0.792		0.336	0.440
Manufacture of rubber and plastic products	0.789	0.322	−0.346	−0.333
Crop and animal production, hunting and related service activities	0.784			
Electricity, gas, steam and air conditioning supply (Energy)	0.768	−0.329	−0.265	−0.221
Manufacture of machinery and equipment n.e.c.	0.761	0.397	−0.301	
Repair and installation of machinery and equipment	0.646	0.270	−0.328	0.304
Printing and reproduction of recorded media		0.882	0.394	
Manufacture of chemicals and chemical products	0.239	0.867	0.266	−0.204
Manufacture of other non-metallic mineral products	0.351	0.849	0.293	
Manufacture of electrical equipment	0.440	0.691	−0.341	
Manufacture of basic metals	0.420	0.683	−0.385	0.348

Table 5. *Cont.*

Components	1	2	3	4
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	0.594	0.679	0.383	
Publishing activities	0.635	0.647	0.391	
Manufacture of coke and refined petroleum products	0.465	−0.644	0.466	
Forestry and logging	0.294	0.381	0.834	
Manufacture of textiles, wearing apparel and leather products	0.295	0.438	−0.808	
Manufacture of computer, electronic and optical products	0.501		−0.684	0.256

Table 6. Principal component analysis factors—Rotated Component Matrix (Rotation Method: Varimax with Kaiser Normalization—Rotation converged in 6 iterations).

Components	1	2	3	4
Education	0.990			
Human health and social work activities	0.986			
Legal and accounting activities; activities of head offices; management consultancy activities	0.976			
Activities auxiliary to financial services and insurance activities	0.974			
Public administration and defence; compulsory social security	0.974			
Other service activities	0.968		0.208	
Computer programming, consultancy and related activities; information service activities	0.965			
Administrative and support service activities	0.962		0.235	
Manufacture of basic pharmaceutical products and pharmaceutical preparations	0.949			
Postal and courier activities	0.948	0.210		
Architectural and engineering activities; technical testing and analysis	0.948		0.264	
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	0.936	0.225	0.212	
Other professional, scientific and technical activities; veterinary activities	0.930		0.295	
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services (Waste)	0.930	0.267		
Water collection, treatment and supply (Water)	0.929		0.311	
Financial service activities, except insurance and pension funding	0.928	0.251		
Real estate activities	0.925		0.278	
Telecommunications (Communication)	0.916	0.322		
Fishing and aquaculture	0.897		0.235	
Accommodation and food service activities	0.896	0.202	0.317	0.226

Table 6. *Cont.*

Components	1	2	3	4
Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	0.893	0.312		0.216
Advertising and market research	0.849	0.257	0.349	0.204
Insurance, reinsurance and pension funding, except compulsory social security	0.847		0.360	0.267
Manufacture of furniture; other manufacturing	0.845		0.456	
Scientific research and development	0.845	0.387	0.225	
Construction	0.828	0.495	0.233	
Electricity, gas, steam and air conditioning supply (Energy)	0.805		0.202	0.300
Manufacture of food products, beverages and tobacco products	0.764	0.314		0.477
Manufacture of paper and paper products	0.757	0.300	0.369	0.234
Manufacture of coke and refined petroleum products	0.714		−0.470	−0.337
Mining and quarrying	0.706	0.449		−0.470
Manufacture of fabricated metal products, except machinery and equipment	0.691	0.394	0.566	
Crop and animal production, hunting and related service activities	0.662	0.224	0.366	0.219
Manufacture of rubber and plastic products	0.580	0.297	0.535	0.496
Printing and reproduction of recorded media		0.947		
Manufacture of other non-metallic mineral products		0.928	0.258	
Manufacture of chemicals and chemical products		0.916		
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	0.349	0.905		
Publishing activities	0.399	0.889		
Forestry and logging	0.227	0.811	−0.329	−0.364
Manufacture of textiles, wearing apparel and leather products			0.954	
Manufacture of basic metals		0.412	0.851	
Manufacture of computer, electronic and optical products	0.324		0.820	
Manufacture of electrical equipment		0.464	0.762	
Manufacture of machinery and equipment n.e.c.	0.517	0.325	0.702	
Repair and installation of machinery and equipment	0.450		0.666	

PCA was employed exclusively as a dimensionality-reduction and multicollinearity-reduction technique. The retained components were subsequently used to identify representative economic sectors, which were then entered into the multiple linear regression model. Therefore, PCA was not used to predict the dependent variable directly but to support the specification of the regression model. Transport was considered the dependent variable only in the regression analysis and not during the PCA procedure.

To estimate the impact of the determinants on the dependent variable transport, a combined approach using Principal Component Analysis (PCA) and Multiple Linear Regression was conducted. Transport value was subsequently modelled as the dependent variable using multiple linear regression (Table 7).

Table 7. Final reconstructed economic coefficients model.

	Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
Model	**B**	**Std. Error**	**Beta**	**t.**	**Sig.**	**Tolerance**	**VIF**
(Constant)	30,507.785	33,157.797		0.920	0.379		
Energy	1.299	0.160	0.178	8.119	0.000	0.365	2.740
Waste	1.739	0.195	0.237	8.918	0.000	0.342	2.924
Communication	1.687	0.195	0.230	8.651	0.000	0.355	2.817
Water	1.735	0.196	0.236	0.852	0.000	0.348	2.874
Printing	1.947	2.059	0.063	0.946	0.366	0.772	1.295
Manufacturetextiles	5.131	3.189	0.098	1.609	0.139	0.930	1.075
Mining	0.546	0.614	0.092	0.888	0.395	0.322	3.109

The final regression model included the four sectors of interest together with the representative variables identified through PCA. The resulting model substantially reduced multicollinearity (VIF < 5 for all variables) while explaining 96.5% of the variance (R^2 = 0.965) (Table 8).

Table 8. R^2 of the final reconstructed economic coefficients model.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
	0.983	0.965	0.952	12,890.002

These findings underscore that the value of transport infrastructure extends far beyond direct user benefits, generating substantial indirect effects through interconnected supply chains and supporting systems.

$$Y_{cr} = 1.299\ X_{cr1} + 1.739\ X_{cr2} + 1.687\ X_{cr3} + 1.735\ X_{cr4} + 1.947\ X_{cr5} + 5.131\ X_{cr6} + 0.546\ X_{cr7} + 30{,}507.785 \quad (1)$$

where X_{cr1}: Value Added from Energy, X_{cr2}: Value Added from Waste, X_{cr3}: Value Added from Communication, X_{cr4}: Value Added from Water, X_{cr5}: Value Added from Printing and Reproduction of Recorded Media, X_{cr6}: Value Added from Manufacture of Textiles, Wearing Apparel and Leather Products, X_{cr7}: Value Added from Mining and Quarrying.

The very high explanatory power of the reconstructed regression model requires careful interpretation. The dependent variable and explanatory variables are all sectoral value-added measures derived from the same WIOD input-output accounting framework and are therefore embedded within a common system of national accounts. Consequently, the observed R^2 should not be interpreted as evidence of an independently identified causal effect of the explanatory sectors on transport value-added. Part of the high explanatory power may reflect the common accounting structure and the inherent interrelationships among sectoral value-added measures. The regression is therefore used here primarily to represent empirical associations and economic interdependencies between transport and other sectors rather than to establish causality. The VIF results indicate that multicollinearity was substantially reduced in the final specification, while the adjusted R^2 provides a measure of model fit after accounting for the number of predictors. Nevertheless, these diagnostics do not eliminate the possibility that the high explanatory power partly reflects the accounting structure of the input-output system. The regression findings are therefore interpreted cautiously and in conjunction with the broader input-output framework rather than as an independent causal estimate of infrastructure value creation.

The findings demonstrate that transport infrastructure is economically complemented by energy, water, communication, and waste infrastructures, confirming that infrastructure investments create benefits extending far beyond the sector in which they originate. Consequently, effective infrastructure planning and policy should explicitly recognize these

interdependencies and adopt integrated, value-based approaches that support long-term sustainability and resilience. These conclusions underscore the importance of combining engineering and economic perspectives when evaluating and designing future infrastructure systems.

3.2. The Environmental Value of Transport Infrastructure

This research examines competing perspectives on environmental value and sustainability, emphasizing that infrastructure both depends upon and affects natural systems. The literature distinguishes between intrinsic, instrumental, and relational environmental values and contrasts weak and strong sustainability paradigms [6,30,128]. Previous research on the environmental assessment of infrastructure has largely relied on life cycle assessment (LCA), ranging from project-specific analyses to holistic frameworks incorporating circularity and multiple forms of capital [6,30]. However, the review demonstrates that bottom-up approaches become increasingly impractical when the object of study is an entire infrastructure sector or national infrastructure system, thereby motivating the use of hybrid methods capable of capturing system-wide effects [6,30].

Different forms of LCA exist, with particular attention devoted to the hybrid environmentally extended multi-regional input–output approach implemented through Environmentally Extended Multiregional Input–Output (EE MRIO) tables [6,160,161]. The latter combines environmental accounts with economic input–output tables, enabling a comprehensive assessment of emissions across sectors and regions.

Environmentally Extended Multiregional Input–Output (EE MRIO) tables are used in this research because they allow us to analyze environmental impacts together with economic interdependencies across sectors in a consistent, system-wide framework [5]. EXIOBASE 3, the EE MRIO database applied here, integrates conventional input–output tables—which map the flow of goods and services between sectors [162,163]—with detailed environmental extensions, including emissions and resource use. Developed through the EXIOPOL, CREEA, and DESIRE projects [164], EXIOBASE 3 combines monetary data with physical supply-use information [165], enabling a hybrid analytical approach grounded in both economic structure and environmental accounting [166].

EXIOBASE 3 is used because it captures complex cross-sectoral and cross-border environmental relationships, making it highly suitable for analyzing infrastructure systems whose impacts extend beyond national boundaries. Its high sectoral resolution and global coverage allow policymakers to understand how resource use and emissions are distributed across interconnected activities [5]. This system-wide perspective is essential for evaluating infrastructure, which interacts with multiple sectors through both material and service exchanges. As a result, EXIOBASE 3 supports large-scale, strategic environmental decision-making, offering consistent macroeconomic and environmental data across countries [5,164].

However, EXIOBASE 3 also has limitations that shape how it can be used in this research. Its detailed coverage includes only 43 countries, with the rest aggregated into world regions [167], and its time series is restricted to 1995–2011 [164]. Some environmental flows are not fully reported, reducing detail for certain impact categories and requiring sensitivity analysis [168,169]. Most importantly, EXIOBASE 3 is not designed for assessing individual infrastructure projects, as its top-down structure provides system-level insights rather than project-specific environmental valuations. For this reason, we use EXIOBASE 3 to understand overall environmental interdependencies, not to compare single projects.

Using the EXIOBASE 3 aggregate national dataset, the study analyses the transport sector and its interdependencies with the energy, water, waste, and communication sectors.

Pearson's correlation coefficients are employed to identify robust environmental linkages among infrastructure sectors.

Secondary data regarding transport emissions were sourced from existing literature, specifically utilizing the EXIOBASE 3 database. This database comprises 85 distinct emission types encompassing both atmospheric and aquatic pollution, structured through environmentally extended multi-regional input-output (EE-MRIO) tables coupled with national economic input-output frameworks [5].

Given the scope and resource constraints of this research, an inductive approach (Figure 7) was employed to refine the dataset, focusing exclusively on emissions relevant to the specific objectives of this study rather than developing a comprehensive deductive theory for all emission types. The analytical boundaries are confined to the following sectors: transport, energy, water, waste, and communication. Emissions were cross-referenced with their respective Input-Output Groups (IOGs) to determine relevance. Notably, the sectoral categorization applied in this environmental analysis diverges from the classification schema used in standard economic input-output tables.

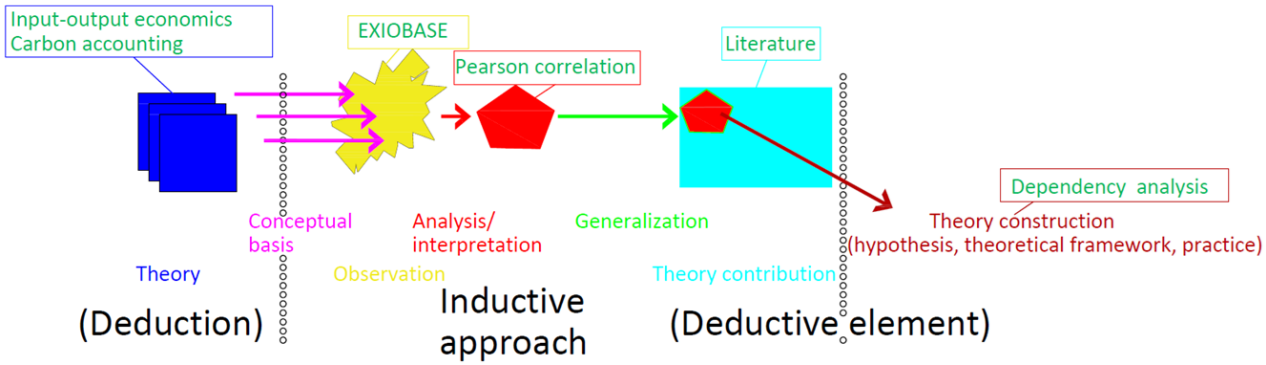


Figure 7. Inductive research workflow adopted in the EXIOBASE analysis [30].

Empirical analysis indicated that 26 distinct emissions originate from the transport sector [5]. In alignment with inductive methodology, these empirical findings were subsequently mapped to existing theoretical frameworks: 23 of the 26 identified emissions are accounted for by COPERT (Calculation of Emissions from Road Transport), an engineering combustion model [170]. Of the remaining three emissions, Arsenic (As) and Mercury (Hg) are generated exclusively by maritime transport, while Non-Methane Volatile Organic Compounds (NMVOCs) constitute a non-combustion pollutant [5].

Total emission outputs were derived by synthesizing sectoral economic demand data published by the UK Government (see Section 3.1) with pollutant-specific environmental coefficients. The total volume of each emission is mathematically defined as the product of sectoral demand and its corresponding environmental coefficient. The specific environmental coefficients (called characterization factors in LCA) for the UK transport sector are detailed in Table 9.

Table 9. Factors for transforming I-O tables to emissions.

Emission	/M.EUR	Transport via Railways	Other Land Transport	Transport via Pipelines	Sea and Coastal Water Transport	Inland Water Transport	Air Transport
CO_2	kg	111,343.9	75,817.3	71,681.49	1,108,655.203	1.83×10^7	1,862,350.55
CH_4	kg	6.238257	4.54647	4.298415	78.72147886	1256.948296	14.3246283
N_2O	kg	42.21357	28.65806	27.09408	73.19358565	4603.169686	53.2051471
SO_x	kg	17.04783	1.969464	1.861975	17,143.43579	152,268.3867	568.83487

Table 9. *Cont.*

Emission	/M.EUR	Transport via Railways	Other Land Transport	Transport via Pipelines	Sea and Coastal Water Transport	Inland Water Transport	Air Transport
NO_x	kg	1811.144	519.2538	490.9285	25,327.8992	408,003.4647	6118.75415
NH_3	kg	0.270514	1.05822	1.000488	0.05264327	0.047646388	0.17962125
CO	kg	371.9159	178.2455	168.5243	2609.062487	41,939.39313	11,860.3205
Benzo(a)-pyrene	kg	0.001062	0.00117	0.001106	6.13×10^{-5}	5.55×10^{-5}	0.0020887
Benzo(b)-fluoranthene	kg	0.001836	0.004233	0.004003	0.007221654	0.113501983	0.00240859
Benzo(k)-fluoranthen	kg	9.78×10^{-4}	6.61×10^{-4}	6.25×10^{-4}	2.80×10^{-5}	2.54×10^{-5}	1.22×10^{-4}
Indeno(1,2,3-cd)pyrene	kg	6.25×10^{-4}	4.27×10^{-4}	4.04×10^{-4}	0.003532855	0.056681484	6.18×10^{-5}
PCDD_F	kg I-TEQ	2.70×10^{-9}	2.46×10^{-9}	2.33×10^{-9}	1.13×10^{-10}	1.02×10^{-10}	4.57×10^{-10}
NMVOC	kg	160.2165	28.55117	26.99358	844.7898495	13,600.89201	435.243209
PM_{10}	kg	50.23377	30.27385	28.62203	2122.43322	18,402.08881	12.4706341
$PM_{2.5}$	kg	47.76662	27.92559	26.40159	2122.333157	18,402.00751	57.8458301
TSP	kg	53.38177	44.33343	41.91496	2123.055043	18,402.64132	14.1566342
As	kg	0	0	0	154.8712546	1086.557878	0
Cd	kg	3.51×10^{-4}	2.74×10^{-4}	2.59×10^{-4}	9.292351941	65.21871018	9.31×10^{-5}
Cr	kg	0.001817	0.003572	0.003377	0.063771562	0.574430091	7.68×10^{-4}
Cu	kg	0.06095	0.092727	0.087669	154.87521	1086.561458	0.02219303
Hg	kg	0	0	0	6.197080476	43.62924232	0
Ni	kg	0.002449	0.001726	0.001632	9.294917712	65.42838692	6.47×10^{-4}
Pb	kg	0.009344	0.006423	0.006072	0.066397099	0.784160389	0.00138649
Se	kg	3.51×10^{-4}	3.02×10^{-4}	2.85×10^{-4}	0.132253666	1.567866517	9.63×10^{-5}
Zn	kg	0.035647	0.047423	0.044836	0.301652597	3.70419127	0.01178429
NMVOC (NC)	kg	94.03963	117.3346	1.142945	11.18485141	22.71792767	44.9018179
Benzo(b)-fluoranthene	kg	0.001836	0.004233	0.004003	0.007221654	0.113501983	0.00240859
Benzo(k)-fluoranthen	kg	9.78×10^{-4}	6.61×10^{-4}	6.25×10^{-4}	2.80×10^{-5}	2.54×10^{-5}	1.22×10^{-4}
Indeno(1,2,3-cd)pyrene	kg	6.25×10^{-4}	4.27×10^{-4}	4.04×10^{-4}	0.003532855	0.056681484	6.18×10^{-5}
PCDD_F	kg I-TEQ	2.70×10^{-9}	2.46×10^{-9}	2.33×10^{-9}	1.13×10^{-10}	1.02×10^{-10}	4.57×10^{-10}
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Hg	kg	0	0	0	6.197080476	43.62924232	0
Ni	kg	0.002449	0.001726	0.001632	9.294917712	65.42838692	6.47×10^{-4}

To analyze inter-sectoral relationships, a correlation analysis was constructed for each pollutant across the sectors of interest, using Carbon Dioxide as an illustrative baseline (see Figure 8). The dataset was refined using a two-step filtering process:

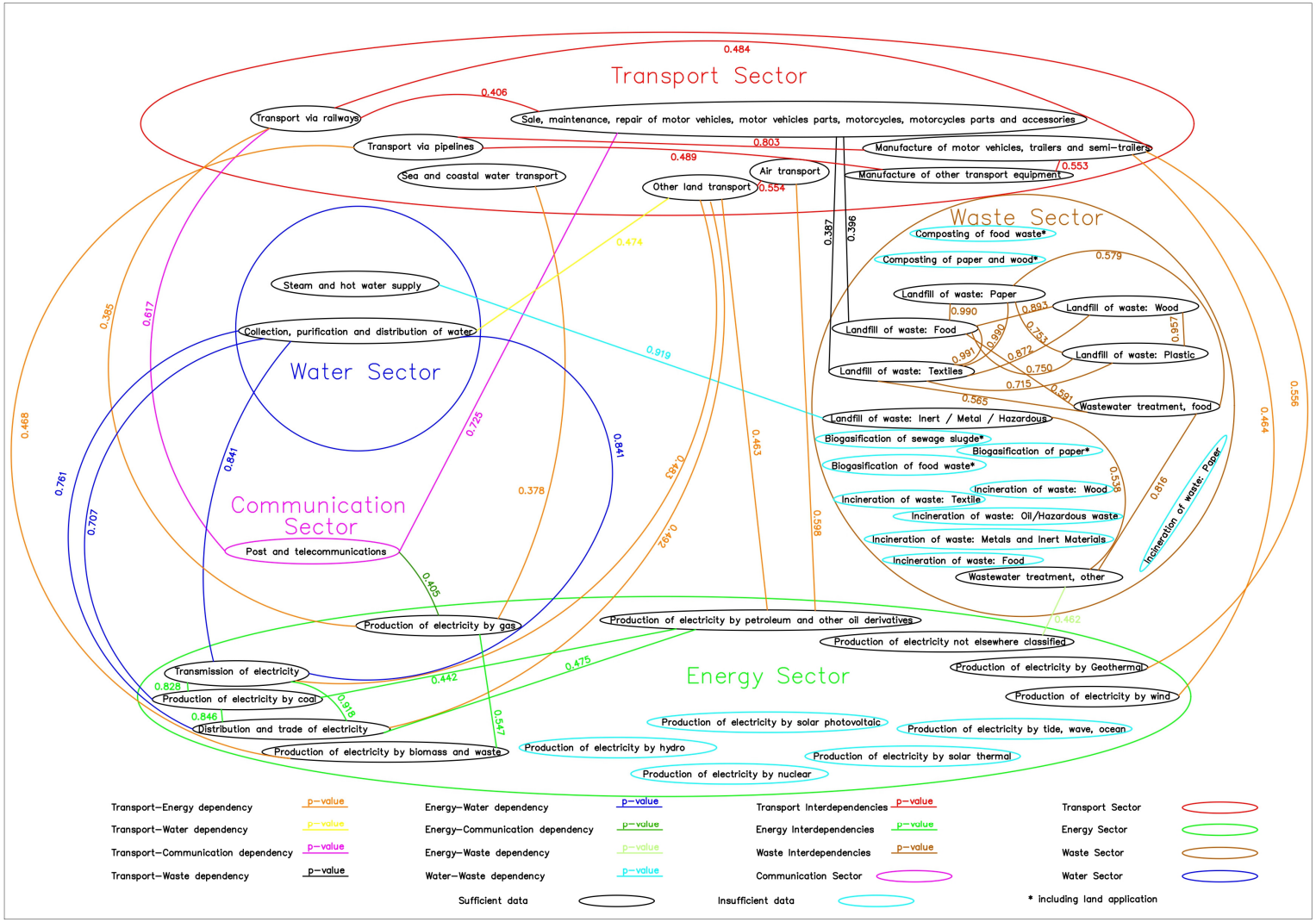


Figure 8. EXIOBASE3-based cross-sectoral CO_2 interdependency analysis [6].

Intra-group Collinearity: Sectors operating within the same aggregate group were highlighted and excluded from further analysis to avoid redundancy.

Data Completeness Threshold: Connections exhibiting a missing data rate exceeding 10% were systematically omitted. For instance, while the 'Energy-Nuclear' sector may exhibit dependencies with other sectors, it was excluded because nuclear energy infrastructure is absent across a significant portion of the sampled regions, rendering robust connection identification unfeasible.

Pearson's correlation analysis was used to identify statistical associations among environmental indicators contained in the EXIOBASE 3 environmental extensions. These statistical associations were not interpreted as evidence of causal relationships. Instead, they were subsequently compared with the dependency framework previously developed through an inductive methodology and with the wider environmental literature [6,30,171] (Figure 8).

Pearson correlation coefficients were evaluated using two-sided significance tests, with ($p < 0.05$) adopted as the statistical significance threshold. No adjustment for multiple comparisons, such as the Bonferroni, Holm, or false-discovery-rate procedures, was applied. The correlation analysis was used primarily as an exploratory screening procedure to identify potentially relevant cross-sectoral interdependencies rather than as a set of independent confirmatory hypothesis tests. Accordingly, statistical significance was not interpreted as evidence of causality. Significant associations were subsequently examined against established theoretical and environmental literature, and only relationships supported by both the statistical evidence and a plausible theoretical mechanism were incorporated into the integrated business model.

After statistical screening, the remaining correlations were checked against established environmental and economic literature. Any relationship lacking a plausible causal mechanism or documented empirical support was marked for qualitative re-assessment.

Accordingly, the dependency relationships used in the integrated business model are supported by the combined statistical evidence and theoretical interpretation rather than by the correlation coefficients alone.

This systematic filtering and literature review protocol was replicated for the remaining 25 emissions [30], with the consolidated results compiled in Table 10.

The analysis reveals extensive environmental interdependencies, particularly between transport and energy, with correlations observed for most major air pollutants and greenhouse gases. Significant, albeit weaker, relationships are also identified between transport and the communication, water, and waste sectors. Land transport exhibits the greatest number of cross-sectoral connections, while communication and water infrastructures display notable dependencies on transport and energy, respectively. These findings demonstrate that environmental impacts are propagated through interconnected infrastructure systems rather than remaining confined to individual sectors.

Hybrid LCA approaches such as EXIOBASE are particularly well suited to strategic infrastructure planning and policy-making at regional and national scales. By explicitly accounting for environmental interdependencies, decision-makers can develop integrated policies and deploy innovative technologies that simultaneously reduce emissions and enhance sustainability across multiple sectors.

Table 10. Transport emissions interdependencies.

Emission	Transport (General)	Air Transport	Land Transport	Water Transport
CO_2	Energy; Communication; Water; Waste	Energy; Communication; Water; Waste	Energy; Communication; Water; Waste	Energy; Communication; Water; Waste
CH_4	Energy	Energy	Energy	–
N_2O	Energy; Communication	–	Energy; Communication	–
SO_x	Energy; Communication; Water; Waste	Energy; Waste	Energy; Communication;	–
NO_x	Energy; Communication; Water; Waste	Communication	Energy; Communication; Water	–
NH_3	Energy; Communication; Water; Waste	Energy; Water; Waste	Energy; Communication; Water; Waste	Energy; Water; Waste
CO	Energy; Communication; Water; Waste	Energy; Communication	Energy; Communication; Water; Waste	–
Benzo(a)pyrene	Energy; Communication; Waste	–	Energy; Communication; Waste	–
Benzo(b)fluoranthene	Energy; Communication; Waste	–	Energy; Communication	Energy
Benzo(k)fluoranthene	Energy; Communication	Energy	Energy; Communication	Energy
Indeno(1,2,3-cd)pyrene	Energy; Communication; Water	Energy	Energy	–
PCDD_F	–	–	–	–
NMVOC	Energy; Communication; Water	Energy	Energy; Communication; Water	–
PM_{10}	Energy; Communication; Water	Energy	Energy; Communication; Water	–
$PM_{2.5}$	Energy; Communication; Water	Energy	Energy; Communication; Water	–
TSP	Energy; Communication; Water	Energy	Energy; Communication; Water	Energy
As	–	–	–	–
Cd	Energy; Water	Energy; Water	Energy; Water	–
Cr	Energy; Communication	Energy	Energy; Communication	–
Cu	Energy; Communication; Water	Energy	Energy; Communication; Water	Waste
Hg	–	–	–	–
Ni	Energy	Energy	Energy	–
Pb	Energy; Communication; Water	Energy; Water	Energy; Communication; Water	–
Se	Energy; Communication; Water	Energy	Energy; Communication; Water	–
Zn	Energy; Communication; Water	Energy	Energy; Communication; Water	–
NMVOC (non-combustion)	Energy; Water; Waste	–	Energy; Water; Waste	–

3.3. The Social Value of Transport Infrastructure

This research reviews the growing emphasis on the social dimension of transport sustainability, highlighting the need to reconcile decarbonization with improvements in physical and mental wellbeing. Previous studies have identified structural factors such as travel time, cost and reliability; experiential factors including comfort and safety; demographic influences; and environmental and health considerations as key determinants of transport mode choice [7,172]. However, existing research typically focuses on a limited number of transport modes or attributes and rarely provides a macro-level assessment

that is directly comparable with system-wide economic and environmental analyses. This research addresses this gap by developing a holistic framework for evaluating the social value of transport infrastructure across England, Scotland, Wales, and Northern Ireland.

A purposive quota-based sampling strategy was adopted to ensure that the sample reflected the characteristics most relevant to the objectives of the study, consistent with the principles of purposive sampling [173]. Rather than aiming for proportional representation of the populations of the four nations, the sampling design sought to achieve adequate coverage of key stakeholder groups. Target quotas were therefore established for each metropolitan area and across the principal socio-demographic characteristics, including age, gender, income, ethnicity, car ownership, and accessibility to each transport mode. Individual participants were then selected randomly within these predefined quotas.

The sampling framework was developed in accordance with established guidance for purposive and quota-based sampling in targeted population studies [173,174]. Accessibility constituted an additional inclusion criterion, as participants were required to have access to all transport modes examined in the study, enabling them to provide informed evaluations across all alternatives. This approach ensured that each respondent was capable of assessing the complete range of transport options within the proposed macro-level evaluation framework.

Ideally, stakeholder classification would also have considered participants' societal roles and responsibilities, such as involvement in transport planning or public policy decision-making, as these factors may influence perceptions of infrastructure value. However, given the size of the sample and the practical constraints of field data collection, it was not feasible to obtain this level of information. Consequently, all respondents were treated as having equivalent stakeholder status for the purposes of the analysis.

The participant distribution presented in Tables 11 and 12 follows the purposive quota-based sampling framework previously applied in studies examining the social value of transport infrastructure. Although the final sample (N = 300) provides adequate coverage of the predefined stakeholder characteristics and is appropriate for descriptive and comparative analyses, it is not intended to be statistically representative of the wider population of the four nations. Furthermore, the relatively small number of observations within certain income categories and ethnic groups limits the statistical power of subgroup analyses. The predominance of white participants broadly reflects the demographic composition of the metropolitan areas included in the study; however, it also limits the extent to which conclusions regarding ethnic neutrality in transport evaluations can be generalized. These limitations should therefore be considered when interpreting the findings.

A total of three hundred structured interviews were conducted across eleven major metropolitan areas in England, Scotland, Wales, and Northern Ireland (Belfast, Birmingham, Bristol, Cardiff, Edinburgh, Glasgow, Leeds, Liverpool, London, Manchester, and Newcastle) between January 2017 and December 2019, following a pilot study undertaken from September to December 2016 (Table 11). Data collection was carried out during peak travel periods (06:00–09:00, 11:00–14:00, and 16:00–19:00), with interview durations ranging from 30 to 90 min. Each participant was asked to identify and evaluate the perceived dependency between the transport sector and other major infrastructure systems. To ensure comparability and analytical clarity, respondents expressed the strength of each dependency using an integer scale ranging from 0 to 5, where higher values indicated stronger perceived interdependence.

Table 11. Sample distribution per metropolitan area, gender, ethnic group and age.

Area	Population	Percentage (%)	Expected Questionnaires
Belfast	585,996	1%	3
Birmingham	3,701,107	12%	36
Bristol	1,006,600	3%	9
Cardiff	1,097,000	3%	9
Edinburgh	1,339,380	4%	12
Glasgow	1,858,517	6%	18
Leeds	2,302,000	7%	21
Liverpool	2,241,000	7%	21
London	13,879,757	43%	129
Manchester	2,794,000	9%	27
Newcastle	1,650,000	5%	15
Total	32,455,357	100%	300
	Gender	Percentage (%)	Expected questionnaires
	Male	49.11%	147
	Female	50.89%	153
	Total	100%	300
	Ethnic group	Percentage (%)	Expected questionnaires
	White	87.17%	262
	Asian	6.92%	21
	Black	3.01%	9
	Other	2.90%	8
	Total	100%	300
Age	Total Percentage (%)	Survey (%)	Expected questionnaires
0–15	17.6%	0	0
15–19	6.3%	7.65%	23
20–29	13.6%	16.50%	50
30–39	13.1%	15.90%	48
40–49	14.6%	17.72%	53
50–59	12.2%	14.81%	44
60–65	6.0%	7.28%	22
65+	16.6%	20.15%	60
Total	100%	100%	300

Table 12. Usage of transport modes in metropolitan areas.

Transport Mode	National Usage	Expected Usage Without Other		Percentage of Usage in This Study	Difference Between National and Study's Usage
Walking	3%	3.09%	Walking	6.62%	3.52%
Cycling	1%	1.03%	Cycling	4.83%	3.80%
Rail	10%	10.31%	Rail	17.20%	6.89%
Bus	5%	5.15%	Bus	10.95%	5.80%
Car/Taxi	78%	80.41%	Car/Taxi	59.33%	−20.01%
Other	3%	-		1.07%	
Total	100%	100%	Total	100%	0%

These metropolitan areas cover all four nations while acknowledging that the sample is not statistically representative of the populations of the four nations. The selected metropolitan areas were intentionally chosen because they represent the only selected metropolitan settings across the four nations in which all transport modes examined in the study are simultaneously available, thereby ensuring comparability across transport modes within a macro-level analytical framework. Accessibility to each public transport mode was assessed using participants' residential postcodes. To ensure that all respondents

could meaningfully evaluate each transport mode, only individuals with access to all public transport modes within a 10-min walking distance were included. Participants lacking access to any of the transport modes were excluded from the study. Walking was assumed to be universally accessible, as none of the participants reported disabilities affecting mobility.

The sample was designed to capture diversity across key socio-demographic characteristics, including income, age, gender, ethnicity, and car ownership. More than one thousand individuals were invited to participate, of whom three hundred completed the full questionnaire. Exclusion criteria comprised incomplete interviews, inability to evaluate all transport modes, age below 15 years, and non-residency within the study areas.

To ensure consistency in data collection, a standardized field protocol was implemented, including a scripted introduction, a uniform explanation of the rating scale, and clarification of the aggregated transport mode categories. It is acknowledged that conducting interviews during peak travel periods may have increased the likelihood of recruiting commuters and other active travelers, thereby introducing a potential source of selection bias. Nevertheless, the use of a standardized sampling protocol and clearly defined inclusion and exclusion criteria enhances the transparency and reproducibility of the research methodology.

For each pair of infrastructures, the mean, median, and mode of the collected evaluations were calculated. These descriptive statistics are presented in Table 13, which summarizes the central tendencies of perceived dependencies across all sectors. The procedure for determining the final accepted dependency value followed a simple but robust rule: when the median and mode coincided, that shared value was adopted as the representative dependency score. In all other cases—where the median and mode diverged—the mean was used as the accepted value. This approach ensured that the final dependency measure reflected both the distribution and the consensus of respondents' perceptions.

Table 13. Social interdependencies.

	Mean				Median				Mode			
Transport	**Energy**	**Water**	**Waste**	**Communication**	**Energy**	**Water**	**Waste**	**Communication**	**Energy**	**Water**	**Waste**	**Communication**
Walking	0.16	0.47	0.75	0.79	0	0	0	0	0	0	0	0
Cycling	0.17	0.51	0.76	0.74	0	0	0	0	0	0	0	0
Rail	4.55	0.55	0.80	3.30	5	0	0	4	5	0	0	5
Bus	4.67	0.35	0.76	2.66	5	0	0	3	5	0	0	5
Car	4.67	0.36	0.41	1.59	5	0	0	1	5	0	0	0
Taxi	4.67	0.31	0.47	3.03	5	0	0	3	5	0	0	5
Air	4.72	0.52	0.62	3.88	5	0	0	5	5	0	0	5
Water	4.35	4.41	0.66	2.63	5	5	0	2	5	5	0	5

The incorporation of dispersion statistics—such as the interquartile range and box-plot visualizations—was examined for the social interdependency scores. The underlying questionnaire employed a highly discrete rating scale, and responses were heavily clustered at the extreme values (primarily 0 and 5). As a result, interquartile ranges were frequently zero, whiskers collapsed, and box-plot representations were effectively absent. Under these conditions, dispersion measures offer minimal additional insight beyond the established measures of central tendency.

The analysis assumes the presence of causality in the evaluative process, not in the strict econometric sense, but in the sense that respondents were explicitly asked whether they recognized a rational and meaningful dependency between transport and other infrastructures. Their numerical evaluations therefore represent informed judgements about perceived causal relationships within the broader infrastructure system.

The pronounced concentration of responses at the extreme points of the rating scale should not be interpreted as a statistical limitation but rather as a substantive empirical

observation. The clustering of scores at 0 and 5 indicates that participants tended to conceptualize infrastructure interdependencies in binary terms, perceiving them as either entirely present or entirely absent. This pattern suggests a limited grasp of the broader notion of social value and the multidimensional nature of infrastructure interdependencies. The finding therefore reinforces the rationale of the present study, namely the need for a framework capable of more effectively capturing and communicating these complex relational structures. In light of this response distribution, measures of central tendency were retained, as they provide a more appropriate summary of the polarized evaluations.

3.4. Designing Value-Integrated Infrastructure Business Models

Based on the business model literature, the three main components of business models are marketing imperative, internal and external value creation, and growth engine. These components are combined and operationalized through one or more of the following: pricing model, revenue model, channel model (such as clicks-and-mortar), commerce process model, market segment, value chain structure, organizational form, value proposition, and position in the value network. The research focuses on all positive and negative consequences of service provision—its benefits, direct costs, and indirect costs such as GHG emissions—and on how these interact, rather than on the more sophisticated strategic considerations of how business models might be deployed in particular market situations. This is because the research develops innovative infrastructure business models intended to capture a far wider range of values, including social and environmental value, than those typically considered in transport, where business models often focus narrowly on cost and time.

Marketing is a necessary component of business model implementation, forming part of the strategy through which value is communicated and delivered. The concept of "value," following Bonnedahl & Eriksson [66], encompasses economic, environmental, and social dimensions. Economic value is defined according to linear economic principles, with GDP serving as the primary measure of economic progress. As a linear index, GDP can be analyzed using linear regression and principal component analysis, but it does not account for societal costs or externalities, which are categorized as social and environmental to align with circular economy definitions. Alternative indices incorporate externalities but are more complex and less easily deconstructed. Environmental value was examined using EXIOBASE, which has a clear environmental and resource focus and is grounded in input–output tables. EXIOBASE was selected because it links directly to economic value (GDP) and excludes social externalities, enabling clear analytical boundaries between the three value types. Social value—how individuals perceive infrastructure irrespective of economic or environmental metrics—was investigated directly through representative cohorts of individuals. No existing studies connect input–output tables with social value, making this the most complex dimension to establish rigorously. Because social value is influenced by environmental and economic factors, the questionnaire captured elements of both. Thus, each value type is investigated individually, with some cross-comparison where appropriate, and, when aggregated, these components provide a complete picture of value.

The growth engine focuses on sources of resources—investors, partnerships, and other actors—who are increasingly interested in social and environmental value and indirect value creation. Stakeholders were identified from the literature [46] and categorized according to their interest in environmental and social value. This framework provides the basis for addressing the research question: how infrastructure business models can enable key infrastructure stakeholders to better understand how transport infrastructure is valued by users, make better informed decisions about infrastructure interdependencies

management, and thereby enable infrastructure systems and the services they deliver to flourish and infrastructure performance to be enhanced.

The first objective, to redefine infrastructure value in terms of the three pillars of sustainability and enable it to escape from its mainstream economic concept, was achieved by incorporating social and environmental factors—reflecting systemic thinking—into the evaluation of business model value, rather than relying solely on economic indices associated with linear thinking. Environmental value was derived from existing datasets, whereas social value required primary data collection through an ambitious social value survey. The second objective, to explore exemplar infrastructure interdependencies when creating and capturing value, was addressed by studying dependencies and interdependencies inductively through correlations between each type of value across different infrastructures. Correlation does not necessarily imply causality [127], meaning that variables may be related without one causing the other. Where correlations did not imply dependency, theoretical confirmation was sought, and in all other cases causal relationships (interdependencies) between correlated variables were verified through rational assumptions. The Pearson correlation coefficient was used for this analysis. The third objective, to develop a suite of alternative new value-integrated infrastructure business models focusing on the value judgements of transport infrastructure users and the impacts on transport infrastructure systems' value from the four 'economic infrastructures,' was achieved by employing interactions between the main elements of business models identified in theory and integrating social and environmental value [30,38,39,45,46]. This enabled the development of alternative business models optimized for multi-value considerations and grounded in the interdependencies that shape infrastructure performance.

Development of the Integrated Infrastructure Business Model

The integrated infrastructure business model was developed through a structured protocol that combined deductive theory development with inductive interpretation of empirical evidence. Rather than generating a new business model theory, the study adopts established business model theory as the underlying architectural framework and populates its components using empirical evidence on infrastructure value. Consequently, the theoretical structure of the model remains constant, while its content can be adapted to different national contexts through country-specific empirical analyses.

The development process began with the identification of the four fundamental components of business models from the literature: the marketing imperative, internal value creation, external value creation, and the growth engine. These four components constitute the structural architecture of the proposed infrastructure business model (Figure 5) and provide the organizing framework for integrating the empirical findings. Their selection was based on the synthesis of the business model literature presented in Section 2, particularly the concepts of value propositions, value creation, value networks, and growth mechanisms.

The second stage consisted of identifying the three complementary value dimensions examined in this research: economic, environmental, and social value. These dimensions were not treated as independent business model components but as different forms of value contributing to infrastructure performance. The economic dimension was derived from the principal component analysis of infrastructure interdependencies, the environmental dimension from the environmental assessment, and the social dimension from the stakeholder analysis. Together, these empirical analyses provided the evidence used to populate the theoretical business model rather than determining its structure.

The third stage involved mapping the empirical findings onto the four theoretical business model components. The marketing imperative and growth engine were primarily

informed by the business model literature and the synthesis of representative funding and financing mechanisms presented in Tables 1–4, reflecting how infrastructure projects communicate value, attract resources, and sustain long-term development. Internal value creation was developed from the infrastructure dependencies and interdependencies identified within infrastructure systems, while external value creation was derived from the interactions among infrastructure sectors, stakeholders, and the economic, environmental, and social value dimensions discussed throughout the study. Consequently, the empirical analyses did not modify the theoretical structure of the business model but provided the contextual evidence necessary to define the relationships represented within each component.

Finally, the four populated components were integrated into a single infrastructure business model (Table 14). During this integration, only relationships supported either by established business model theory or by the empirical findings were retained. The arrows included in the model represent conceptual value relationships, stakeholder interactions, and infrastructure dependencies and interdependencies rather than statistical or causal relationships. Where multiple value dimensions influenced the same relationship, these were treated as complementary rather than conflicting because the objective of the business model is to integrate economic, environmental, and social value within a unified decision-support framework.

Table 14. Development protocol for the integrated infrastructure business model.

Business Model Component	Theoretical Source	Empirical Source	Decision Rule	Relationship Represented
Marketing imperative	Business model literature; value propositions	Tables 1–4	Include mechanisms communicating value and attracting resources	Value flow between infrastructure and stakeholders
Internal value creation	Value chain theory	Economic analysis; infrastructure dependencies and interdependencies	Include relationships occurring within infrastructure systems	Infrastructure dependencies and internal value creation
External value creation	Value network and co-creation theory	Economic, environmental and social analyses	Include interactions between sectors and stakeholders	Infrastructure interdependencies and external value creation
Growth engine	Business model growth theory	Funding and financing mechanisms	Include mechanisms sustaining long-term resource mobilization	Resource flows supporting long-term value creation

The proposed development protocol is reproducible and transferable to other countries. Reproducing the model does not require changing its theoretical architecture. Instead, the same four-component business model shown in Figure 5 can be populated using country-specific evidence on economic, environmental, and social value, allowing the framework to be adapted while preserving its theoretical consistency.

4. Results

Understanding value creation is fundamental to analyzing an infrastructure business model and its evolving relationship with stakeholders. The value of the new infrastructure business model, illustrated in Figure 9, provides a holistic representation of how value is generated across economic, social, and environmental dimensions, and how different stakeholder groups capture this value. The structure of the model is grounded in academic literature and informed by empirical data, which together shape the interdependencies visualized in the figure.

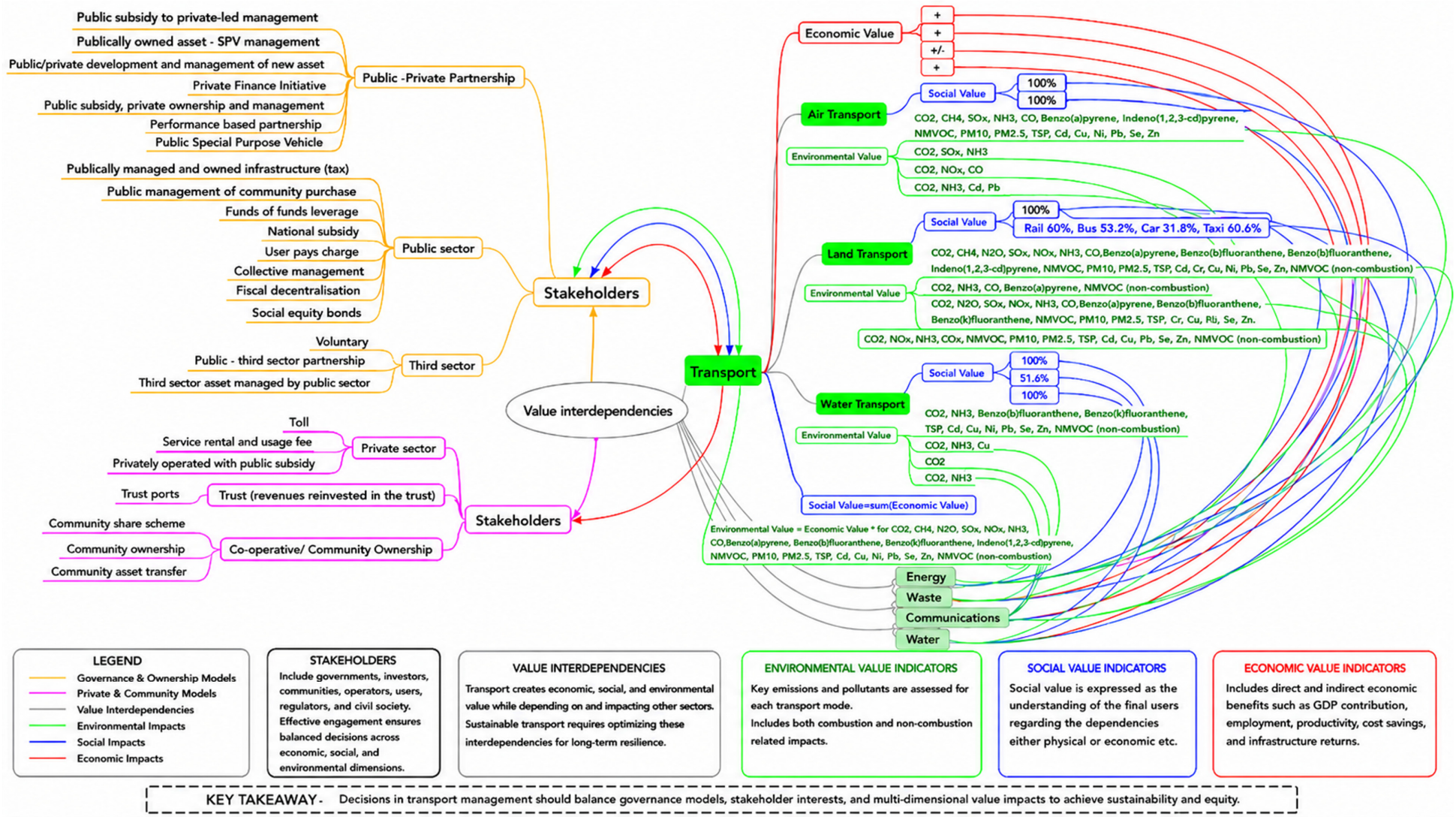


Figure 9. The value of the new business model for infrastructure interdependencies management.

The model was developed using FreeMind 1.0.1, a mind-mapping software capable of representing both established and novel business model structures [175]. The system under consideration corresponds to the macro-level infrastructure landscape of England, Scotland, Wales, and Northern Ireland, represented quantitatively through aggregated national data. Its structure is organized across three analytical levels: (1) broad infrastructure categories and stakeholder groups, (2) detailed infrastructure types and the growth engine, and (3) types of value (economic, social, environmental).

This multi-level structure enables the model to capture complexity while maintaining conceptual clarity.

In Figure 9, the left side depicts the stakeholders—the growth engine—while the right side illustrates value creation by different infrastructure types for air, land, and water transport, as well as transport's own contribution. Color coding is used to differentiate value types: green for environmental value, red for economic value, and blue for social value. The figure also shows which stakeholders capture which type of value through color-coded connecting lines. Representative qualitative information is included for each value type, based on both primary and secondary data.

The business model is hierarchical in nature. This structure helps address the multi-level analytical challenges discussed throughout this research. For example, transport is grouped into land, water, and air modes based on similarities in vehicles, networks, and terminals.

The model incorporates cross-correlation by investigating interdependencies. In hierarchical models, higher-level values are typically considered outcomes of lower-level variables. However, in this case, all newly investigated interdependencies occur at the same hierarchical level. This raises the question of which values should be treated as dependent and which as independent (e.g., social and environmental values may be influenced by economic value). The deeper challenge, as argued in this research, is that interdependencies amenable to mathematical formulation behave as independent variables for each type of value. Consequently, it is not methodologically safe to develop a single mathematical model that simultaneously incorporates economic, social, and environmental values into one equation. The purpose of this framework is therefore not to optimize or mathematically rank alternative combinations of economic, environmental, and social values. Rather, the framework provides a structured representation of how these dimensions contribute to value creation and how their interdependencies can be incorporated into infrastructure business-model design. Accordingly, decision-making within the framework refers to the identification and structuring of appropriate business-model components, stakeholder relationships, ownership arrangements, financing and funding mechanisms, and value-creation processes, rather than to the mathematical optimization of a predefined objective function.

To develop the new final infrastructure business model, the elements presented in this research are structured in a workflow diagram (see Figure 10). This diagram maps out a comprehensive framework for planning, structuring, and delivering infrastructure or major asset development projects. It distinguishes between Financing (raising the upfront money that must be repaid) and Funding (the long-term revenue streams used to pay for the project or service).

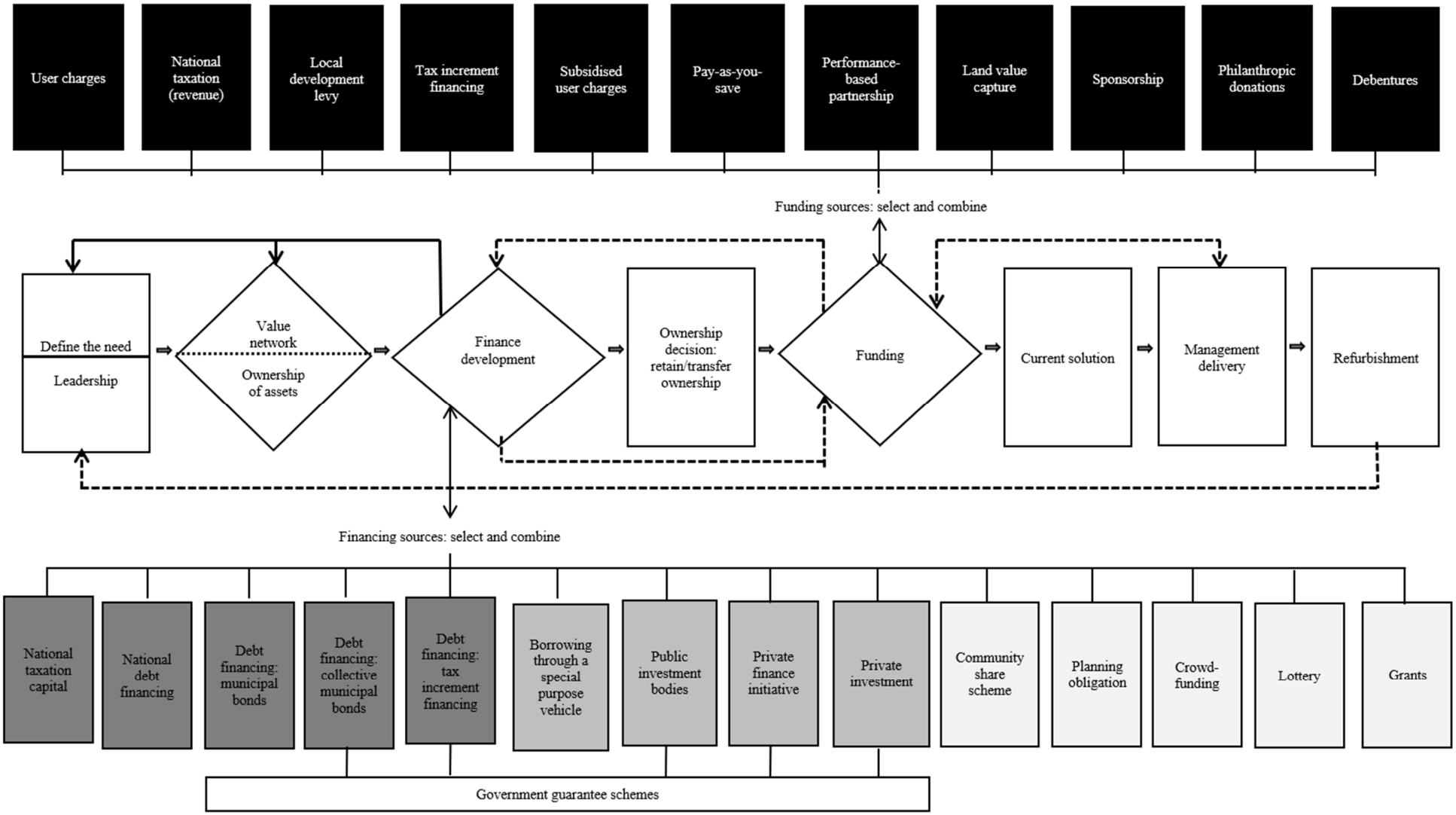


Figure 10. The new infrastructure business model [adapted from [30,46].

4.1. The Core Decision-Making Process

The middle row of the diagram outlines the sequential lifecycle of a project from inception to its ultimate renewal. The process begins with defining the need and establishing leadership, which sets the foundational goals and governance for the asset. This moves into evaluating the value network and ownership of assets to determine which partners are involved and who controls the property. Next, the project undergoes finance development to structure the initial capital required for construction. This triggers an ownership decision where stakeholders choose whether to retain or transfer the asset ownership. Once that is settled, the long-term funding mechanism is established to secure operational revenue. The plan materializes into the current solution, which transitions directly into management delivery and operational execution. Finally, the asset reaches the refurbishment stage for upgrades and modernization, which creates a feedback loop back to defining new needs.

4.2. Funding Sources

The funding sources were investigated inductively (see Table 3). The top row details the operational revenue streams that keep the project self-sustaining and help pay off initial debts. User charges place the cost directly on the consumer through tolls or fees, while national taxation draws from centralized government revenues. Local development levies collect fees from private developers benefiting from the area, whereas tax increment financing borrows against the predicted future rise in local property taxes. Subsidized user charges offer discounted rates to the public by offsetting costs with public grants, and pay-as-you-save models fund upgrades using the exact utility savings generated by the new asset. Performance-based partnerships tie operator revenue to strict quality metrics, while land value capture recovers the unearned property value increases that private landowners gain from nearby public investments. Sponsorships and philanthropic donations introduce private marketing capital and charitable gifts into the mix, and debentures offer long-term debt backed by the credit of the issuer.

4.3. Financing Sources

The financing sources were investigated inductively (see Table 4). The bottom row addresses the mechanisms used to raise the massive upfront capital needed to launch the project. National taxation capital utilizes saved government reserves for building infrastructure, and national debt financing relies on sovereign bonds issued at the federal level. Debt financing through municipal or collective bonds allows local cities to borrow directly from public investment markets. To isolate financial risk, authorities often use borrowing through a special purpose vehicle, which sets up a dedicated legal entity just for the project. Public investment bodies and private finance initiatives utilize state-backed development banks or structured public–private partnerships to share the financial load. Standard private investment draws from commercial banks and corporate developers, while community share schemes and crowd-funding gather smaller investments from local citizens. Lotteries and grants provide non-repayable cash injections, all of which are stabilized by government guarantee schemes at the base, which protect lenders by underwriting the default risks of the project.

5. Discussion

The present study extends previous infrastructure valuation research by integrating economic, environmental, and social value dimensions into a unified infrastructure business model. While each of these dimensions has previously been investigated independently, their integration demonstrates how multiple forms of infrastructure value can be considered simultaneously within a single analytical framework. Rather than treating value as a purely

economic concept, the proposed model recognizes that infrastructure systems generate interconnected economic, environmental, and social outcomes that collectively influence decision-making, investment priorities, and long-term system performance.

The practical distinction between the present study and the preceding studies [1,6,7] is therefore not the measurement of an additional value dimension, but the conversion of independently established value evidence into a business-model structure. The previous studies enable infrastructure stakeholders to identify economic, environmental, and social value separately; the present framework enables these findings to be incorporated into the organizational and financial structure of an infrastructure project. In particular, the framework connects value dimensions with the stakeholders responsible for creating and capturing value, the Growth Engine and Marketing Imperative, ownership arrangements, financing and funding mechanisms, infrastructure interdependencies, and the project lifecycle. Consequently, the framework provides a practical bridge between value assessment and business-model development. A policymaker or infrastructure manager can therefore use the framework not only to understand the value generated by an infrastructure system, but also to identify how stakeholders, resources, funding, financing, ownership, and value-creation mechanisms can be structured around that multidimensional value.

The integration of the three value dimensions also addresses an important limitation in previous infrastructure business model research. Existing approaches frequently focus on financial performance or individual stakeholder perspectives, often overlooking the complex interactions that exist between infrastructure systems and the wider economy, society, and environment [2]. By combining the three empirical value dimensions with an explicit representation of infrastructure interdependencies, the proposed framework provides a more comprehensive understanding of how value is created, transferred, and captured across infrastructure systems. Consequently, the business model extends beyond conventional organizational business models by recognizing infrastructure as a complex socio-technical system whose performance depends on multiple interacting stakeholders and interconnected infrastructure networks.

The proposed framework further contributes to infrastructure systems research by demonstrating that infrastructure interdependencies should be incorporated directly into business model development rather than treated as external influences. Infrastructure systems rarely operate independently, with transport, energy, communication, water, and waste systems continuously exchanging resources, services, and information. These interactions influence infrastructure resilience, investment performance, sustainability, and user outcomes. Incorporating these interdependencies within the business model therefore enables a more realistic representation of infrastructure value creation and provides decision-makers with improved understanding of the indirect consequences of infrastructure interventions.

The present research also contributes methodologically by demonstrating how previously independent empirical studies can be synthesized into a unified conceptual framework. The economic, environmental, and social analyses incorporated in this paper provide complementary empirical evidence rather than independent conclusions. Their integration enables relationships that are not apparent when each value dimension is considered separately, thereby supporting a system-level understanding of infrastructure value. Consequently, the principal contribution of this study is not the individual valuation methods themselves but the development of a coherent business model capable of integrating multiple value dimensions within a single decision-making framework.

Nevertheless, several limitations should be acknowledged. First, although the framework has been developed using transport infrastructure as the primary application domain, its transferability to other infrastructure sectors requires further empirical validation. Sec-

ondly, infrastructure systems evolve dynamically over time, whereas the present framework represents value relationships at a conceptual level and does not explicitly model temporal changes in infrastructure performance or stakeholder preferences. Finally, although the framework incorporates the three principal dimensions of infrastructure value considered within this research, additional dimensions, including institutional, governance, cultural, and technological factors, may further enrich future business model development.

A further limitation concerns the temporal currency of the social-value evidence. The structured survey was conducted between January 2017 and December 2019 and therefore represents pre-pandemic travel conditions. Subsequent changes associated with COVID-19, including increased remote and hybrid working, changes in commuting frequency, altered travel patterns, and potentially changing perceptions of public and private transport, may limit the direct applicability of the reported social-value results to current travel behavior. The findings should consequently be interpreted as evidence of pre-pandemic perceptions of transport infrastructure rather than as a contemporary representation of post-pandemic travel behavior. Future research should replicate the social-value analysis using post-pandemic data to assess whether the identified value relationships and infrastructure interdependencies have remained stable or have evolved.

6. Conclusions

This study has demonstrated that conventional approaches to infrastructure business models are too narrowly focused on economic performance and fail to capture the broader value generated through infrastructure interdependencies. By integrating economic, social, and environmental dimensions of value within a single analytical framework, the research provides a more comprehensive understanding of how transport infrastructure creates and captures value across interconnected infrastructure systems.

The findings broadly support the central hypothesis that transport infrastructure should not be evaluated in isolation but within an integrated business model that incorporates economic, environmental, and social value. This support should be interpreted within the exploratory scope of the present research, as the proposed framework represents a conceptual integration of complementary empirical evidence rather than a fully validated decision-support model. The three research objectives were addressed by (i) developing an integrated business model grounded in established business model theory, (ii) identifying the economic, environmental, and social interdependencies between transport infrastructure and supporting infrastructure sectors, and (iii) synthesizing these complementary findings into a unified value-integrated infrastructure business model. Together, these findings indicate that transport infrastructure performance and value are influenced by its relationships with energy, water, waste, and communication infrastructures, as well as by stakeholder perceptions of infrastructure value.

The proposed value-integrated business model extends existing business model theory by placing stakeholders and value co-creation at the center of infrastructure management. Rather than treating infrastructure solely as an economic asset, the framework recognizes that long-term infrastructure success depends on balancing financial performance with social wellbeing and environmental sustainability. This multidimensional approach aligns infrastructure management with the broader objectives of sustainable development and resilience.

From a practical perspective, the research offers policymakers, infrastructure owners, and managers a structured approach for evaluating infrastructure investments beyond traditional cost–benefit analysis. The framework may support investment prioritization, infrastructure planning, funding selection, and governance by explicitly considering the interactions between infrastructure sectors and the multiple forms of value they generate.

The study also contributes theoretically by advancing infrastructure business model theory through the integration of interdependency analysis, stakeholder value, and sustainability principles into a unified framework. The proposed model demonstrates how business models can be used not only to capture economic value but also to facilitate the creation and management of social and environmental value throughout the infrastructure life cycle.

Nevertheless, the research has several limitations. The empirical analysis is based primarily on infrastructure across England, Scotland, Wales, and Northern Ireland and on secondary datasets available at the aggregate national level, which may limit the direct generalizability of the findings to other countries or institutional contexts. In addition, social value remains inherently difficult to quantify and depends on stakeholder perceptions that may change over time.

The proposed model was evaluated through theoretical consistency with established business model theory and by triangulating three independent empirical analyses representing the economic, environmental, and social dimensions of infrastructure value. Future research should undertake external validation through expert panels and applications in different national contexts.

Future research should validate the proposed business model across different countries, infrastructure sectors, and governance arrangements. Further work could also develop dynamic methods for measuring infrastructure value over time, incorporate digital technologies and real-time infrastructure data, and examine how emerging challenges such as climate adaptation, artificial intelligence, and smart infrastructure influence value creation and infrastructure interdependencies.

Overall, this research demonstrates that infrastructure business models should evolve from economically focused frameworks towards integrated value-based models that recognize the interconnected nature of modern infrastructure systems. Such an approach provides a stronger foundation for achieving sustainable, resilient, and socially beneficial infrastructure that delivers long-term value for all stakeholders.

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Abbreviations

The following abbreviations are used in this manuscript:

CSR	Corporate Social Responsibility
GDP	Gross Domestic Product
ICT	Information and Communication Technology
I–O	Input–Output
PCA	Principal Component Analysis
PPP	Public–Private Partnership
PFI	Private Finance Initiative
SPV	Special Purpose Vehicle
TfL	Transport for London
CIL	Community Infrastructure Levy
TIF	Tax Increment Financing
PWLB	Public Works Loan Board
UKMBA	UK Municipal Bonds Agency
UKGS	UK Guarantees Scheme
NHS	National Health Service
FCA	Financial Conduct Authority
GHG	Greenhouse Gas
UK	United Kingdom

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