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Review

# Interdependencies between Urban Transport, Water, and Solid Waste Infrastructure Systems

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**Abstract:** Developing integrated, sustainable, and resilient urban systems requires consideration of the different types of interdependencies between their infrastructure systems. The degree and nature of interdependencies among infrastructure systems vary widely. This article identifies and analyzes the interdependencies between urban transport, water, and solid waste. A comprehensive review is conducted, an interdependency matrix for the three systems is developed, and the interdependencies are analyzed qualitatively. The analysis shows that the three systems are highly interdependent, indicating that an integrated approach that considers the mutual impacts, conflicts, and interactions among them at all stages of their life cycles is necessary to promote sustainability and resilience. This article also identifies opportunities for developing new integrated planning and design approaches and emphasizes the need for further research in this area to quantify infrastructure interdependencies. This is particularly important in the context of rapid urbanization and the pressure on cities to adapt to climate change.

**Keywords:** interdependency; transport; water; solid waste; infrastructure; integration

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## 1. Introduction

As urban infrastructure systems and their operations are becoming highly interconnected and interdependent due to their complex and dynamic nature, it has become virtually impossible to isolate them and seek solutions to problems with individual infrastructure systems that do not impact others. The traditional silo-based approach of planning, designing, and operating infrastructure systems individually and in isolation potentially misses vast opportunities to make infrastructure more sustainable and resilient. In fact, it may create unnecessary vulnerabilities. Indeed, a solution for a critical issue in one infrastructure system can create problems in another that may itself create problems for another system, and so on, in a cascading manner. For example, transport infrastructure is affected by water and wastewater infrastructure because water conduits are buried under streets. If water conduits undergo any maintenance work or expansion, not only are road infrastructure and travel patterns impacted around this location, other systems that require road access (e.g., solid waste collection) are impacted as well. Another example is the use of de-icing agents on road networks in cold countries in the winter. These agents eventually penetrate the groundwater, impacting water quality and the entire aquatic system. While the presence of interdependencies between different infrastructure systems is known and may appear conceptually simple [1], identifying, understanding, and analyzing them is challenging, in part because they are predominantly non-linear in nature [2]. Their relationships can be direct or indirect, simple, or complex, instantaneous, or delayed. The degree of interdependency also varies across infrastructure systems [3].

While every infrastructure is meant to provide a specific service, they have evolved to be complex, adaptive, and mutually interacting [2]. As humans are involved in the planning, design, utilization, and operation of infrastructure, changes in these systems' states and their interactions are constant and inevitable. We posit that more, not fewer, interactions are expected in the future, in part due to the pervasiveness of sensing technologies, the Internet of Things (IoT), and the incessant pressures associated with increased urbanization, aging infrastructure, and climate change.

Transport, water, and solid waste infrastructure systems are among the most commonly identified critical infrastructures that constantly support essential services and daily needs of a city. At some point, everything we consume needs to be transported in a truck via roads, needs water for manufacturing and cleaning, and eventually, proper disposal at the end of its life. These three infrastructure systems are vital for our society's health, safety, security, resilience, and economic prosperity. They are the focus of this study.

Most existing studies that attempt to identify and analyze infrastructure interdependencies tend to focus on pairs of infrastructure systems, such as transport and energy. Interdependencies between transport and energy infrastructure [4–10], between building and energy infrastructure, and between building and water infrastructure [11–15] are the most common; however, few studies have attempted to analyze the interdependencies between transport, water, and waste infrastructure. Studies that have identified the interdependencies between transport and waste infrastructure are mainly limited to aspects of pollution such as waste gas (e.g., greenhouse gases) and air particle matter emissions associated with transport infrastructure [16–20]. This article aims to fill the knowledge gap by identifying and analyzing the interdependencies between urban transport, water, and solid waste infrastructure systems.

The objective of this study is, therefore, to extend our understanding of how these three infrastructures interact today and how this interconnection can be explored to design infrastructure interdependencies that support sustainable, resilient, and smart cities of the future. Once the interdependencies between these three infrastructures are identified, several dimensions are used to analyze interdependencies: type (physical, geographical, cyber, or logical); directionality (either unidirectional or bidirectional); nature (relating to complexity); and strength (the degree of impact on one infrastructure caused by a failure of the other infrastructures). This article can assist urban planners, designers, and engineers, including transport planners, waste managers, operators, and emergency response personnel, in planning and developing tools and in considering the potential cascading impacts of failure or disruption.

## 2. Description of Keywords and Selection of Infrastructure Elements

Infrastructure systems, which play a vital role in urban growth, are defined in various ways in the literature [2,21–23]. They are a network of systems and processes that function collaboratively and synergistically to continuously provide essential services to citizens. Infrastructure systems can also be categorized in various ways. Derrible [3] considered seven types of infrastructure systems: transport, water, utility (gas, district heating, and cooling), electricity, telecommunication, solid waste, and buildings. Of these seven types of infrastructures, this article focuses on three critical infrastructures: transport, water, and solid waste. In addition to the typical physical infrastructure elements discussed in the literature, such as roads, buildings, and pipelines, this article also considers the flows that provide services, for example, traffic flow—including all motorized and nonmotorized movement of goods, passengers, workforce, and garbage collection trucks—as well as waste, water, and wastewater flow. A list of infrastructures and associated elements on which this article focuses is given in Table 1.

**Table 1.** Elements of the three infrastructure systems selected.

| Infrastructure | Elements |
|---|---|
| Transport | Roads, bridges, airports, ports, waterways, tunnels, parking lots, gas stations, rail, transit stations, automobiles and parts, and passengers. |
| Water | Potable water, wastewater and stormwater, water pipelines and drainage systems, treatment facilities including buildings, and workforce. |
| Solid waste | Solid waste, garbage collection trucks, garbage bins, treatment facilities, including buildings, and workforce. |

All cities have a set of infrastructures, sometimes working in harmony and sometimes with discord, to provide essential services for human needs. A dependency exists when one infrastructure has a direct impact on the performance of another infrastructure. Interdependency occurs when there is a mutual connection between two systems, a bidirectional relationship through which the state of each infrastructure influences (or is correlated to) the state of the other [2,24]. Understanding interdependency types between infrastructure systems has received some attention in the past and slightly different approaches are presented in the literature [2,23,25–27]. Rinaldi et al. [2] categorized interdependencies among infrastructures into four classes: physical (material or physical flow from one entity to another), cyber (information transfer), geographical (physical proximity affecting components across multiple infrastructure systems), and logical (dependencies other than the above three categories). Zhang and Peeta [27] described interdependency types among infrastructure systems as either functional (functionality of one system requires inputs from other systems, e.g., electric power needed for the functioning of systems such as traffic control and telecommunication failure leading to cascading effects on other infrastructures), physical (e.g., shared right of way between a transit network and roadway network), budgetary (budget interdependency for resource allocation), or economic market supply and demand interdependency (e.g., fuel price affecting both supply and demand of transport, eventually affecting supply and demand for fuel).

Although identifying and analyzing all the interdependencies between the infrastructures is equally important, it is also a very complex and challenging task. Derrible [3,28] presented a non-exhaustive infrastructure interdependency matrix for seven types of infrastructures. The matrix specified how one infrastructure is influenced by another infrastructure, mainly with reference to the physical infrastructure elements. For instance, transport infrastructure is also affected by electricity infrastructure, as electricity is needed for electric vehicles, and raw material transport is needed to generate electricity. Saidi et al. [23] presented a multilayer network of infrastructure systems showing the connections and links between them with different dependency types to provide a holistic view. They also developed an interdependency matrix summarizing existing studies to better understand the interdependencies among different infrastructures. Interested readers can refer to [27,29–33], which also reviewed infrastructure interdependencies in detail.

## 3. Interdependency Matrix for Transport, Water, and Solid Waste Infrastructure Systems

The first step in this study is to identify the interconnectedness and impact of one infrastructure (e.g., transport infrastructure) on the other two (i.e., water infrastructure and solid waste infrastructure), and vice versa. Figure 1 shows a schematic diagram of the interdependencies among the three selected infrastructure systems. Table 2 shows an interdependency matrix between them, considering both the physical infrastructure elements and the flows that provide services. The interdependency matrix is developed partially based on the authors' experience and expertise on the three infrastructures and partially based on a comprehensive literature review. Each cell in each row in the matrix shows how one infrastructure system is impacted by the other infrastructure systems. For example, the second row in the last column (i.e., Cell # 3) shows how transport infrastructure impacts solid waste infrastructure, while the second column in the last row (i.e., Cell # 7) shows how solid waste infrastructure impacts transport infrastructure.

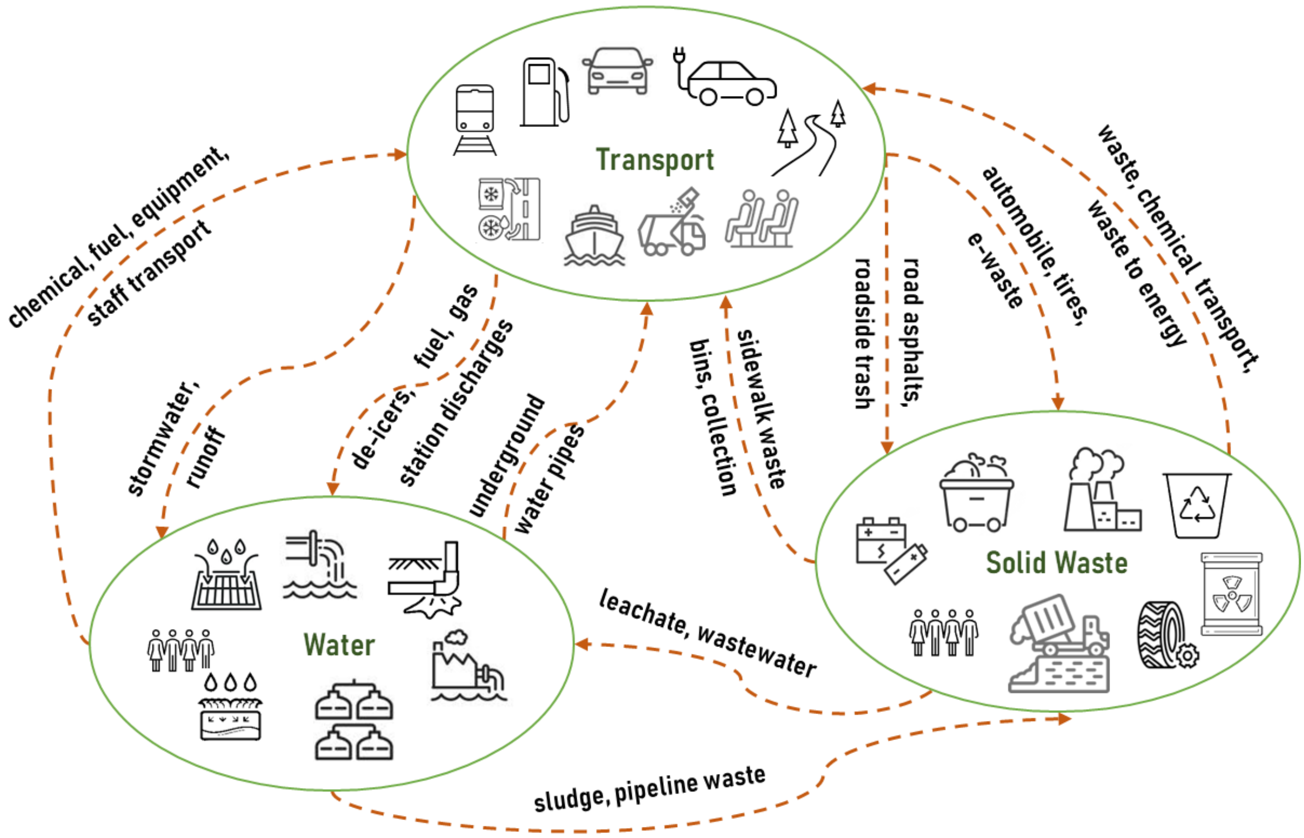


**Figure 1.** Schematic diagram of the interdependencies between transport, water, and solid waste infrastructure systems.

**Table 2.** Interdependency matrix of transport, water, and solid waste infrastructure systems.

| | Transport | Water | Solid Waste |
|---|---|---|---|
| Transport | Cell # 1 to Cell # 3 → | • Stormwater/run off goes to sewer systems.<br>• Compete for land space e.g., roads and retention basins, or low-impact developments.<br>• De-icing agents and fuels leaking from automobiles and gas stations impact water quality.<br>• Parking lots, airport runways, road pavements, and street designs impact the amount of runoff, stormwater quality, and flooding potential.<br>• Waterway transport (e.g., marine) impacts water quality. | • Construction and maintenance of waste from transport infrastructure (road, railways, pavement, buildings, etc.).<br>• Automobiles and parts (e.g., tires) end-of-life and manufacturing-related waste.<br>• E-waste from sensors, traffic signals, cables, end-of-life electric vehicle batteries, and solar panels from traffic signs.<br>• Hazardous waste and petroleum hydrocarbon contamination and risks associated with other Hazmat transport.<br>• Other wastes from traveling passengers/roadside trash. |

**Table 2.** *Cont.*

| | Transport | Water | Solid Waste |
|---|---|---|---|
| Water | • Underground water conduits/infrastructure on streets.<br>• Water transport/wastewater treatment chemicals, fuel, and equipment.<br>• Staff transport to treatment facilities.<br>• Construction, operation, and maintenance-related items need to be transported.<br>• Water maintenance work disrupts traffic circulation. | Cell # 5 | • Wastewater treatment processes generate solid waste (e.g., sludge).<br>• Construction, maintenance, and operation of water and wastewater treatment facilities produce waste.<br>• End-of-life pipelines/equipment-related wastes.<br>• Occurrence of inflow/infiltration between water/wastewater pipelines during extreme weather events, related waste. |
| Solid Waste | • Waste bins located on sidewalks/back alleys, garbage trucks use roads to transport waste to disposal facilities.<br>• Special waste such as nuclear waste require special transport regulations that can disrupt the transport network.<br>• Construction, operation, and maintenance of waste facilities.<br>• Staff need transport to treatment facilities.<br>• Land reclamation creates space for transport.<br>• Waste-to-energy: alternative biofuels that can be used for transport. | • Improper waste disposal generates leachate and impacts water quality.<br>• Groundwater and surface water contamination with landfill leachate.<br>• Waste treatment processes also generate wastewater that requires treatment.<br>• Waste treatment facilities need water to operate. | Cell # 9 |

## 4. Understanding the Interdependencies between the Three Infrastructure Systems

It is important to consider all key elements in the infrastructure system, including physical infrastructure and the associated demands characterized in the form of flows and movements that provide essential services, and their corresponding logical functions and relationships. Some of the elements and interactions may seem less interdependent, indirect, and not critical in the short term, but they would have significant long-term impacts over the life cycle. In particular, end-of-life automobile and tire waste streams are rapidly growing and posing challenges in the waste management industry [34,35]. Cities will soon need to deal with the increased number of cobalt batteries in electric vehicles, the solar panels used in traffic signs, and the electrical and electronic wastes (also known as e-waste) at the end of the products' life. Furthermore, the infrastructure elements and relationships may vary greatly from one urban system to another; however, the overall impacts share many similarities.

### *4.1. Impacts of Transport on Water Infrastructure*

Transport infrastructure is geographically highly interdependent on the other infrastructure systems. Physical infrastructures such as roads, railways, ports, and related buildings (e.g., transit stations and gas stations) and structures (e.g., bridges and tunnels), and the associated flows, including construction materials, de-icing agents and fuels, automobiles and parts, and passengers, were considered when identifying the interdependencies of transport infrastructure.

Transport infrastructure impacts water quality heavily, although sometimes these impacts are not apparent. Contaminated wastewater from gas stations and contaminated stormwater have become serious issues of concern in urban environments [36]. This wastewater is characterized by a high concentration of oil–water emulsions and toxic compounds and needs special handling and treatment. Environmentally friendly and economical practices would necessitate the use of biological treatment methods [37,38].

Another significant impact of road infrastructure on water infrastructure is the resulting pollution of freshwater ecosystems by contaminating waterbodies from other materials and chemicals used in operational processes, e.g., salts from de-icing agents used to enhance driving safety during winter and spring seasons. Traffic accidents sometimes also lead to the spread of hazardous contaminants that infiltrate surrounding surfaces and nearby waterbodies. Chemicals such as firefighting foam used to mitigate vehicle fires could impact water quality through fire–water runoff. These contamination-related interdependencies seem to be unidirectional, direct, and geographical, where contamination of freshwater bodies may simply be due to their proximity to gas stations; however, the state of water infrastructure does not influence transport infrastructure directly in this case [2]. The degree of these interdependencies could be considered high.

On the other hand, when transport infrastructure is impacted by an extreme event such as flooding, stormwater systems are also disturbed as an effect. Moreover, as described by Derrible [3], poor street designs can impact the runoff and cause flooding. Another design-related impact appears when parking lot surfaces and driveways are designed to be impermeable to water. Contaminated runoff from these surfaces becomes a significant source of water pollution in urban areas. Beyond these, if marine-related transport infrastructure is considered, the huge amounts of oily wastewater generated by ships would cause a major disposal problem because of the accumulation of persistent xenobiotic compounds in the environment [39,40]. Traditionally, bioremediation approaches have been used, to a certain level, to mitigate these impacts.

### 4.2. Impacts of Transport on Solid Waste Infrastructure

Construction waste materials generated from transport infrastructure such as road asphalt, concrete, and wood have traditionally been limited to landfill disposal; however, materials such as steel and aluminum have been recycled or reused for other applications [41]. Hazardous and contaminated solid waste, such as soil and/or materials contaminated with petroleum hydrocarbons from gas stations and automobiles, require special handling, collection, and disposal, including site remediation [42,43]. If not managed in a sustainable manner, these waste and related externalities such as emissions will have negative impacts on human health and the environment.

Automobiles are a major consumer of materials, and with the rapidly increasing number of automobiles, there is an urgent need to increase waste management initiatives to reuse and recycle waste materials such as metal, solvents, batteries, plastics, and rubber when automobiles and their parts reach the end of their life [44]. This may not be an issue in the short term for an individual automobile owner; however, it becomes an issue where the life cycle of the automobile is concerned. Although unapparent, the management of tire wastes generated from transport-related infrastructure is another challenge for the waste management industry due to the difficulties associated with recycling its complex polymeric structure. Difficulties also arise when it comes to collection, transport, and storage, as tires occupy significantly larger spaces [45].

Furthermore, e-waste is one of the fastest-growing waste streams and poses additional risks as they contain hazardous elements and compounds that can contaminate the environment to a higher degree if not properly managed [46]. Transport infrastructure also contributes to the e-waste stream: examples include automobile circuit parts, waste batteries, electric batteries, plug-in electric vehicles, information technology, and telecommunications-related equipment such as traffic sensors and traffic lights.

Another interdependency between transport and waste infrastructures, which may be categorized as indirect, bidirectional, and logical, is waste generated by passengers during travel, leading to the accumulation of roadside trash (e.g., plastic bottles, paper, and food waste). In addition to polluting and contaminating the environment and wildlife, roadside trash can also create safety risks due to its likelihood of distracting drivers from focusing and affecting driving conditions [47].

### 4.3. Impacts of Water on Transport Infrastructure

Similar to transport, water infrastructure also has an impact on the other infrastructures, both directly and indirectly. This study focused mainly on wastewater and stormwater, including pipelines, and analyzed the construction, operation, and maintenance of treatment facilities, as well as essential chemicals, fuels, equipment, and workforce.

Water pipes and gas lines are generally buried underground. The maintenance of underground water pipes often involves closing the streets in surrounding areas. If a water pipeline bursts or a gas line leaks, streets must be dug up to repair the damaged infrastructure, significantly impacting traffic. There is a potential for damaging water pipes as well when the street is dug up. Although the maintenance activities benefit the water infrastructure, the transport infrastructure is disrupted by such activities [48]. These interdependencies are therefore physical, bidirectional, and direct, and the strength of the impacts can be categorized as high.

Although some of the impacts are less noticeable, both wastewater and solid waste treatment facilities need to be designed by incorporating a proper transport infrastructure for vehicles and trucks to be able to transport construction-related raw material, equipment, operational items such as chemicals and fuel, and workforce. If chemicals, fuels, staff, and other necessities required to operate the wastewater and solid waste treatment facilities are not transported to the facility safely, the entire treatment system can get disrupted; thus, the strength of this impact can be considered high. However, to our knowledge, there is no formal and objective way of measuring the degree of interdependency available in the literature, at least as of this writing.

Beyond these aspects, both wastewater and solid waste treatment facilities 'compete' with transport infrastructure for space. However, reclaimed land spaces could be used to build transport infrastructure that also works as green infrastructure and low-impact development strategies. Rain gardens are a good example because they are part of both transport and water infrastructures.

### *4.4. Impacts of Solid Waste on Transport Infrastructure*

Each infrastructure generates some sort of waste, and the smooth operation of waste infrastructure depends on all the other infrastructures. In fact, it depends heavily on transport infrastructure; thus, the interdependencies are mostly bidirectional. Solid waste infrastructure includes waste collection, waste transport to treatment or disposal facilities, the workforce, as well as the construction, operation, and maintenance of these facilities.

Solid waste bins are usually located on sidewalks and back alleys, and waste transfer trucks (i.e., garbage trucks) must have access to collect the bins and transport them to treatment or disposal facilities (e.g., landfills, waste-to-energy plants, or recycling facilities). A few key factors associated with waste collection and transport include urban traffic jams that interfere with the flow of service fleets, additional congestion, noise, and emissions generated by the stop-and-go and travel patterns of waste collection trucks, and economic considerations [35]. Thus, managing transport infrastructure effectively and creating an integrated approach is critical for solid waste infrastructure. This is even more critical when special types of waste such as nuclear waste and hazardous waste transport require unique transport regulations [49].

Furthermore, fuels (e.g., biodiesel and green hydrogen) derived from waste are emerging as promising eco-friendly and renewable fuels for transport, especially as substitutes for non-renewable fossil fuels. Utilizing various types of wastes that would otherwise end up in landfills also promotes the circular economy and sustainability [50,51].

Some of these impacts, such as waste generated from transport infrastructure, waste collection using trucks, and waste transport to treatment facilities via roads and railways can be categorized as physical, direct, and bidirectional interdependencies, and the degree of impact considered to be high. For example, if waste management facilities are not willing to accept the waste streams generated from transport infrastructure, and if the collected waste is not being properly transported to waste management facilities, piles of waste would accumulate on roads and sideways, resulting in many negative environmental impacts and risks to human health resulting from contamination.

### 4.5. Impacts of Water on Solid Waste Infrastructure

Physical and logical interdependencies between water and solid waste infrastructure cannot be neglected. Water and wastewater treatment processes produce solid waste that requires appropriate handling and disposal. One of the key challenges of water and wastewater treatment is the disposal of the excessive volumes of sludge produced in the process that requires careful consideration due to its toxicity. The quantity and quality of sludge varies based on the raw water, wastewater quality, and treatment process. Sludge may contain heavy metals with potential consequences for human health and the environment [52]. Sustainable options for managing sludge includes its recovery and reuse as an adsorbent for contaminants or as a substrate in constructed wetlands. It can also be used in cement production, ceramic making, manufacturing of artificial lightweight aggregates, and in agricultural practices and other land-based applications [53].

Similar to other infrastructures, construction, renovation, and demolition of water and wastewater treatment buildings and other physical infrastructures generate large amounts of solid waste, including wood, asphalt roofing, concrete, and drywall. Furthermore, water pipelines ultimately reach the end of their life and become a burden on the solid waste infrastructure. Water infrastructure also indirectly contributes to the e-waste stream when considering the end-of-life of equipment associated with smart water monitoring systems.

### 4.6. Impacts of Solid Waste on Water Infrastructure

Solid waste disposal in open dumps, nearby waterbodies, or poorly designed landfills poses direct threats to the water systems, specifically due to the contamination of surface and groundwater with uncontrolled leachate discharge. Landfill leachate is formed when water percolates through the waste matrix. Leachate picks up organic and inorganic components from waste through physical, hydrolytic, and fermentative processes [54]. Engineering landfill designs should consider collecting leachate and recirculating it through a waste matrix several times—instead of in a single pass—in order to enhance microbial activity [55]. Furthermore, biological solid waste treatment processes such as wet anaerobic digestion require water to support microbial activities. These processes also produce wastewater that requires proper treatment before being discharged into waterbodies.

Considering the extent of transport, water, and solid waste infrastructures, many other hidden and indirect interdependencies may exist, and the three infrastructures are likely to become even more interdependent in future. Planning and operating transport infrastructure cannot proceed without considering the other infrastructures. Identifying and understanding the nature of infrastructure interdependencies are fundamental and essential steps in developing a framework for dealing with these complex systems. However, urban planners and designers might need to extend their understanding beyond qualitative analysis prior to incorporating these impacts into their development plans. Further analysis of their interconnections using system thinking perspective and quantitative analysis would be useful.

## 5. Opportunities and Moving Forward

As described above, transport, water, and waste infrastructure systems are highly interconnected, and they function as a 'system of systems', exhibiting simple to complex interdependencies that can leave critical functions vulnerable to cascade failures [56]. It is important to look at these interdependencies positively without eliminating their impacts, as they provide opportunities for enhancing resilience, robustness, and sustainability of urban systems [57]. A holistic and integrative approach is necessary, not only to mitigate the associated risks but also to identify novel innovations. Figure 2 identifies some of the potential opportunities available. The sections that follow describe these opportunities in detail.

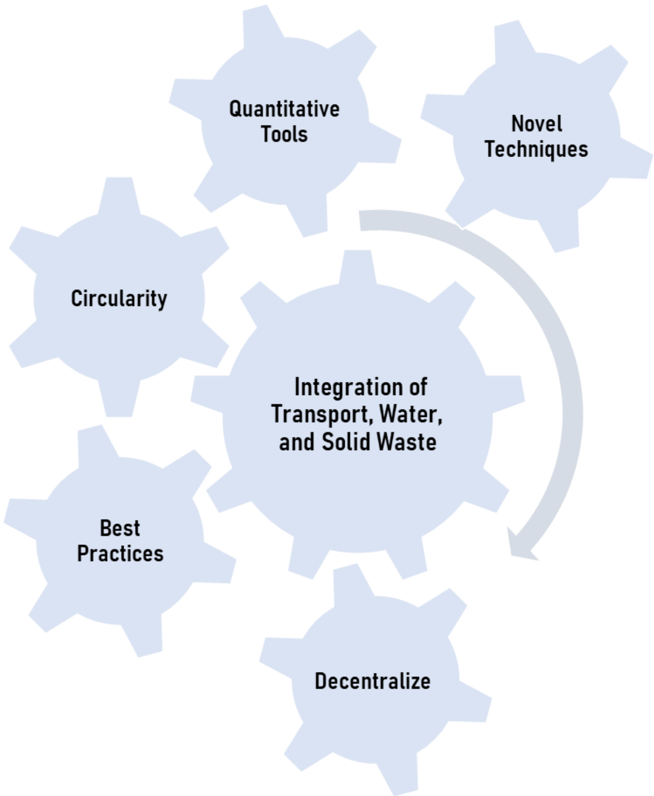


**Figure 2.** Interdependencies and integration opportunities.

### 5.1. Integrated and Decentralized Infrastructure Systems

Integrated infrastructure concepts were initially examined to identify and protect vulnerabilities in critical urban infrastructures in the case of attacks or failures. However, researchers and designers have now noted the potential for integrated infrastructure to address critical, long-term, and contemporary urban problems [2,23,28,32,56,58–63].

Integrated infrastructure systems can be described as a combination of two or more infrastructure systems working with an explicit awareness of one another [23]. For example, transport infrastructure should incorporate proper water and waste management programs, and these programs should consider implementing a good transport plan to allow them to function properly. This integration can occur at various scales (e.g., urban, rural, or regional) and various levels (e.g., high or low). As opposed to traditional silo-based approaches of analyzing infrastructures in isolation, an integrated infrastructure system approach offers considerable benefits. Some of these benefits include enhancing system-wide efficiencies and resiliency; minimizing service disruptions, rehabilitation work, and costs; promoting sustainability goals, including resource minimization and proper allocation that takes into account the life cycle of individual components; identifying and managing short-term and long-term impacts; and many other environmental and economic benefits [23,28,59,61,63].

Integration of urban infrastructure can take multiple forms. One of the attractive dimensions is merging integration and decentralization, where integration occurs in a decentralized manner, as opposed to being limited to a centralized location [3,64–66]. Buildings in urban systems, including residential, commercial, industrial, and institutional buildings, are key producers of waste and wastewater and key consumers of water and transport services. Therefore, managing and shaping this demand through buildings and land use design and retrofit is an instrumental step in moving towards systematic solutions that deal with the root cause of these problems. An example of an extreme decentralization approach involves moving towards self-sufficient buildings, higher density, and diverse land use. While the higher density and diversity of land use supports active and sustainable transport modes such as transit, walking, and cycling, smart self-sufficient buildings also compost their waste and capture rainwater to reuse. Other related solutions include incorporating green infrastructure initiatives such as local waste treatment facilities (e.g., bio-digesters) and incorporating low-impact development and greenification strategies such as rain gardens, pervious pavements, rainwater harvesting systems, and green corridors in every street, since they contribute to both transport and waste infrastructure, thus providing both economic and environmental benefits [3,28].

From a solid waste management lens, an integrated waste management approach involves a combination of reduce, reuse, recycle, and recovery of materials, and residual disposal activities as opposed to the use of one activity alone. This approach could be the most effective way of managing automobile-related waste (e.g., tires) and end-of-life pipeline waste. One such example includes reusing scrapped and shredded tires in various geotechnical engineering applications such as subgrade-backfilling, landfilling, retaining wall, and slope reinforcement; transforming waste tires into raw materials that can be reintegrated into the system as a resource in applications such as sports and leisure infrastructures, walkways, and as an additive in asphalt for constructing highways and bridges; and thermally converting tire waste into energy [67–70]). An integrative e-waste management approach also includes reducing the volume, extending the life of the equipment, incorporating recycling techniques, and adopting a circular economy approach [71,72].

Demand management (DM) is another essential framework for developing integrated urban systems. Evaluating community or consumer demands, service needs, and infrastructure assets would assist with allocating resources and infrastructure services in a sustainable manner. In this context, solid waste management evolves into resource management, providing opportunities for innovation, tipping fees for waste disposal encourage less consumption, water conservation measures reduce stormwater collection, and transportation demand management strategies encourage shifts towards sustainable transportation modes.

### 5.2. Best Practices and Circular Economy Approach

Another dimension that has received significant focus in recent years is the shift towards a circular economy approach as opposed to the traditional and unsustainable linear economy approach. The circular economy promotes a cyclical flow of resources in the production–consumption system within a closed loop, looking throughout the system's life cycle to minimize consumption of natural resources and energy to achieve zero-waste goals and mitigate associated environmental impacts while providing opportunities for identifying the best practices, thus moving towards sustainability [34,35,73–77].

In recent years, researchers have highlighted the importance of incorporating circular economy-related best practices in each life cycle stage of automobiles [34,35,78]. Producing a minimal amount of waste reduces pressure on both waste and transport infrastructures. Some examples include the utilization of secondary and recycled resources as raw materials, developing eco-designs and utilizing biodegradable materials in manufacturing, using cleaner modes of transport, and increasing recycling and energy recovery from waste.

Eco-design plays a vital role in a circular economy, as it uses a 'cradle-to-cradle' approach as a framework. McDonough and Braungart [79] recognized two kinds of nutrients and metabolisms that promote this framework. The first is biological nutrients, which are biodegradable materials that cycle in the biological metabolism, and at the end of their use, become food for other living organisms without generating waste. The second is technical nutrients, which are inorganic or synthetic materials that circulate within the technical metabolism indefinitely and are possibly degraded, but without being transformed into waste [79–82]. In the context of sustainable systems and designs, all products, materials, and wastes are categorized under either biological or technical nutrients. Biological nutrients are designed to re-enter ecological cycles to be consumed by microorganisms; technical nutrients are designed to go back into technical cycles [81]. As an example, researchers have been attempting to develop greener agro-based alternative materials and additives to mitigate the negative environmental impacts associated with traditional de-icing agents [83–85].

Another principle of circularity is its regenerating nature. In this context, regenerative designs aim to produce quantifiable ecological and social health outcomes rather than simply minimizing energy and water use or the emission of pollutants [86]. Biomimicry becomes a key element in this, as it no longer exploits nature, but rather learns from nature. One example involves utilizing the drainage properties of the soil and the absorptive capacities of the plants to purify livestock wastewater, allowing onsite reuse, mitigating biosolids, and minimizing water and wastewater transport through pipelines.

Circularity is also increasingly considered in the realm of water infrastructure, especially in water-scarce areas. For example, Arora et al. [87] studied how treated wastewater is reused in Singapore, particularly for industrial purposes. By 2019, 25% of the water used in Singapore came from secondary flows (mostly treated wastewater).

### *5.3. Novel Techniques and Quantitative Tools*

As new innovations increasingly rely on technology, emerging artificial intelligence (AI) techniques are becoming essential tools for facilitating integration across various infrastructures. These novel approaches can be integrated at every stage of infrastructure integration, including modeling, design, analysis, and management. As an example, this can be done by relying on digital twins, which are virtual replicas of the infrastructure and their interactions. Digital twins use real-time data to provide a comprehensive understanding of infrastructure performance, behavior, and potential issues. The use of digital twins to analyze infrastructure interactions can provide valuable insights and enable organizations to make data-driven decisions.

Particular to our infrastructure systems of interest, robotics coupled with AI and machine learning can have a significant impact on waste prediction, collection, transport, and sorting, especially for hazardous waste and in water and for wastewater treatment modeling and optimization. Some example uses of AI-based techniques in waste management include smart recycling bins, automated sorting systems, and autonomous waste and recycling collection trucks [88–90]. Furthermore, accurate forecasting of waste trends using AI-powered tools plays a key role in decision making processes such as vehicle routing and optimization, optimization of waste collection time based on hauling truck capacity, and elimination of waste throughout the process, thus providing many environmental and economic benefits [91].

With the advents in information and communications technology (ICT) and IoT, urban infrastructures will become more instrumented with intelligent sensing and monitoring technologies. These technologies will not only collect, predict, and store a wealth of data in real-time, they will also be endowed with communication capabilities, enabling real-time communication between one infrastructure and another infrastructure (I2I). The plethora of data collected and mined can be used for infrastructure planning and designing, as well as managing their demands and interdependencies, thus enabling a truly integrated and efficient urban ecosystem. With this next generation of interconnected and intelligent systems, transport, water, and waste infrastructures will soon possess the ability to gather information, predict their states, and communicate with one another to engage, when needed, in strategic negotiations using the principles of cooperative game theory to manage conflicting situations. In the context of infrastructure integration, game theory uses mathematical tools to model various stakeholder preferences, costs, and action payoffs to facilitate negotiations among stakeholders to reach a mutually beneficial agreement. Stakeholders can then use this information to evaluate and negotiate the options available and agree on mutually beneficial solutions. Mohebbi et al. [92] showed the successful use collation games to resolve planning conflicts between water distribution systems and the transport network. Combined with what-if scenarios and machine learning, cooperative games open the door for new research avenues for modeling infrastructure system interactions and resolving disputes with the objective of optimizing performance, efficiency, and resilience while also improving sustainability. In doing so, the city becomes more like a living organism, responding to the needs of its inhabitants in real-time.

Some simple and linear models and tools might be appropriate for analyzing individual infrastructures in isolation; however, a set of comprehensive tools and a framework with the ability to model, simulate, analyze, and manage interdependencies are needed to assess the integrated infrastructure systems. Rinaldi et al. [2] highlighted the important characteristics of integrated infrastructure models, including screening, network analysis, policy testing, and impact analysis, with the ability to accommodate a broad range of analyses ranging from planning, design, operation, management, policy analysis, and risk mitigation. They should also have access to a wide variety of data, including data on dependency relationships, and should be able to capture dynamic interactions and coupling among models [2]. Several approaches and tools for modeling integrated infrastructure systems were previously analyzed [22,26,27,93,94]. Saidi et al. [23] summarized them into five broad categories: system dynamic-based approaches; agent-based simulation and modelling; input–output models (economic flows); network-based approaches; and empirical approaches.

One important approach that supports urban infrastructure integration and interdependency quantification is urban metabolism [95]. Kennedy et al. [96] defined urban metabolism as 'the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste'. In practice, urban metabolism quantifies the mass and energy balance of the inputs, outputs, production, and consumption in an urban system, hence assessing existing conditions [96]. Urban metabolism can help identify not only interdependencies between infrastructure systems but also interrelationships in how their services are used. For example, Movahedi and Derrible [97] looked at the interrelations between the consumption of electricity, water, and gas in New York City.

Developing a comprehensive and integrative framework is critical but also very challenging. It primarily requires multi-disciplinary knowledge and expertise with versatile and compatible tools and models for different scales, parameters, boundaries, and outputs. The framework should also have the capacity to overcome the challenges associated with risk and risk management, integrate complexity into the models, embed human behavior and inclusion of communities, and finance, plan, make and implement decisions and policies [2,3,23,48,63]. Additionally, as mentioned previously, this study identified and analyzed the interdependencies between transport, water, and waste infrastructures; however, further research is needed to quantify and model these complex interdependencies and to identify ways of overcoming the challenges associated with integrating the infrastructure systems.

## 6. Conclusions

Identifying and understanding the interdependencies between urban infrastructure systems is critical for the development of sustainable and resilient cities. The failure of one system can have cascading impacts on other systems, leading to significant economic, social, and environmental consequences. This article identified and qualitatively analyzed potential impacts and interdependencies between urban transport, water, and waste infrastructures. The insights and knowledge presented can assist urban planners and stakeholders to make more informed decisions.

Transport, water, and waste are critical infrastructures in a city; however, the interdependencies between these three systems have not been analyzed in great detail in the past. This article emphasized the importance of adopting an integrated infrastructure system approach. Novel techniques, quantitative tools, best practices, and a circular economy approach are recommended to facilitate infrastructure integration. Further research aimed at better quantifying interdependencies and generating a deeper understanding of the integration and nexus approach remains necessary.

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