Efficacy in developing a Sustainable, Resilient, and Interdependent Infrastructure System in the Gulf Region

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Abstract

The world is becoming increasingly interconnected, and the exchange of information, knowledge, and services assists in developing and managing many aspects of the built environment. Sustainable, resilient, and interdependent development of infrastructure emphasizes relationships among systems with benefits of creating one system-of-systems that includes enhancing the delivery of primary services, increasing systems efficiency in performing more than one function, exchanging benefits between systems, sharing information among systems, reducing carbon emission, eliminating waste, enhancing the operation of all systems, and reducing the cost of developing, managing, operating, and maintaining them. Infrastructure development in the Gulf region presents many challenges, such as excessive use of scarce natural resources, limited areas of development, and high cost of development, operation, and maintenance in each system. This study addresses the importance of developing a sustainable, resilient, and interdependent infrastructure system that can work with the natural processes and flows and respond to challenges specific to the Gulf Region. Its findings will guide decision-makers in the appropriate choices and the economic, environmental, and social opportunities in developing an integrated and efficient one-system network. Relationships between infrastructure systems, such as simple, colocation, or geographical relationship, and an integrated relationship in the Gulf region will be compared with other relevant international projects. Data from project-specific literature and case studies were used to carry out this study.

Keywords: Infrastructure system; Sustainable; Resilient; Interdependent; Gulf region

1. Introduction

Infrastructure systems, such as telecommunications, electric power systems, movement of natural gas and oil, transport, and water treatment and supply, are essential for the continuous and reliable functioning of economic and social systems, as they supply the main services that support economical production, safety, security, and a high quality of life. Infrastructure systems are developed, operated, and maintained to meet service requirements, resist deterioration such as fatigue, cracking, and corrosion, and withstand hazards such as floods, earthquakes, and winds. Many factors must be considered during infrastructure development, such as strength, rigidity, serviceability, and maintainability, in addition to sustainability, resilience, and interdependence of infrastructure (Grafius et al., 2020).

Sustainable infrastructure is based on development that meets the needs of the present without compromising the future. It must respond to environmental protection concerns, reduce consumption of scarce and non-renewable natural resources, and adapt to climate change, economic development, and social equity. Sustainable development must have a friendly impact on the environment during the design, construction, rehabilitation, and maintenance stages. This should involve all project elements, including structural systems, construction materials, and maintenance plans. Infrastructure resilience is the ability of the developed systems to absorb or mitigate the impact of damage or hazard and to restore normal operation as soon as possible with minimum cost. Infrastructure interdependency is a two-way relationship between two or more systems in which the serviceability of any one system can influence other systems; operate depending on each other; and be developed to be part of or follow the natural systems (Chester et al., 2019).

This paper emphasizes and discusses the importance of developing sustainable, resilient, and interdependent infrastructure systems in the Gulf Region and the benefit of developing a practical and reliable level of relationship among the systems towards an integrated system that makes all systems work as one system.

2. Sustainable, Resilient and Interdependent Infrastructure Systems

2.1 Sustainable Infrastructure System

Sustainable development is development that addresses the requirements of the present without adversely affecting the needs of future generations. Sustainability is accepted as an important performance measure that should be included in the design, construction, operation, and maintenance of infrastructure systems (Hinge et al., 2020). Sustainable infrastructure can be achieved through three main execution measures, economic measures that meet the operation and maintenance requirement throughout the life cycle at minimal cost, environmental measures that utilize suitable materials and construction with the least influence on the environment during the construction, operation, repair, and dismantling, and social measures related to security, safety, and social equity. Infrastructure systems' construction, operation, and maintenance require large amounts of resources such as land, water, materials, and energy, which pollute the environment, including water contamination, sound, and greenhouse gas emissions.

Scarce natural resources and the environment must be protected by the proposed high-level workable design and rehabilitation strategies that reduce the impact on the natural environment, such as flora, fauna, soil, water, and air. The socioeconomic development of communities must be considered during the infrastructure development, including health, security, safety, equity, reliability, functionality, accessibility, operability, serviceability, maintainability, and costs (Lounis & McAllister, 2016).

2.2 Resilient Infrastructure System

Infrastructure resilience is the ability of substantial networks to withstand hazards, reduce interruption of functionality, and minimize recovery periods and costs. Various hazards and deterioration act and periods, such as reduction in capacity, corrosion, and fatigue (Kong et al., 2019). The resilience of an infrastructure system depends on many factors, such as the system’s function within the community. Important services of the infrastructure systems that serve the community, such as power, transportation, and communication systems, are required to be at a high-performance level of continuous operation, minimum damage, fewer hazard events, and quick recovery to normal operations.

The consequences of damage to any system affect the system’s operativity and functionality to meet the required objectives (Ouyang & Wang, 2015). The recovery period is subject to the infrastructure system's condition during the hazard period, the degree of deterioration, and the required maintenance and repair. Resilience development examines economic, social, and community influences, functionality, and performance during recovery. Design solutions enhance structural designs to reduce loss of functionality and damage during hazard events and shorten recovery periods (Lounis & McAllister, 2016).

2.3 Interdependent Infrastructure System

Infrastructure interdependency is the approach in which one or more systems need the services of one or more systems to operate or in which the service of one or more systems is influenced by the service of other systems (Hasan & Foliente, 2015). Interdependent infrastructure can be defined as networks in which the circumstances of one or more networks affect another (Grafius et al., 2020). According to Rinaldi et al. (2001), there are four different types of interdependent relationships among infrastructure systems according to the nature of resources of each system. These include:

- Physical/geographic relationship: the systems are connected by sharing the same material or proximity, such as in colocation in corridors and tunnels.
- Cyber relationship: systems are related to each other by transferring information or data between systems.
- Logical relationship: in which systems are connected according to developing, managing, operating, and financing resources.
- Integral relationships: the relationship in which one system can use the output or advantages of another system or systems.

3. Development of Sustainable, Resilient and Interdependent Infrastructural System

The goal of developing resilient and interdependent infrastructure systems is to promote interdisciplinary studies and research that propose innovative approaches and creative solutions for designing and operating infrastructure, to enhance the realization of the design for interdependent infrastructure networks and procedures, to generate awareness and expertise for innovation in interdependent infrastructure which enhances the networks and their serviceability and operability in term of security, safety, efficiency, and effectiveness (Wang et al., 2011). The mentioned goals guide many defined objectives in the development, including creating advanced knowledge approaches and creative solutions to enhance resilience, achievement, and operation in interdependent infrastructure, building conceptual frameworks to analyze the adapting behavior of the interdependent system during the natural and/or climatic change and its impact on the serviceability, maintainability, and repairability, developing a workable strategy that links the opportunities in interdependent infrastructure such a cyber, logical, physical, economic, environmental, social, and integral relationship, and understanding the barriers to interdependent infrastructure development that hinder the upgrade of systems such as the legal, political, psychological, and socioeconomic barriers (Hasan & Foliente, 2015). According to Brown (2014), the concept of the future infrastructure network is the design of a multipurpose, interconnected, multifunctional, resilient, and sustainable system in a closed loop that exchanges characteristics with the natural ecosystem and benefit from each other. The steps in developing sustainable, resilient, and interdependent infrastructure of existing and new systems are shown in Figure (1).

The benefits from the emphasis on the relationships within the infrastructure systems include enhancing the delivery of the main services; increasing system efficiency in performing more than one function and/or exchanging benefits between them; sharing information among systems; reducing carbon emission; eliminating waste; enhancing the sustainability and resilience of the overall system, and reducing the cost of development, management, and maintenance (Brown, 2014).

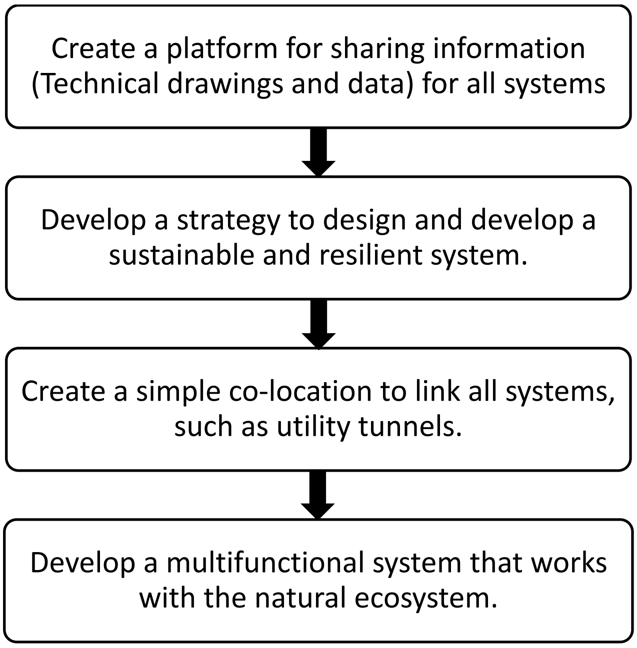

Fig. 1: Steps for developing Sustainable, Resilient and Interdependent Infrastructure

In the platform, different data models and workflow processes can be utilized in the development, management, operation, and maintenance of the infrastructure systems, such as Building Information Modeling (BIM), Digital Twins (DTs), and Emerging Technologies (EMs), (Callcut et al., 2021).

4. Case Studies

The following group of case studies on sustainable, resilient, and interdependent infrastructure development can be used to understand the different approaches for linking the systems and the benefits gained from each development. Table (1) shows the relationship and Locations of each case study.

4.1 Case Study 1: Underground Utility Tunnel in Shanghai, China

This is a new sustainable underground structural system developed in 2015 in Shanghai, China, to house more than one network of the utility system to enhance the development, renovation, adaptation, maintenance, and repair of the systems without any obstructions to the urban area and to improve the quality of urbanization. In contrast, the standard procedure of building the utility systems separately under the roads or in congested shallow-level corridors can lead to recurrent road cutting for maintenance, causing leakage, damage, or rupture to other systems. These can cause damage to the surrounding environment as well as noise, safety, and security problems (Yang & Peng, 2016).

4.2 Case Study 2: Photovoltaics Noise Barriers

Photovoltaic noise barriers are a combination of noise barrier systems and photovoltaic systems used to reduce traffic noise while at the same time producing renewable energy. It includes a grid-connected solar panel array located along railways or highways and mounted to produce electricity for the grids and deflect noise away from a densely populated area. It can be utilized in a limited area in crowded locations, supply the area with electricity, reduce energy transmission costs, enhance energy efficiency, reduce carbon dioxide (CO_2) emissions, and minimize traffic noise. Examples of large photovoltaic noise barriers are those located along the A90 highway near Ouderkerk, Amsterdam, the Netherlands, and another along a viaduct near Zurich, Switzerland (Vallati et al., 2015).

4.3 Case Study 3: The Stormwater Management and Road Tunnel in Kuala Lumpur, Malaysia

The Stormwater Management and Road Tunnel (SMART) project, completed in 2007, was developed to serve two main purposes required by the city, to solve the problem of traffic congestion and to manage stormwater flooding. The tunnel is about 9.7 km in length with two sections, used according to the seasons; during the light rain season, no water is rerouted into the tunnel, and the traffic moves as normal during moderate rainfall; the lower section of the tunnel acts as storage for the water and the upper section used for traffic; during heavy rain, no traffic is allowed in either section, and the tunnel is used completely for water storage. this occurs about twice a year (Grafius et al., 2020). This innovative colocation project emphasizes the relationships between the two systems and works with nature to manage flooding, which cannot be avoided. The project solves two significant urban problems, saving costs and using fewer resources (Kim-Soon et al., 2016).

4.4 Case Study 4: Infrastructure Ecology in Stockholm, Sweden

This is an interactive and cooperative exchange project between the energy and materials flows of the locality. It uses a transformative approach based on an integrated and nearly closed system in which energy and resources flow and cycle from one utility to another. The heat from the Combined Heat and Power plant (CHP) and the sewerage treatment facility is retrieved to supply district heating. Biogas drawn out from the sewage plant is processed as fuel for local vehicles and domestic cooking stoves, and a portion of the sewage facility returns sludge for agricultural use. Mixed combustible household waste and forestry waste are appropriated for combustion in the CHP plant, and household commercial organic waste returns as fertilizer for agriculture or landscape use. Solar panel arrays supply local and distributed energy and domestic hot water systems (Brown, 2014).

4.5 Case Study 5: Combined Power and Distillation Plant in the Gulf Region

In the Gulf region, electrical power and freshwater supplies are developed at the same time. Thermal distillation of seawater needs large amounts of steam as an energy source. However, the latest technologies require only low-pressure and grade steam. Thermal distillation can be multi-stage flash (MSF) form and/or multiple-effect distillation (MED) units. The water and steam plants are firmly interconnected. The integrated cycle plant gives low-pressure steam to the desalination plant’s MSF units and goes back through the condensate recovery process. A distillate from the desalination plant is supplied to the combined cycle plant, which utilizes it for cooling towers and steam cycle (Maadhah & Wojcik, 1981). Some examples of combined power and flash distillation plants are the Marafiq integrated water and power plant in Jubail, Kingdom of Saudi Arabia, and the Ras Laffan power and water plant located in Ras Laffan industrial city, Qatar (Rahman & Zidih, 2018).

4.6 Case Study 6: Water Treatment Plants in the Gulf Region

Wastewater treatment plants in the Gulf region use a combination of physical, chemical, and biological processes to treat sewage water from household, industrial and commercial use. Specialized equipment and technical chemical feed stations sanitize the water effectively. Wastewater treated at a sewage treatment plant can supply nutrient-rich water for irrigation, agricultural, industrial, and municipal purposes. Wastewater treatment also offers economic value by contributing to conserving the country's very scarce freshwater resources. The environmental benefits include reducing the pollution of water resources and sensitive receiving bodies and controlling saline water intrusion through groundwater recharge (Ouda, 2015).

4.7 Case Study 7: Doha Metro Project

This is one of the most recent and significant infrastructure projects in Qatar; phase one was completed in 2020, which includes three main metro lines (the red line from Al Wakra to Lusail, the green line from Al Mansoura to Al Riffa, the gold line from Ras Bu Abboud to Al Azizyah), and 37 passenger stations. The stations were developed on three levels: the first level includes the entrance and creative hard and soft landscape features; the second level is the station hall which includes the ticket office, restrooms, retail shops, restaurants, and other facilities; the third level is the platform for accessing the metro. The metro station is an innovative example of colocation that enhances connectivity between different modes of transportation, reduces environmental impact, enhances sustainability, and creates multifunctional activities. The metro is electrically powered, which can reduce air pollution and energy consumption and enhance economic development (Amerio, 2020).

Table1: Interdependent Relationship and Locations of the Case Studies

No.	Case Study	Location	Interdependent Relationship
1	Underground Utility Tunnel	Shanghai, China	Geographical
2	Photovoltaic Noise Barriers	Amsterdam, Netherlands, and Zurich, Switzerland	Geographical
3	The Stormwater Management and Road Tunnel	Kuala Lumpur, Malaysia	Geographical
4	Infrastructure Ecology	Stockholm, Sweden	Cyber and Integral
5	Combined Power and Distillation Plant	Gulf region (Qatar, Saudi, and UAE)	Cyber and Integral
6	Water Treatment Plants	Gulf region (Qatar, Saudi, and UAE)	Cyber and Integral
7	Doha Metro Project	Doha, Qatar	Geographical and logical

5. Conclusion

Historically, infrastructure networks such as energy, telecommunication, and transportation were developed, managed, operated, and maintained separately. With the development and expansion of urban areas in the cities in the Arabian Gulf Region, the development of additional new systems such as district chilled water systems and district heating water systems, the logical need to link systems with each other, and the requirement for more efficient and reliable services, there is an urgent need to develop a more sustainable, resilient, and interdependent system that enhances the delivery of major services, raises the efficiency of the system in operating many functions, interchanging benefits, sharing information between systems, reducing carbon emission, minimizing waste, improving the sustainability and resilience of the overall system, and minimizing costs. This kind of development can start with creating a platform to share information such as technical drawings and data, developing a strategy for designing and managing the networks as one system, developing a collocation program to link all systems in an underground utility tunnel, and later creating a multifunctional network that is linked with natural ecosystem if possible. In this regard, the infrastructure systems must be multipurpose, interconnected, and synergistic, contribute fewer carbon emissions, be resilient and adaptable to predicted changes in nature and the climate, work with natural processes, improve social contexts and serve local communities.

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