

# Digitalization Evolution of Urban Water Infrastructure Management to Facilitate Digital Twin Technologies Adoption

by

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## **FOREWORD**

This thesis is dedicated with love to my parents, Mahmoud and Eftikhar, to my lovely family, Nael, Abedalaziz, Faris, and Tameem, and to my princess, Salma, and to all my brothers and sisters. This work would not be possible without you all.



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# **Évolution numérique de la gestion des infrastructures d'eau urbaines pour faciliter l'adoption des technologies de jumeaux numériques**

Inas ABUAWAD

## **RÉSUMÉ**

Les systèmes d'infrastructure hydraulique urbaine sont essentiels au fonctionnement des villes, fournissant des services d'eau indispensables qui soutiennent les besoins et la commodité publiques. Cependant, ces systèmes font face à des défis de plus en plus complexes que les approches de gestion traditionnelles peinent à relever. La planification et la conception des projets d'infrastructure hydraulique sont cruciales pour le bon fonctionnement du réseau d'eau. Pourtant, leur gestion est souvent déficiente, en raison de la complexité et de l'inefficacité causées par des pratiques héritées fragmentées, caractérisées par un manque de données et une faible collaboration. Les technologies de Jumeau Numérique offrent des cadres prometteurs, basés sur les données, pour améliorer la performance des projets tout au long du cycle de vie de l'infrastructure. Cependant, leur adoption dans le secteur de l'eau reste limitée en raison d'une faible sensibilisation, d'un manque de preuves empiriques sur les facteurs d'adoption, de peu d'études de cas, et de problèmes d'acceptation par les utilisateurs. Cette thèse étudie les causes de la lenteur de l'adoption des Jumeaux Numériques parmi les diverses parties prenantes du secteur de l'eau, dans le but de faciliter leur intégration dans la gestion de l'eau. Pour ce faire, trois études empiriques ont été menées aux Émirats arabes unis (EAU), un environnement non contraint financièrement et un leader en innovation technologique au Moyen-Orient et à l'échelle mondiale.

La première étude examine les obstacles à l'adoption des technologies numériques lors de la conception et de la construction de projets hydrauliques, du point de vue des acteurs du secteur de l'eau maîtrisant les outils numériques. Une approche mixte a été utilisée, comprenant un questionnaire structuré suivi d'une discussion de groupe afin de contextualiser et de valider les résultats. Les résultats indiquent que les principaux obstacles sont les problèmes de cybersécurité et de disponibilité des données, le manque de normalisation, la promotion limitée par les pouvoirs publics, les lacunes en compétences numériques de la main-d'œuvre et les préoccupations liées aux coûts supplémentaires. Les analyses qualitatives mettent en évidence les lacunes en compétences de la main-d'œuvre comme l'obstacle le plus important, suivies par la cybersécurité, la qualité des données, les besoins en matière de gouvernance et les résistances culturelles. Les résultats démontrent comment les dimensions liées à la main-d'œuvre, aux données et aux aspects techniques, culturelles et institutionnels façonnent collectivement la perception de l'adoption des technologies numériques dans les projets d'infrastructures hydrauliques. L'étude fournit des pistes concrètes aux gestionnaires des secteurs de l'architecture, de l'ingénierie et de la construction (AIC), aux fournisseurs de technologies et aux décideurs politiques afin de faciliter l'intégration des technologies numériques et de renforcer les capacités numériques, contribuant ainsi à la réalisation de la vision des Émirats arabes unis en matière de gestion durable de l'eau. L'étude propose un cadre d'analyse des obstacles à deux niveaux, enrichi des facteurs sous-jacents. De plus, elle met en évidence les obstacles contextuels, contribuant ainsi au débat mondial sur la numérisation de la gestion de

l'eau en milieu urbain. Elle facilite ainsi l'adoption précoce de ces solutions et ouvre la voie à de futures études sur la transformation numérique de la gestion de l'eau.

Pour répondre à la méconnaissance des facteurs d'adoption des DT et au manque de preuves empiriques de succès des projets, la deuxième étude examine les principaux moteurs et la perception du succès des projets d'eau numérique au sein des Émirats arabes unis. L'analyse se concentre sur les réponses à un sondage recueillies exclusivement auprès de parties prenantes expérimentées dans le numérique, et triangule ces données avec des études de cas mondiales sur la digitalisation de l'eau. Les résultats du sondage indiquent que l'optimisation des performances, l'utilisation des données pour réduire les coûts, la mitigation des risques liés aux actifs, et la gestion de la sécurité publique sont les principaux moteurs de l'adoption des DT. Les participants ont partagé un consensus sur tous ces moteurs, sauf pour la réduction des coûts et le service client, ce qui reflète des priorités organisationnelles variées. La triangulation avec des études de cas mondiales confirme ces résultats et met en évidence la conformité réglementaire comme un moteur plus dominant à l'échelle mondiale qu'au sein du contexte des Émirats. Les deux résultats montrent que les initiatives de jumelage numérique sont associées à des perceptions positives du succès des projets, comme en témoigne la réalisation des objectifs et la satisfaction des équipes. L'étude fournit des insights pour les décideurs aux Émirats, soulignant la nécessité de cadres réglementaires adaptatifs, d'une gouvernance coordonnée, et de mandats clairs liant le déploiement des DT à la gestion des actifs et aux enjeux de durabilité. Ces résultats enrichissent la littérature émergente sur la digitalisation des infrastructures critiques en identifiant, pour la première fois, des facteurs empiriques d'adoption au Moyen-Orient. De plus, ils offrent une perspective sur l'évaluation du succès des projets, ce qui informe les acteurs de l'eau et oriente les recherches futures.

L'évolution rapide des applications numériques offre un potentiel pour améliorer la prestation de services en favorisant l'engagement citoyen. Une application basée sur l'Internet des objets (IoT) proposée par l'autorité de l'eau à Dubaï fournit aux usagers des notifications d'alerte en cas de consommation excessive d'eau. L'acceptation par les utilisateurs est essentielle pour gérer efficacement la consommation d'eau via des outils numériques destinés aux ménages. Cependant, malgré la technologie en place, l'acceptation des utilisateurs continue de freiner l'adoption et la mise en œuvre réussie de l'outil. Cette étude propose un modèle d'acceptation étendu basé sur le cadre du modèle d'acceptation de la technologie (MAT), intégrant des facteurs pertinents pour prédire les intentions des utilisateurs à utiliser l'outil. Les données principales ont été recueillies auprès de citoyens de Dubaï via une enquête transversale, aboutissant à 149 réponses valides. Les réponses ont été analysées à l'aide de la modélisation par équations structurelles (MES) dans l'environnement de programmation R. Les résultats indiquent que la préoccupation pour la sécurité de l'eau (PSE), une construction nouvelle, et l'utilité perçue (UP) sont les facteurs directeurs de l'intention comportementale (IC). L'auto-efficacité mobile (AEM) est un prédicteur positif significatif de la facilité d'utilisation perçue (FUP), tandis que l'anxiété liée à l'utilisation des appareils mobiles (AUM) la prédit négativement. Les politiques gouvernementales (PG) influencent significativement l'utilité perçue (UP). Comme prévu, la FUP prédit positivement l'UP, qui à son tour prédit significativement l'IC, soulignant les relations du MAT. Dans l'ensemble, le modèle étendu a démontré une forte capacité prédictive, expliquant 93,2 % de la variance de l'intention

comportementale. Les implications de l'étude offrent un cadre prédictif valable pour la planification des outils numériques liés à l'eau, étendent le MAT dans des contextes de gouvernance durable, et ouvrent la voie à de futures études expérimentales sur l'adoption et la post-implémentation.

**Mots-clés:** technologie de jumeau numérique, numérisation de l'eau, obstacles, moteurs, validation, Internet des objets (IoT), acceptation de la technologie, gestion des parties prenantes.



# **Digitalization evolution of urban water infrastructure management to facilitate digital twin technologies adoption**

Inas ABUAWAD

## **ABSTRACT**

Urban water infrastructure systems are crucial to cities' operations; they deliver vital water services that support public needs and convenience. However, these systems face escalating complex challenges that traditional management approaches struggle to cope with. Planning and design of water infrastructure projects are fundamental for water network functionality. Yet water projects are poorly managed and suffer from complexity and inefficiency due to fragmented legacy practices, insufficient data, and poor collaboration. Digital Twin (DT) technologies offer integrated, data-driven frameworks to enhance project performance over the entire infrastructure life cycle. However, their adoption in the water sector remains limited due to low awareness, a lack of empirical evidence on adoption factors, few case studies, and user acceptance issues. This thesis investigates the causes of slow adoption of DTs among diverse water stakeholders, aiming to facilitate their adoption in water infrastructure management. To achieve this, three empirical studies were conducted in the United Arab Emirates (UAE), a leader of technological innovation in the Middle East and globally.

The first study investigates barriers to adopting DTs during the design and construction of D&C of water projects from the perspective of digitally savvy water stakeholders. A mixed-method approach was used, comprising a structured questionnaire followed by a focus group discussion to contextualize and validate the results. The findings first indicate that key barriers are cybersecurity and data availability issues, a lack of standardization, limited government promotion, workforce digital skill gaps, and concerns about incremental costs. Qualitative insights highlight workforce skill capacity gaps as the most salient barrier, followed by cybersecurity, data quality, governance needs, and cultural resistance. The findings demonstrate how workforce, data-technical, cultural, and institutional dimensions collectively shape perceptions of DT adoption in water infrastructure projects. The study provides actionable insights for architecture, engineering, and construction (AEC) managers, technology providers, and government policymakers to facilitate DT integration and strengthen digital capacity, advancing the UAE's vision for sustainable water management. The study contributes with a refined two-level insight framework on barriers analysis with underlying factors. Besides, it validates context-specific barriers, adding to the global discourse on digitalization in urban water management. Thereby, it facilitates early-stage adoption and open avenues for future studies on digital transformation in water management.

To address insufficient awareness of adoption drivers and the limited empirical evidence of project success. The second study examines the key drivers and perceived project success of digital water project implementations in the UAE. The analysis focuses on survey responses collected exclusively from digitally experienced stakeholders and triangulates with synthesized qualitative data on water case studies. The survey results indicate that performance optimization, leveraging data to reduce costs, asset-risk mitigation, and public-safety

management are the key drivers of DTs adoption. Participants concurred on all drivers, except cost reduction and customer service, reflecting varying organizational priorities. Triangulation with global case studies corroborates the findings but highlights regulatory compliance as a more dominant driver globally than perceived within the UAE context. Both results show that digital twinning projects are associated with positive perceptions of project success, as evidenced by goals' achievement and team satisfaction. The study provides insights for policymakers in the UAE, underscoring the need for adaptive regulatory frameworks, coordinated governance, and clear mandates that connect DTs deployment to asset management and sustainability outcomes. The results advance the emerging literature on digitalization in critical infrastructure. They identify, for the first time, empirical drivers of adoption in the Middle East and offer a perspective on project success, thereby informing water stakeholders and guiding future research directions.

The fast evolution of digital platforms offers new opportunities to improve service delivery through citizen engagement. An Internet of Things (IoT)-enabled application offered by the water authority in Dubai provides the public with alert notifications for high water use. User acceptance is essential for effectively managing water consumption through households' digital tool. However, user acceptance continues to hinder the tool's adoption and successful implementation. The third study proposes an extended acceptance model based on the technology acceptance model (TAM) framework, incorporating relevant factors to predict users' intentions to use the digital tool. Primary data were collected from Dubai citizens via a cross-sectional survey, resulting in 149 valid responses. The responses were analyzed using structural equation modeling (Weighted Least Squares Mean and Variance-adjusted (WLSMV) in the R programming environment. The results indicate that water security concern (WSC), a novel construct, and perceived usefulness (PU) are the direct enablers of behavioral intention (BI). Mobile self-efficacy (MSE) is a significant positive predictor of perceived ease of use (PEOU), whereas mobile device anxiety (MDA) negatively predicts it. Government policies (GP) significantly influence perceived usefulness (PU). As expected, PEOU positively predicted PU, which in turn significantly predicted BI, underscoring the TAM relationships. The extended model demonstrated substantial predictive power in behavioral intention. The study's implications offer a valid predictive framework for planning digital water tools, extend TAM into governance sustainability settings, and pave the way for further experimental studies on adoption and post-implementation settings.

**Keywords:** Digital twin technology, water digitalization, barriers, drivers, validation, Internet of Things (IoT), technology acceptance, stakeholder management.

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## LIST OF ABBREVIATIONS

AFNOR	The French Standardization Association
BIM	Building information modeling
CAPEX	Capital Expenditure
CEO	Chief Executive Officer
CSS	Combined Sewer System
DM	Direct Manager
DOA	Decision of adoption
DT	Digital Twin
EFA	Exploratory Factor Analysis
EPA	Environmental Protection Agency
GIS	Geographic Information Systems
HCI	Human-computer interface
ICT	Information and Communication Technology
IDT	Infrastructure Digital Twin
IIoT	Industrial Internet of Things
IoT	Internet of Things
IoT-UPM	IoT User Perceptions Model
IS	Information systems
KMO	Kaiser-Meyer-Olkin
MDA	Mobile Device Anxiety
MENA	Middle East and North Africa
MSE	Mobile Self-efficacy
NASA	National Aeronautics and Space Administration
NSI	Network Society Index
O&M	Operations and Maintenance
OPEX	Operational Expenditure
PCA	Principal Component Analysis

PPP	Public Private Partnership
PLM	Product Life Cycle Management
SM	Simulation Model
SS	Separated Sewer Systems
SSA	Storm and Sanitary Analysis
SWMM	Storm Water Management Model
TAM	Technology Acceptance Model
TPB	Theory of Planned Behavior
TRA	Theory of reasoned action
U.S.	The United States of America
UAE	United Arab Emirates
UK	United Kingdom
UNDRR	United Nations Disaster and Risk Reduction
UTAUT	Unified theory of acceptance and use of technology
UWS	Urban Water Systems
WMS	Watershed Modeling System
WSN	Wireless Sensor Network
WUI	Water Utility Infrastructure

## INTRODUCTION

### Smart Cities Systems

Cities are expanding at an accelerated pace; current projections estimate that nearly two-thirds of the world's population will reside in cities by 2050 (UN-Habitat, 2022). This rapid, frequently unplanned urbanization, combined with challenges in public health, environmental pollution, traffic, climate change, poor resource management, and deteriorating infrastructure, has placed immense stress on urban governance and city management (Marzouk & Othman, 2020; Joshi et al., 2016). Consequently, research institutions, policy bodies, and academic communities have intensified efforts to develop strategies to address the multifaceted challenges facing modern cities. Within this context, the concept of the smart city has gained significant attention over the past two decades, inspiring numerous initiatives and research agendas (Marzouk & Othman, 2020).

The term broadly refers to the integration of advanced digital platforms and data-driven technologies that enhance the operational efficiency of urban systems while improving the quality of citizens' lives (Haque et al., 2022). This paradigm is driven by rapid advancements in information and communication technology (ICT) and the increasing complexity of urban needs, which require innovative solutions. Accordingly, substantial efforts have been directed toward developing various smart sub-systems that collectively constitute the broader smart city framework. These include smart transportation networks, intelligent water management systems, smart energy grids, and smart building technologies, all of which continue to evolve in scope and sophistication (Hämäläinen, 2020; Joshi et al., 2016).

Besides, cities have begun to formulate and implement smart city policies through diverse pathways and from various perspectives. While some cities emphasize social inclusion, citizen well-being, and economic growth, others were driven by visionary leadership, data-centric decision-making, or technological optimism (Noori et al., 2020). A growing body of research has demonstrated that integrating digital technologies enables cities to optimize performance,

accelerate digitalization, and support broader economic development goals (Hämäläinen, 2019).

As a result, digitalization has emerged as a noticeable direction in modern urban development agendas (Hämäläinen, 2020). Digital systems, such as integrated platforms, virtual models, and a wide range of digital services, have been recognized as tools for enabling the digitalization of urban environments (Ablyazov, 2021). In the context of water management, digitalization has become increasingly evident. Smart water systems have been defined as the increasing implementation of digital tools, such as interactive applications, real-time sensing networks, and automated monitoring technologies, into daily interactions between society and water (Wang & Yin, 2022; Lee et al., 2018).

The rapid evolution of “smart” concepts and their associated technologies has extended beyond technical instrumentation to encompass the dynamic interplay between physical and social systems, both of which are essential components of effective urban digitalization (Joshi et al., 2016). Brennen and Kreiss (2016) contend that digitalization is not merely about developing digital tools; it also transforms social practices, institutional logics, and the structure of societal relationships. These transformations can be understood as sociotechnical processes through which social, cultural, and institutional contexts co-evolve alongside emerging digital environments (Rijswijk et al., 2020). Such processes require substantial alignment and adaptation across organizational, social, and technological dimensions before achieving a fully digital form (Danielsen, 2021). Consequently, digitalization reorganizes numerous domains of social life, increasingly influenced by interactive digital platforms and social media applications (Brennen & Kreiss, 2016). This underscores the critical role of social factors in shaping technology uptake: the elements that influence user perceptions and drive social dynamics ultimately determine technology acceptance and adoption (Venkatesh, 1999; Lee et al., 2015).

### **Urban Water Systems Context**

Urban infrastructure systems form the foundational framework that enables mobility and circulation, provides essential utilities and recreational amenities, and protects urban areas

from natural hazards and disasters. These systems not only sustain the daily functioning of cities but also foster business growth and contribute to a safe and convenient quality of life (CIRC, 2019). Infrastructure projects are typically large-scale undertakings characterized by substantial capital investments, complex stakeholder relationships, extensive spatial scope, and long implementation periods. Such projects are economically vital for the delivery, expansion, and long-term management of the built environment and urban operations (Cheng et al., 2016; Rahman & Vanier, 2004). Moreover, the construction sector, particularly building and infrastructure development, plays a strategic role in urban economies by contributing to output, employment generation, and ongoing development and maintenance (Vilutienė et al., 2020). In recognition of the strategic role of infrastructure in economic resilience and sustainable urban growth, major investment programs and initiatives have been noted to accelerate the transition to digitally enabled infrastructure (ATKINS, 2017).

The Canada Infrastructure Report Card (CIRC, 2019) raises serious concerns regarding the state of existing public infrastructure assets across multiple categories. The report concludes that a considerable proportion of them are in poor condition and at elevated risk of failure. Additionally, it reveals that many inspected assets are aging and deteriorating, and have suffered long-term neglect, reinforcing the urgent need for systematic investment, modernization, and enhanced asset management strategies. Urban water systems are fundamental components of municipal infrastructure and are crucial. They provide safe drinking water and collect, convey, treat, and discharge wastewater for cities' operations (CIRC, 2019). Despite their importance, these systems face challenges that conventional management approaches cannot cope with.

Urban water networks are highly congested underground corridors, sharing limited space with a wide array of other utilities while lying adjacent to buildings and roadways (Yang et al., 2021). Within a compact area, numerous utility lines, such as potable water mains, sewer and stormwater pipes, natural gas and steam lines, electrical cables, telecommunications networks, and traffic control systems, may coexist (Lieberman et al., 2017). Such spatial limitations create interdependencies and facilitate operation, yet they may increase system vulnerability.

For instance, failure in one utility can propagate to others, causing cascading disruptions with potentially severe and unpredictable consequences (Lieberman et al., 2017). Repeated incidents are evident among drainage, transportation, energy, and building systems, and have resulted in catastrophic losses across the urban environment (Dao et al., 2021; Ferrante et al., 2020).

Urban water systems management also faces a range of internal and external challenges that magnify their operational complexity (UN-Habitat, 2022; Marzouk & Othman, 2020). Internally, many networks are aging, deteriorating, and are urgently in need of renewal and expansion to meet rising service demands driven by rapid, unplanned urbanization (CIRC, 2019; Marzouk & Othman, 2020). Externally, these systems are increasingly exposed to climate change impacts, natural hazards, surrounding land-use conditions, and heavy traffic loads, intensifying their vulnerability (Wang, 2015). Unforgetting that these networks are buried underground, invisible, difficult to access, and characterized by significant data lack. Those challenges limit planning, design, and operation capabilities, resulting in uncertainty and poor management practices (Tanoli et al., 2019; Marzouk & Othman, 2020).

Poor management of urban water systems is rooted in the lack of data regarding the location, characteristics, and actual condition of underground assets. This problem is magnified by limited data sharing and poor stakeholder collaboration, resulting in fragmented information environments often described as “information isolated islands”. The absence of common digital platforms further reinforces this fragmentation. Consequently, even when data exist, they are rarely digitized or shared; instead, they remain in paper-based records that get lost over time, leading to repeatedly capturing the same information (Tanoli et al., 2019; Marzouk & Othman, 2020; Huang et al., 2022; Fenais et al., 2018; Zhao et al., 2019). Integrated datasets and shared digital platforms that capture all information essential for informed and coordinated decision-making remain lacking (Alperen et al., 2021; Ghaith et al., 2022; Yu et al., 2021; Ashworth, 2021). However, these challenges serve as catalysts, compelling managers and policymakers to rethink conventional practices and pursue innovative, technology-enabled solutions (UN-Habitat, 2022).

## **Adoption of Digital Twin Technologies**

Adopting new digital technologies and platforms has brought noticeable improvements both at the community level (Hämäläinen, 2020; Lu et al., 2020) and in workers' environments (Wang, 2021; Tanoli et al., 2019). The rapid evolution of digital technologies offers the potential to transform service delivery and promote citizen engagement. Among the latest and most advanced technologies is the digital twin DT technology. DT is an emerging technology that focuses on the viability of building a digital informational counterpart (twin) of a physical system (Grieves & Vickers, 2017). Recently, DT has been presented as an integrated solution, rather than as models for data connections, as described by Curl et al. (2019). The technology made remarkable improvements across many sectors, including manufacturing, aviation, buildings, and transportation (Grieves & Vickers, 2017; Gao et al., 2021; Coupry et al., 2021; Rasheed, San, & Kvamsdal, 2019).

Gartner (2017) projected that by 2021, half of all large firms would employ some form of Digital Twin (DT) technology, resulting in an estimated 10% improvement in operational efficiency. Similarly, the SWAN 2022 Annual Recap Report highlighted that DTs' distinctive advantages over traditional simulation models lie in their real-time data integration and enhanced accuracy. Consequently, the adoption of DT technologies has been gaining momentum within the built environment and civil infrastructure sectors. However, as Naderi and Shojaei (2023) reviewed, their application in water systems remains limited. Despite the technology's promising potential, the adoption and evolution of DTs in the water sector have been comparatively slow, even in developed countries (Bartos & Kerkez, 2020; Beal & Flynn, 2015; Ablyazov, 2021; Schmidt et al., 2024).

It is well established that digitalization in the water sector remains at an early stage, with numerous barriers at various levels contributing to vague understanding and reluctance among stakeholders to adopt digital tools, despite their promising potential. Several successful implementations have emerged, although they often lack proper documentation and recognition within the stakeholder community. Therefore, efforts to promote the adoption of Digital Twin (DT) technologies in water management should emphasize the central role of stakeholders in advancing these innovations. Unaware and hesitant stakeholders must be

informed, adequately prepared to adapt to the evolving technological landscape, and supported through targeted governance frameworks and enabling conditions.

## CHAPTER 1

### RESEARCH FOCUS AND OBJECTIVES

This chapter introduces the research focus and objectives. It provides the rationale that connects the motivation to pinpointing the problems, which in turn, define the objectives. Accordingly, the problem statement was articulated, and the research questions were formulated. Additionally, an overview of the thesis studies, including their questions, target samples, and a brief description of the scientific production of three manuscripts. In addition, the theories adopted and the thesis contribution.

#### 1.1 Research Motivation

My motivation started when I earned my master's degree in water and environmental civil engineering. There, I was introduced to many courses in water engineering, in which I excelled with high grades. I conducted my master's thesis on the application of simulation modeling and hydrological analysis to a local catchment, from which several recommendations were derived. As I recall, one recommendation that stood out to me was the importance of enhancing simulation modeling performance through real-time data connections. I experienced this practically through my research, where I realized the model's limitations, even after many calibration and validation steps. The deviations in results occurred repeatedly between the natural system responses and their virtual simulation models. Therefore, an improvement is urgently required: more advanced models with greater capabilities are needed to accurately represent physical assets and natural systems (e.g., urban watersheds). My guided reading course fueled this ambition at the beginning of my PhD journey. I started reading about the new digital tools and models, specifically BIM and GIS, and their crucial role in digitalizing the built environment. This led me to focus on urban water systems and to ask why these complex systems lag behind other urban environmental systems in their digital approach. Accordingly, I narrowed down my interests and performed more focused readings.

Urban water systems are a principal component of cities' infrastructure and are crucial to their operations (CIRC, 2019). However, these systems encounter various challenges and are increasingly stressed, especially in the Middle East. The Middle East is home to mainly developing countries that face severe challenges related to water scarcity and security. They struggle with limited rainfall and scarce water resources, as seen in the Gulf countries (e.g., the UAE) (Qureshi, 2020), besides being affected by political instability and major conflicts, such as in Jordan (Yorke, 2013). This has increased demand and magnified stress, while operation processes remain constrained by legacy management practices and funding limitations. A dialogue should be initiated by several stakeholders in the region on emerging digital tools that have gained attention and have demonstrated improvements. More importantly, for urban water management and the struggle to deliver essential water services. Among the latest and most advanced solutions are the Digital Twin DT technologies. DTs can integrate various technologies and fuse heterogeneous data to provide a unified data-driven decision-support tools that address current deficiencies and limitations in management practices.

## **1.2 Problem Statement**

Urban water systems are critical infrastructure components of cities' built environment. They deliver essential water services while collecting, conveying, treating, and discharging wastewater to ensure public safety, health, and convenience. However, they are long-neglected, aging, and deteriorated, facing increasing challenges, and are poorly managed by conventional methods (CIRC, 2019). Emerging digital technologies (e.g., digital twin, DT) offer significant improvements across sectors such as aviation, manufacturing, transportation, and the built environment (ATKINS, 2017). However, their adoption in the water domain is lagging. Given the rapid evolution of 'smart' technologies that has notably expanded into physical and social systems (Joshi et al., 2016), the water sector is no exception. The digitalization of water can be represented by the increasing adoption of digital tools and interactive applications for managing interaction with water services (Wang & Yin, 2022). Based on a preliminary investigation driven by the research motivations, various knowledge

and empirical gaps hinder the adoption of DTs in water management practices among stakeholders. These gaps collectively inform the main objective of the thesis: “to identify ways to facilitate the adoption of DTs in the water infrastructure management.” Digitalization adoption in the water domain lags behind due to several reasons, such as and not limited to a lack of awareness, unvalidated benefits and unclear barriers, and a scarcity of successful case study demonstrations, as well as the users’ acceptance issues (Bartos & Kerkez, 2020; Boyle et al., 2022; Naderi & Shojaei, 2023).

Despite the DT term’s growing popularity and the increasing interest in its benefits, stakeholders agree that many aspects of DTs remain misunderstood. There is a plethora of definitions and ambiguity about whether the technology is a product, a process, or a methodology. In addition, there is a lack of formal standards, leading to confusion about DT use cases and outcomes (Ammar et al., 2022; Callcut et al., 2021; Broo & Schooling, 2023; VanDerHor & Mahadevan, 2021). Given the early stage of adoption and the limited body of research, the technology remains understudied and unexplored, resulting in a fuzzy understanding and limited awareness, particularly in the water domain (Daniel et al., 2023; Naderi & Shojaei, 2023).

The adoption of DTs is still in its early stages; several gaps exist at multiple levels, including social, technical, organizational, institutional, and others. Therefore, significant efforts are required to establish the approach in the water sector, which is lagging behind other infrastructure systems (Boyle et al., 2022; Daniel et al., 2023). Many specific-sector barriers hinder proper adoption, in addition to the technical barriers of data security and ownership. Moreover, stakeholders face challenges related to interoperability options, enabling technologies, data collection, storage, and analysis for operationalization, as well as other cultural barriers. Cultural barriers rooted in human factors, such as cultural acceptance, the difficulty of transitioning to a digital environment, resistance to adopting and using new tools, and a poor understanding (Opoku et al., 2023; Schmidt et al., 2024; Broo & Schooling, 2023). Additionally, there are skill and workforce barriers caused by an aging workforce, a limited supply of training and education courses, the need to attract and retain talented and skilled workers amid favorable market conditions, and the limited number of subject matter experts (Broo & Schooling, 2023).

Digital twin technology is advancing in the urban infrastructure domain (Naderi & Shojaei, 2023; Ammar et al., 2022). Many previous studies have employed various approaches to investigate the application of DT technologies, given the early stage of adoption and the limited number of case studies. Broo & Schooling (2023) and Callcut et al. (2021) reviewed the status of DT adoption in the infrastructure domain in developed contexts. Opoku et al. (2023) highlighted the limited contribution of developing countries to scientific research on the adoption of DT technologies, in their reviews focused on the construction field. Hence, in this thesis, the author chose to focus on the Middle East, a region comprising mainly developing countries that struggle with water security issues, financial constraints, and poor management. Building on the growing attention that DT technology has gained, as evidenced by the dramatic increase in publications since 2021 (Opoku et al., 2023). The existing literature is rich in articles demonstrating the barriers and benefits of DT applications across various industries; however, it lacks comprehensive coverage of water systems. The situation in the water sector remains unclear, primarily due to the early stage of DT application, the limited number of case studies, and the lack of validated barriers and benefits (Naderi & Shojaei, 2023). Therefore, the adoption factors of DT have not been fully revealed to domain stakeholders, and the technology is not yet established or widely adopted.

However, validated benefits are crucial for adoption and essential for influencing implementation (Al-Ashmori et al., 2020; Chan et al., 2019). Additionally, a clear set of readily identifiable barriers can facilitate the development of well-informed strategies, while most barriers are derived from the literature and lack empirical validation (Opoku et al., 2023). As a result, adoption barriers and benefits are not fully demonstrated or validated in practical water projects; therefore, adoption dynamics remain unclear.

Defining benefits in terms of scale and nature, along with quantifying and validating them monetarily through cost studies, is essential for convincing stakeholders (Jones et al., 2020; Ford & Wolf, 2020). However, the lack of monetary data, the scarcity of case studies due to limited implementations, and the difficulty of quantifying both tangible and intangible benefits are evident issues. Given that even economic evaluations have proven ineffective and complex approaches at times (Yang & Chou, 2019). These reasons make subjective validation a suitable approach at this early stage of technology adoption, as argued by Yang & Chou (2019),

drawing on Powell (1992). Particularly, considering the vital role that stakeholders play in adopting and accepting digital artifacts (Ablyazov, 2021).

Thus, understanding and acknowledging the factors that affect DT technology adoption from the perspective of experienced early adopters can raise awareness and promote the adoption of new technologies (Schmidt et al., 2024). The subjective validation of adoption factors (e.g., benefits, barriers, drivers) by experienced perceptions can shift them from anticipated to well-demonstrated. Without such substantial effort, it is challenging to present DT technologies as the best solutions that can overcome limitations and to convince domain stakeholders of their value, as noted by Jones et al. (2020).

Despite ongoing advances in digital tools, human roles cannot be fully automated or replaced, not even in the near future. According to Schmidt et al. (2024), the knowledge and expertise of experienced stakeholders are invaluable; engaging them in discussions about new technologies can lead to more robust, accurate solutions. Additionally, the high dependence of technology adoption on social factors makes the well-validated socio-technical approach in information systems (IS) research highly relevant (Recker, 2021). Studies have identified user acceptance and user profiles as significant barriers to the adoption of new technologies in construction (Lee et al., 2015). Therefore, more focus on user studies that address the fundamental factors influencing acceptance is essential. These points justify analyzing stakeholders' perceptions and adopting an information systems (IS) research perspective in this thesis.

In summary, various knowledge, empirical and theoretical gaps can be addressed as identified by the literature among water stakeholders that make the adoption of DTs slow, as outlined below:

1. Lack of Awareness regarding the DT technologies' features, definitions, and maturity levels among the water stakeholders.
2. Barriers and benefits are not established nor acknowledged by stakeholders; they are literature-derived and lack demonstration and validation in practice.
3. The empirical drivers of adoption are not readily available or validated in real-world examples, and the perceptions of project success implementation are unexplored.

4. User acceptance and its significant influential factors to use technology tools are not identified or determined.

### 1.3 Overview of the Research Studies

The gaps identified and discussed in the previous section raised several specific inquiries that required answers through multiple research studies. This project adopts a scientific exploratory-descriptive approach in two studies and an explanatory-predictive approach in the third. Three research studies were conducted to answer the defined questions and, collectively, fulfill the thesis's main objective, while filling gaps in the literature.

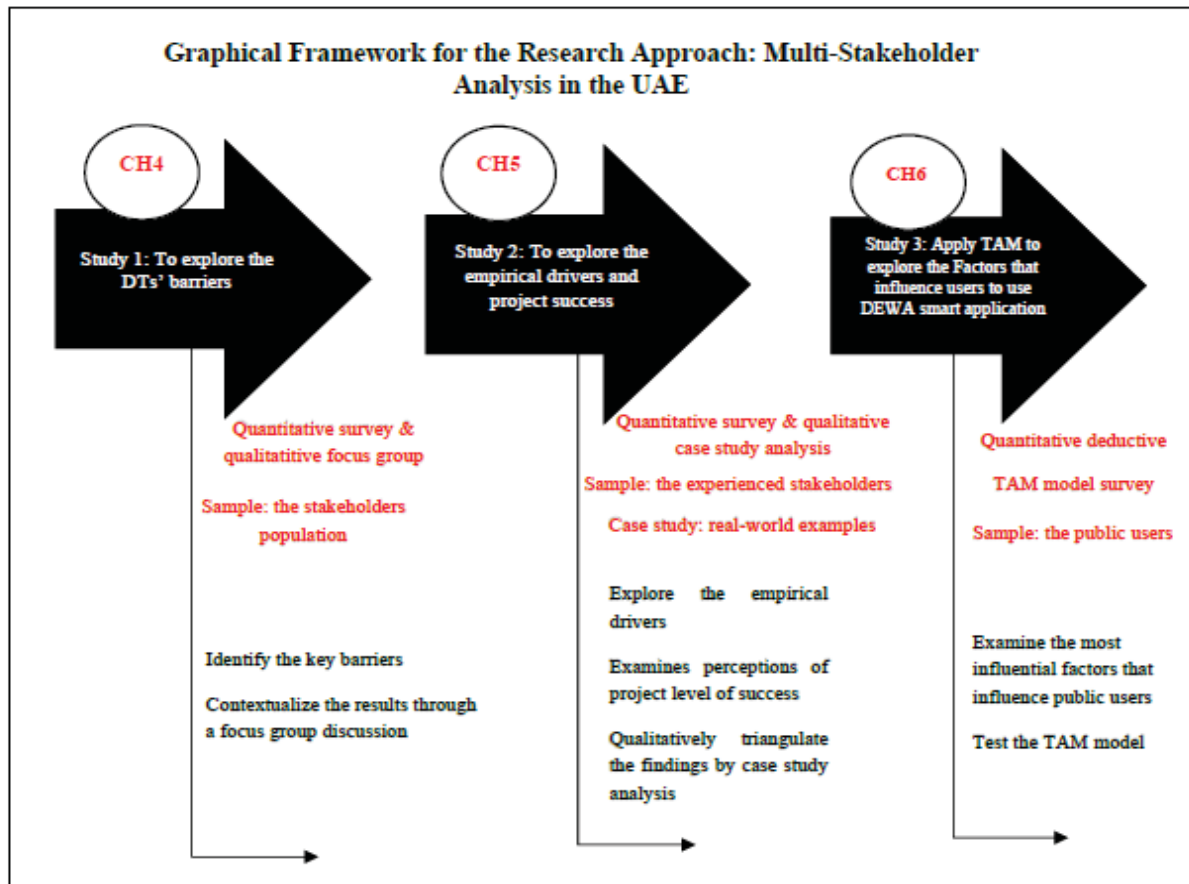


Figure 1.1 Graphical Framework of the Research Studies

The main aim of the thesis is to identify ways to facilitate the adoption of DTs in water infrastructure management. Each research addresses specific gaps by posing relevant questions and seeking answers through various methodologies and data analysis techniques (Figure 1.1).

The figure is a graphical representation that illustrates the research approach and flow. The first study identified a population in a pioneering area in the Middle East that is digitally advanced and non-financially constrained based on comprehensive searches and investigations. The individuals in this population were identified through an intensive search of leading consultation, contracting, and project management infrastructure companies based in the UAE, especially in Dubai. A total of one hundred sixty (160) key stakeholders were identified within their organizations based on their profiles, expertise, and involvement in digital projects. After a thorough investigation, the author considered this group to represent the entire population of stakeholders who are digitally inclined to, or familiar with, DTs in the UAE, as approached by Taheri et al. (2022).

The study developed a customized questionnaire divided into four sections to collect data. The data analysis was intended to include the responses from the entire population. Two main groups were identified among respondents: those with hands-on experience and those without experience but familiar with DT technologies. By addressing specific gaps through questions and analyzing the responses, the research tries to fulfill its objectives. The specific research questions are:

1. What are the key barriers to Digital Twin adoption in water infrastructure project management in the UAE?
2. How do qualitative insights validate and contextualize the perceived barriers?

The research assessed stakeholders' perceptions of adoption factors, particularly the barriers to the adoption of DTs in the planning and management of water projects. The barriers were identified based on quantitative data analysis. Then, qualitative analysis of the results was conducted using focus group discussions to refine the understanding of the barriers. The findings offer valuable insights for domain stakeholders, public officials, and water decision-makers on potential barriers and recommended strategies for improved integration, and guidance for future research.

The second research study was a mixed-methods (quantitative and qualitative) analysis of survey data and case-study results, focusing on the perception of experienced stakeholders and

case-study analysis. To achieve its primary objectives of exploring the empirical drivers and evaluating the projects' success, it sets three specific objectives as follows:

1. Explore the drivers of the DTs adoption based on actual project implementation experience and examine the differences in perceptions.
2. Investigate how experienced participants assess the DTs project's success in terms of the delivery achievement and the stakeholders' satisfaction.
3. Qualitatively triangulate the findings by drawing on real-world examples of digital water utilities' efforts.

The research employed an exploratory-descriptive quantitative approach based on the experienced responses. Then triangulate the results with a qualitative analysis of several case studies on the drivers and the project's success. The experienced stakeholders answered three experience-tailored questions specific to their backgrounds and the study objectives. Additionally, six real-world utility case studies from around the world (the U.S., Canada, and the UK) were qualitatively analyzed by content analysis, focusing on drivers, initial project goals, and realized benefits. The qualitative data triangulate with the quantitative and contextualize the drivers and the project's success in practical contexts. The research is an exploratory study serving as a starting point rather than a broad generalization. It highlights the drivers and discusses them in various contexts to enrich understanding and enhance the credibility of the findings on what initiates the adoption of DTs for water systems.

The findings are relevant and valuable to public officials, city planners, and utility managers seeking to embark on a digitalization journey. The results may guide countries in the Middle East and worldwide, with similar contexts and economic capacities. However, it cannot be generalized to the entire region due to varying digital maturity and the regional focus.

Considerable caution should be exercised when attempting broader generalizations.

The third research is a technology acceptance model (TAM) survey, a theory-based, deductive, quantitative study focusing on public users in Dubai. Public users are vital stakeholders in the adoption and successful deployment of new digital tools. The study addresses citizen engagement with new digital tools, a new approach to the governance of digitalization in urban management. It predicts what may influence public perceptions and addresses the users' acceptance through the extended TAM proposed relations. The Dubai Electricity and Water

Authority (DEWA) is the sole water service supplier in Dubai. The authority is a successful example recognized globally for its technological advancements. DEWA is driven by several national strategies and a visionary leadership approach aimed to be the world's first AI-native utility (Jones, 2024). The organization has made a massive investment in a smart application intended for public users to manage their water consumption digitally. Therefore, the third study aim is to identify the most influential factors affecting public acceptance and to extend and validate a new TAM model in the context of water research. By asking the following question, the study aims to fulfill its objectives.

1. How capable is the extended TAM for predicting users' intention in Dubai, to adopt IoT-digital tools in households' water management?
2. What are the significant influential factors that may predict the public users' intention to accept the digital tool?

The research is a user study that applies a socio-technical approach. TAM is extended by a set of relevant factors from several fields to form a novel conceptual model. Four factors are integrated into the three generic ones inherited from the original TAM model.

#### **1.4 Overview of the Manuscripts**

This section presents the project's primary scientific output, comprising three manuscripts that address the identified gaps and problems. The three manuscripts are expected to collectively contribute to the main objective and identify ways to facilitate the adoption of DTs among water stakeholders at multiple decision-making layers.

As discussed before, various empirical and knowledge gaps contribute to the slow adoption of DT technologies, as reported among stakeholders. To address this, the authors integrate various domains of knowledge through a literature mapping, resulting in three manuscripts, as shown in Figure 1.2. The figure illustrates the broad main knowledge domains integrated at the macro scale; however, each study incorporates sub-domains at the micro level as it is conducted. The three manuscripts offer practical insights and provide a coherent body of evidence to facilitate the adoption of DTs for urban water management in the UAE, a non-financially constrained environment.

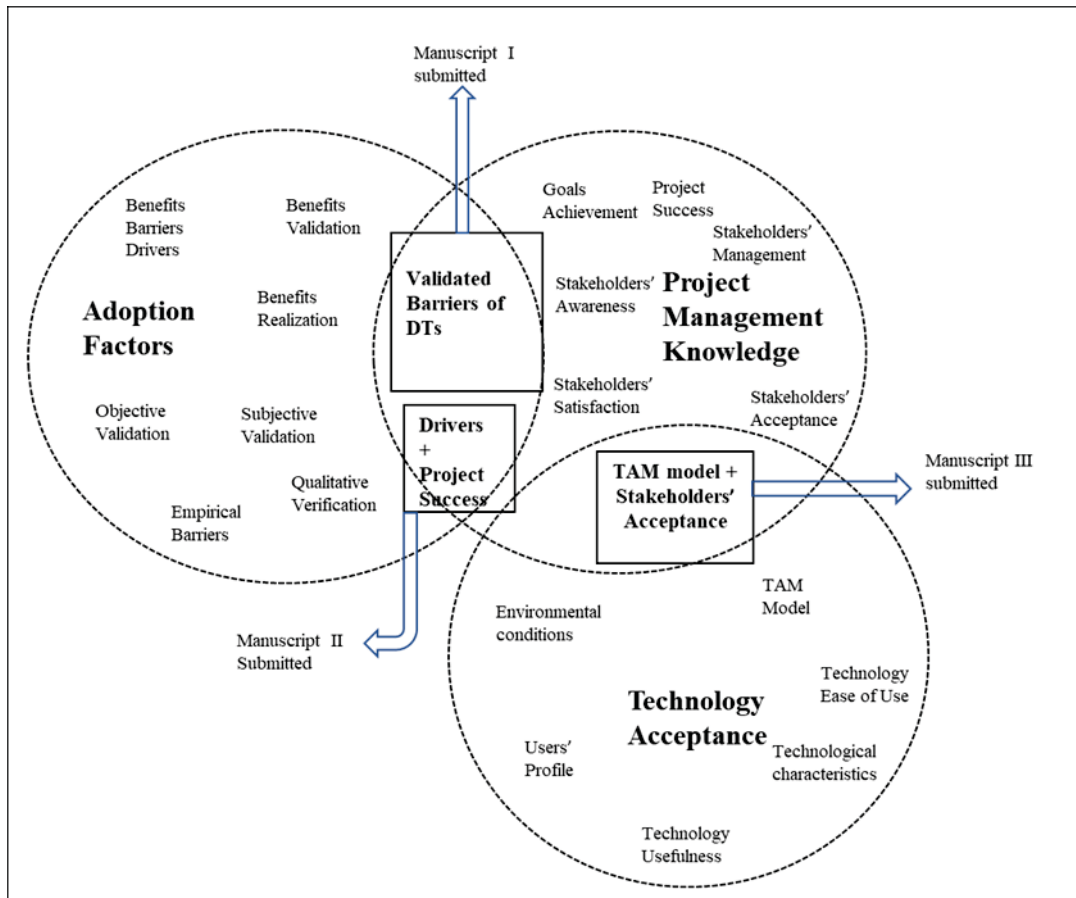


Figure 1.2 Literature Knowledge Mapping and Publications Domains

The first two manuscripts are mixed-methodology, exploratory, descriptive studies of stakeholders in primarily managerial roles involved in decision-making regarding the adoption of digital technologies at the project level. The first manuscript explores the entire population in Dubai and identifies the empirical barriers that are currently unclear to water stakeholders. It incorporates the adoption factors (barriers) and the importance of stakeholders' perceptions and knowledge to produce the first manuscript, as shown in Figure 1.3. The study employed a mixed-methods approach, using primary data collected through a cross-sectional survey and focus group discussions to target the entire population. A manuscript titled "Beyond Financial Constraints: Barriers to Adoption of Digital Twins in Water Projects Planning and Design Management" was produced and submitted for publication.

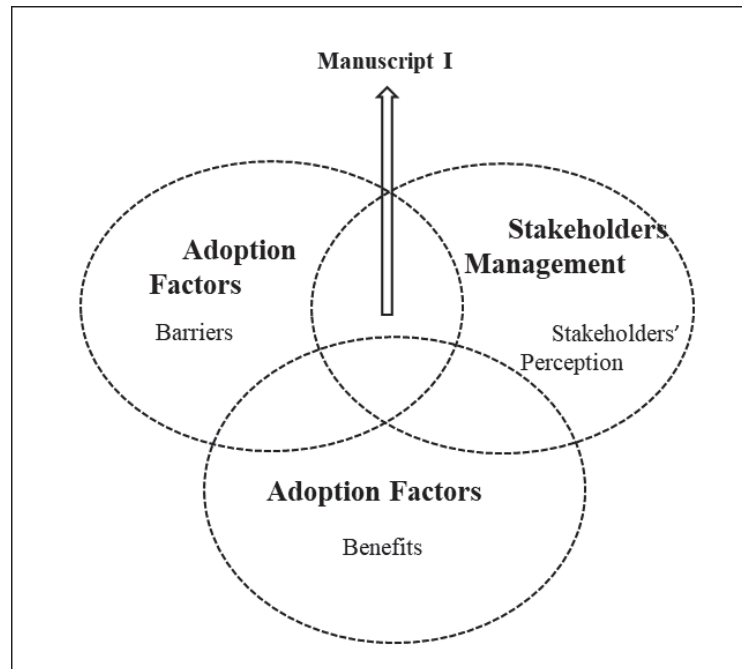


Figure 1.3 First Research’s Knowledge Domains

The second manuscript explores the key drivers of adoption and discusses the perceived project success from the perspective of project implementation. It incorporates adoption factors (drivers) and project success dimensions from the project management literature, resulting in the second manuscript, as shown in Figure 1.4.

The study employs an exploratory approach, utilizing a combination of quantitative and qualitative data. The primary quantitative results from the experienced respondents were triangulated with secondary qualitative data from real-world digital water projects to enhance credibility. The study initiates a dialogue on the key drivers of digitalization in water projects and the factors that determine project success, offering a starting point. A manuscript titled “Digital Twin Adoption Drivers and Perceived Project Success in Water Infrastructure Projects: UAE Stakeholders' Perspective and Global Case Evidence” was submitted for publication.

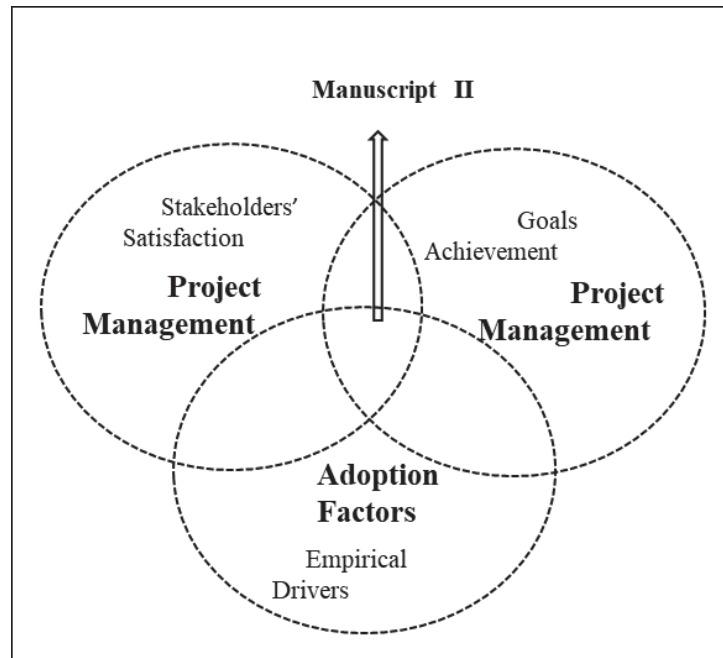


Figure 1.4 Second Research's Knowledge Domains

The third is an explanatory-predictive, theory-based survey of public users regarding their potential acceptance of the tool at the pre-implementation stage. It examines the acceptance issues and addresses citizen engagement with the digital tools provided by water authorities. Public users are vital stakeholders in the adoption of new technologies and in realizing their benefits. The study incorporates the technology acceptance TAM from information systems IS research literature, along with stakeholders' acceptance factors (personal profile) and facilitating conditions (environmental sustainability and governance factors) as shown in Figure 1.5. The study employed a socio-technical approach, based on a theoretical model, and collected quantitative data using a cross-sectional mode among Dubai's residents. A manuscript titled "Water Monitoring Management Using Households' Digital Tools: An Extended Socio-Technical Acceptance Model" was produced and submitted for publication.

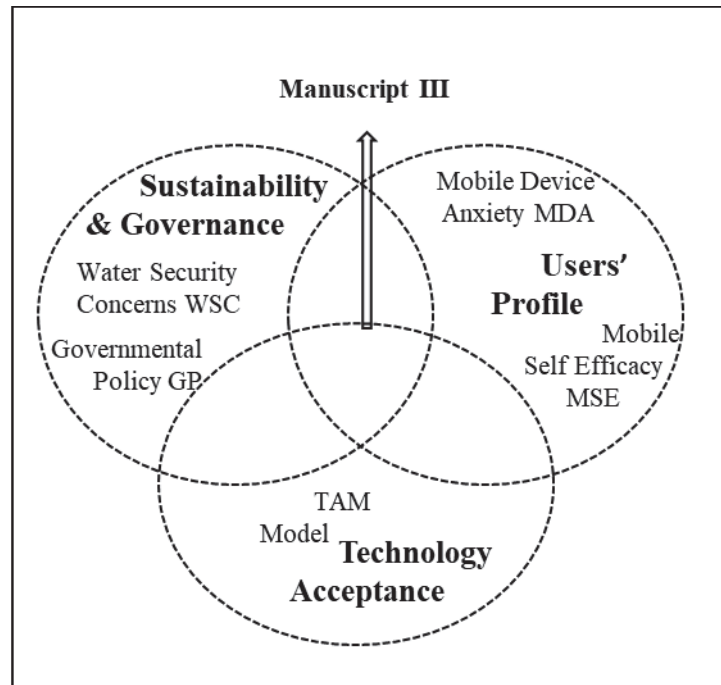


Figure 1.5 Third Research's Knowledge Domains

### 1.5 Theoretical Adopted Bases

The Technology Acceptance Model (TAM) is a social science, theoretically grounded model by Davis (1989). It builds on two theories: reasoned action (TRA) (Fishbein & Ajzen, 1977) and planned behavior (TPB) (Ajzen, 1985). TAM is one of the most widely used and validated models for assessing users' acceptance of new technologies (Saylam & Ozdemir, 2022). The model is extensively applied in information systems (IS) research (Recker, 2021). Recker (2021) describes the information systems perspective as primarily concerned with socio-technical systems involving individuals and groups who interact with digital information and communication technologies ICTs to accomplish tasks in private, business, or social contexts. The IS research field centers on the societal impact of the development and use of digital information and communication technologies.

TAM established its effectiveness in modeling technology acceptance before its introduction (Hutchins & Hook, 2017; Morienyane & Marnewick, 2019), during and after its implementation (Liu, Li, & Carlsson, 2010; Raes & Depaepe, 2020; Nikou & Economides,

2017). Hence, the model has been widely deployed across many domains, such as finance research for mobile payment acceptance (Rabaa'i et al., 2022), cloud-computing technology adoption (Ferri et al., 2021), the acceptance of autonomous vehicles AV for transportation management (Hewitt et al., 2019), the IoT technology acceptance for management of water service at a municipality (Morienyane & Marnewick, 2019), and for consumers' acceptance to use smart water meters (Madias et al., 2023).

However, TAM faces criticism for being too broad, lacking in-depth insights, concentrating mainly on acceptance factors, and ignoring inhibitors. Therefore, including other relevant factors is crucial for investigating the specific use of technology in any context (Dou et al., 2017; Flavián et al., 2022). To improve the TAM model's explanatory and predictive power and address its limitations, a set of relevant external variables was incorporated, guided by Economides (2016). In the review of IoT acceptance, Economides (2016) introduced the IoT User Perceptions Model (IoT-UPM), which highlights factors influencing users' perceptions of IoT technology acceptance across various domains and settings. These factors include four areas: user characteristics, producer characteristics, IoT system characteristics, and environmental characteristics. This research adopted a set of relevant external variables including: mobile self-efficacy (MSE), mobile device anxiety (MDA) from user profile factors; water security concerns (WSC), and governmental policy (GP) from environmental factors, along with the TAM constructs, perceived usefulness (PU), perceived ease of use (PEOU), and behavioral intention (BI).

## **1.6 Thesis Contribution**

Urban water networks constitute critical infrastructure that faces multifaceted, escalating challenges in delivering essential water services. These challenges encompass the impacts of water resource stress, climate change, natural disasters, urban expansion, evolving regulatory and development needs, and the limitations posed by conventional management practices and funding issues. Given this complexity, numerous studies propose digital twin (DT) technologies as frameworks for decision support and resource optimization within water systems. While digital twin technologies may support informed decision-making, their

widespread adoption in the water domain is hindered by implementation barriers, including knowledge gaps, water-sector-specific challenges, and financial constraints. This thesis addresses foundational knowledge and practice gaps by investigating the dimensions of digital twin technology adoption for water management in a digitally advanced, non-financially constrained environment. Consequently, three investigations were conducted in the study area, addressing different decision-making levels by targeting various water stakeholders; thereby, the thesis sought to achieve its aim.

The three studies explore, identify, validate, and predict factors that facilitate the adoption and implementation of digital twin technologies for urban water management. The results can inform water stakeholders, utilities, and governmental authorities about the demonstrated barriers and actionable insights to overcome them, as well as lessons learnt on the empirical drivers and the success of digital projects. Nevertheless, they also provide a socio-technical, governance, and sustainability lens that informs technology providers, governmental authorities, and utility managers about the essential user profiles. In addition, the necessary conditions to secure broader public acceptance of digital tools. The studies recommend the strategies required to enhance adoption and implementation in the context. In addition, they enhance understanding of DTs' adoption for water project management by providing a snapshot of progress and lessons learnt in a digitally advanced yet arid and water-stressed context. To the best of author's knowledge this thesis represents one of the first efforts in the Middle East to discuss and assess the digitalization for urban water systems. The approach has been unaddressed until now; even though, it is inevitable and essential for water management. The thesis contributions are elaborated in the three manuscripts as follows:

The first study quantitatively assessed the current state of DTs' adoption for design and construction of water projects, highlighting previously unaddressed barriers. The study explored perceived barriers through stakeholders' perceptions and contextualized them through qualitative focus group discussions. This approach provided a nuanced understanding of their details and gave a refined framework of barriers. Thus, the study provides evidence-based descriptive insights within the defined population on the barrier and recommends strategies to promote the adoption of DTs for the design and construction of water project management.

Thereby, the study contributes to the emerging body of knowledge on Digital Twin adoption in infrastructure management by providing an empirical description of barriers within a technologically advanced context. Future research may build on these findings through confirmatory studies that examine causal relationships, assess implementation outcomes, or comparative studies of DTs adoption dynamics across different geographical settings.

These barriers should be communicated to city planners, decision-makers within AEC firms, and governmental bodies. These parties should be informed about the advantages digitalization has brought and the barriers that they may face in adopting new technologies. The findings fill knowledge gaps in the literature by enhancing understanding of the empirical barriers and informing stakeholders on strategies to improve the adoption of digital technologies. They provide clear insights that guide water stakeholders and policymakers on the barriers to digital transformation (DTs), helping them plan accordingly. The proposed strategies to improve adoption are expected to directly influence work efficiency, workforce capacity, digital skills, cybersecurity concerns, and, collectively, water project management in the planning and design. Addressing water project management issues through digitalization is expected to enhance efficiency, improve work quality and environmental conditions, and reduce redundancy and losses at the project level in the UAE, a water-stressed region.

The second research contributes to the body of knowledge by uncovering the empirical drivers of DTs' adoption and discussing the project's success in water project implementation. The research analyzed the perceptions of experienced stakeholders through real projects and qualitatively triangulated them with real-world global utility cases. A comparative analysis focused on key drivers and project success, aiming to triangulate, enrich understanding, and enhance the credibility of the findings. The results reveal the empirical drivers and evaluate the perception on project success from early adopters' perspectives. Additionally, they underscore the need to establish regulations and design mandates that track performance and ensure compliance with regulatory requirements. It also highlights the importance of connecting the outcomes to sustainability and asset management purposes, and of communicating these efforts to stakeholders to raise awareness and knowledge.

Although it is an exploratory study, it provides insightful findings that are transferable to many other contexts. This work can serve as reference points for other case studies and comparable contexts in the Middle East that aim to digitalize urban water systems, drawing on lessons learnt. The study advances the body of knowledge by identifying, for the first time, the key drivers of DT technologies adoption in the Middle East. It fills knowledge gaps and improves understanding of the factors that influence DT adoption in water project management. Additionally, it discusses project success dimensions lacking in water projects, examines stakeholders' agreement, and recommends a regulatory framework and compliance mandates that are essential for the UAE context.

The case study findings triangulate the quantitative results, complement the low representation of utilities, and support and expand on the survey findings. The results are highly relevant for government agencies, water authority officials, and industry practitioners in the UAE. They help focus on the significant drivers when initiating or promoting a digitalization journey for urban water systems. Moreover, they are valuable to the water industry and stakeholders in developing countries in the Middle East, demonstrating how the adoption of advanced technology can help address and potentially lead efforts to overcome water scarcity and security issues through successful projects. The findings may apply to other countries in similar contexts and with comparable economic capacities; however, generalization should be approached cautiously given the regional focus, varying levels of digital maturity, and contextual settings.

The third research is a user study that addresses citizen engagement in planning a digital water initiative, making significant contributions to both theory and practice. Theoretically, it introduces and validates a new extension to the TAM model theory that assesses users' intentions to accept digital tools. By including a set of relevant factors that extend the traditional TAM and validating them, a valid predictive tool is provided to test perceptions. The set of factors includes, for the first time, water security concerns as an environmental factor that aligns well with the UAE water strategy 2036 aims, namely the urgent need to incorporate environmental responsibility into social networks and behaviors. Additionally, it broadens the application of the socio-technical approach in water research, which is currently underutilized, particularly in developing countries and the Middle East. Furthermore, it

contributes to the body of scientific research promoting the adoption of digital technologies for water management through citizen engagement.

Practically, the study identifies influential factors that may affect public users' adoption of the water digital tool introduced by DEWA in Dubai. The results inform multi-disciplinary water stakeholders in the UAE on raising awareness of water security issues, updating curricula, designing digital policies, implementing incentive programs, and conducting community outreach campaigns. They are also constructive for technology providers and software developers regarding which obstacles hinder acceptance and which promote it. As a result, they may guide them in incorporating intuitive features and eliminating frustrating aspects that can lead to user dissatisfaction. Thereby, increase acceptance and facilitate easier use based on operational readiness, informing the necessary user profile and the facilitating conditions. The study implications offer a valid predictive framework for planning digital water tools, extend TAM to governance sustainability settings, and pave the way for further experimental studies on adoption and post-implementation.

## CHAPTER 2

### LITERATURE REVIEW AND BACKGROUND

#### 2.1 Digital Twin Technology

##### 2.1.1 Digital Twin Technology History and Definitions

Since its inception in 2002 at the University of Michigan during a presentation on manufacturing, the digital twin concept has focused on the feasibility of creating a digital informational counterpart of a physical system, serving as a linked, end-to-end life-cycle twin (Grieves & Vickers, 2017). The technology was first proposed by manufacturing as an accurate virtual representation of physical systems, effectively mirroring existing assets (Tao et al., 2017). Industry and academia have defined the concept differently across various disciplines; however, they maintain the core idea of digitally mirroring physical systems.

In 2012, NASA presented the most widely adopted definition of the technology as: “DT is an integrated multi-physics, scale, probabilistic simulation of a system that uses the best available physical models, sensing technologies updates, and history, to replicate the life of its flying twin.” (Glaessgen & Stargel, 2012). In business management, Deloitte (2017) report defines DT as “DT is a near-real-time digital image of a physical process that helps optimize performance.” One of the most developed areas where DT technology has made significant advances is manufacturing, where Tao et al. (2017) defined DT as “the computerized virtual replica of a physical system.

In the built environment digitalization, Building Information Modeling (BIM) has captured the most attention since its emergence; however, BIM alone is insufficient for asset management, especially during the operational and maintenance (O&M) phase. Therefore, it is both essential and timely to incorporate the concept of Digital Twin (DT) into urban management. ATKINS (2017) report defined the technology as “a computer model, mirroring and simulating assets or systems of assets and their environment.” The report described DTs for the built environment as extending beyond 3D representation: they are rich data sources that enhance the planning of new assets, the understanding of existing ones, and the verification of as-built conditions, while

supporting ‘what if’ predictions and providing a digital version for future work. In the context of infrastructure, Naderi & Shojaei (2023) reviewed and synthesized a definition for infrastructure digital twin (IDT) as “a virtual replica of a physical asset connected by two-directional data flow, making it part of a system-of-systems.” For urban water systems (UWS), Pedersen et al. (2021) defined DT technology as “a systematic virtual replication of the dynamics of the physical system, with a set of features connected by data links while ruled by open data standards.” Principal features of DT in water systems may include data links, coupling, identifiers, security, and storage, as well as the user interface, simulation models, analysis, artificial intelligence, and computation. From their perspective, the UWS DT can be implemented at multiple scales, both technical and societal. All definitions highlight the importance of digitally representing and accurately mirroring the asset, component, process, system, or system of systems over the whole lifecycle state.

### **2.1.2 Digital Twin Technology Components**

Grievess (2014) early defined the Digital Twin as comprising three entities: a physical product, a virtual representation, and data links and connections (VanDerHorn & Mahadevan, 2021; Grievess, 2014). Wu et al. (2020) insisted that DTs are not static data models; instead, they are dynamic process models that evolve as data is generated. This means the concept encompasses multiple dimensions and can integrate various technologies. Jones et al. (2020) provided a more detailed characterization system of the digital twin concept and its components in their review of the manufacturing industry. They defined 13 components: the (physical entity/twin; virtual entity/twin; physical environment; virtual environment; state; realization; metrology; twinning; twinning rate; physical-to-virtual connection/twinning; virtual-to-physical connection/twinning; physical processes; and virtual processes). Additionally, the study identified 11 use cases based on the revised corpus; the most prominent use cases were simulation modeling and optimization, data management, and data-driven design. Tao et al. (2017) argued that the “DT models are composed of five elements: physical, virtual, connections, data, and their resulting applications.”

In the infrastructure context, Naderi & Shojaei (2023) reviewed the main technological components used to build digital twins for infrastructure (IDT) and grouped them into four functional technology groups: (1) data acquisition, (2) information model, (3) data processing, and (4) interoperability technologies, as shown in Figure 2.1. This reference model illustrates how to integrate these different technologies to create a digital twin (DT) for civil infrastructures. The data acquisition connects physical and virtual entities by capturing and transmitting data. Information model technologies represent the collected information on physical entities, and data processing technologies that fuse multi-sourced data to extract knowledge and enable well-informed decisions. Finally, through interoperability techniques, these technologies are harmonized to ensure data flow between technological components and physical entities. Based on this categorization, maintaining a digital twin requires integrating multiple technologies to mirror the physical entity in its operational state and view its output.

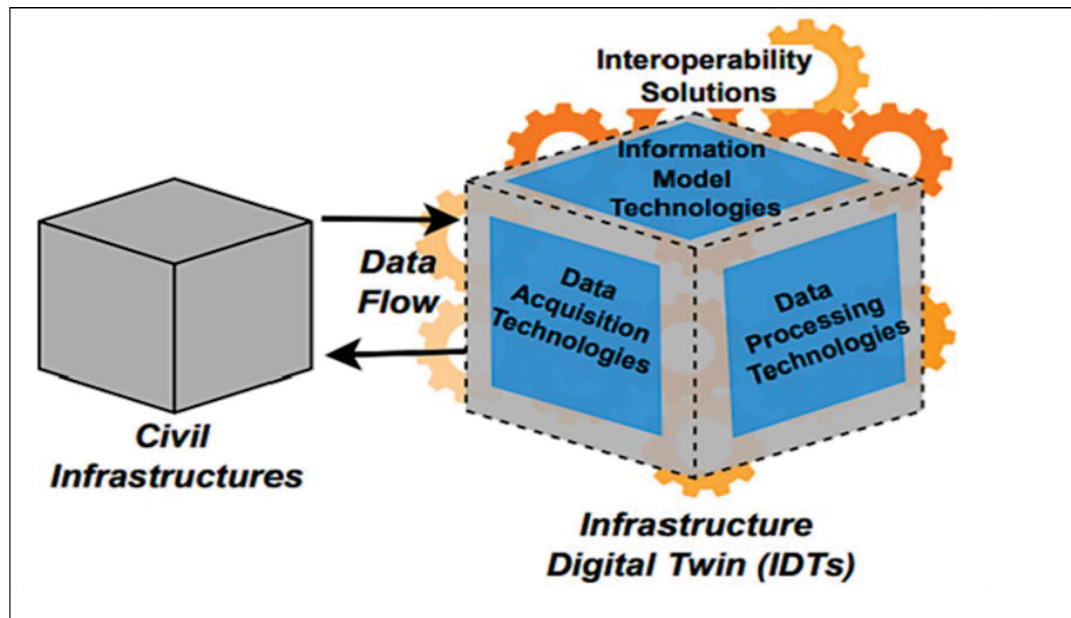


Figure 2.1 Conceptual Model of Digital Twin Components in Infrastructure, taken from Naderi & Shojaei (2023, p.5)

Regarding the technologies commonly used to develop digital twins in infrastructure, the most dominant technologies are building information modeling (BIM), geographical information systems (GIS), simulation models (SM), supervisory control and data acquisition (SCADA),

asset management information (AMI), automated meter readings (AMR), and computerized maintenance management systems (CMMS) according to Naderi & Shojaei (2023), and Conejos Fuertes et al. (2020). Li et al. (2022) argued that each digital twin has specific requirements depending on the use case it supports. However, a successful paradigm necessitates the existence of three principal components: (1) a high data connection and communication, which can be maintained through high-performance sensors (2) the modeling technology that accurately represents the asset, and can perform optimization and prediction analysis for decision-making support, and (3) an easy to use and more intuitive human-asset interface that provides visualization and enables interaction for end users who are expected to have no knowledge of the DT technology. This aligns with Grieves' (2014) early definition and emphasizes the exact requirement for building a successful digital twin.

However, Pedersen et al. (2021) distinguished two digital twin DT developments for water systems based on the coupling potentials of the physical system, the living DTs, and the prototype DTs. According to their results, if the model is attempting to replicate a real physical system and evolves over time, it is considered a living DT. In this case, the simulation model is exploited for operational or control purposes. Nevertheless, creating digital twins for prototyping does not require replicating a physical system; simulating the system's behavior with a simulation model is sufficient for design and planning purposes. Accordingly, the simulation model serves as the central functioning component of digital twins in urban water systems. This coupling approach aligns with Kritzinger et al. (2018), who categorize DT models by the degree to which data connects physical and digital entities into digital models, digital shadows, and digital twins. While digital models do not necessitate the automatic exchange of data, digital shadow allows only one-way data flow. In contrast, a digital twin enables two-way data flow between the two counterparts. However, Lu et al. (2020) emphasized that DT can be achieved with minimal one-way data transfer; they argued that unidirectional data transmission is sufficient for real-time monitoring of the physical system.

### **2.1.3 Digital Twin Technologies: Architecture and Tools**

Since its inception in 2002, digital twins have focused on the viability of creating a digital information construct that represents a physical system, serving as its entire life-cycle-linked

twin (Grieves & Vickers, 2017). Since then, the concept has penetrated many domains, reflecting on its projected improvements and demonstrated success. In urban water systems (UWS), the technology definition by Pedersen et al. (2021) insisted that, among the set of features DT includes in water systems, a user interface is crucial. Li et al. (2022) argued that the successful DT paradigm necessitates three principal components: the third is an easy-to-use, more intuitive human-asset interface that provides visualization and enables interaction for end users. Even though the first two principal components are technical, the third is related to the human-machine interaction HMI aspects and aimed at the system usage by its potential users. According to Curl et al. (2019), DTs are presented as a complete and comprehensive system, rather than as an automatic data-flow connection, where an intuitive graphical interface for user interaction is essential.

Early adopters have produced many successful case studies documented in industry reports. For instance, in Grand Rapids, Michigan, US, the city leveraged data from a network of 90 flow-meter sensors and 10 rain gauges to collect actual data on its sanitary pipes. Xylem, a technology provider, equipped the city with DT technology that collects, organizes, analyzes, and displays data via dashboards (HMI), as shown in Figure 2.2. Through the dashboard interface, operators can visualize, understand, and regulate the sewer system's operation more safely and quickly (Xylem, 2023). Additionally, for the Durliegh Water Treatment Center in Wessex, UK, building a digital twin for three assets in the facility enables their 3D models to be tagged with historical and real-time data, accessible from multiple devices simultaneously, offering advanced search functionality and facilitating information sharing among stakeholders (digitalAECOM, 2025).

Thus, new technologies can offer significant benefits that were not achievable with traditional management practices and strategies. The importance of having essential data available at the right time for all relevant stakeholders, visualized within a secure, accessible shared environment, cannot be overstated. Besides, the intuitive interface features that convey output results and communicate them to users are invaluable.

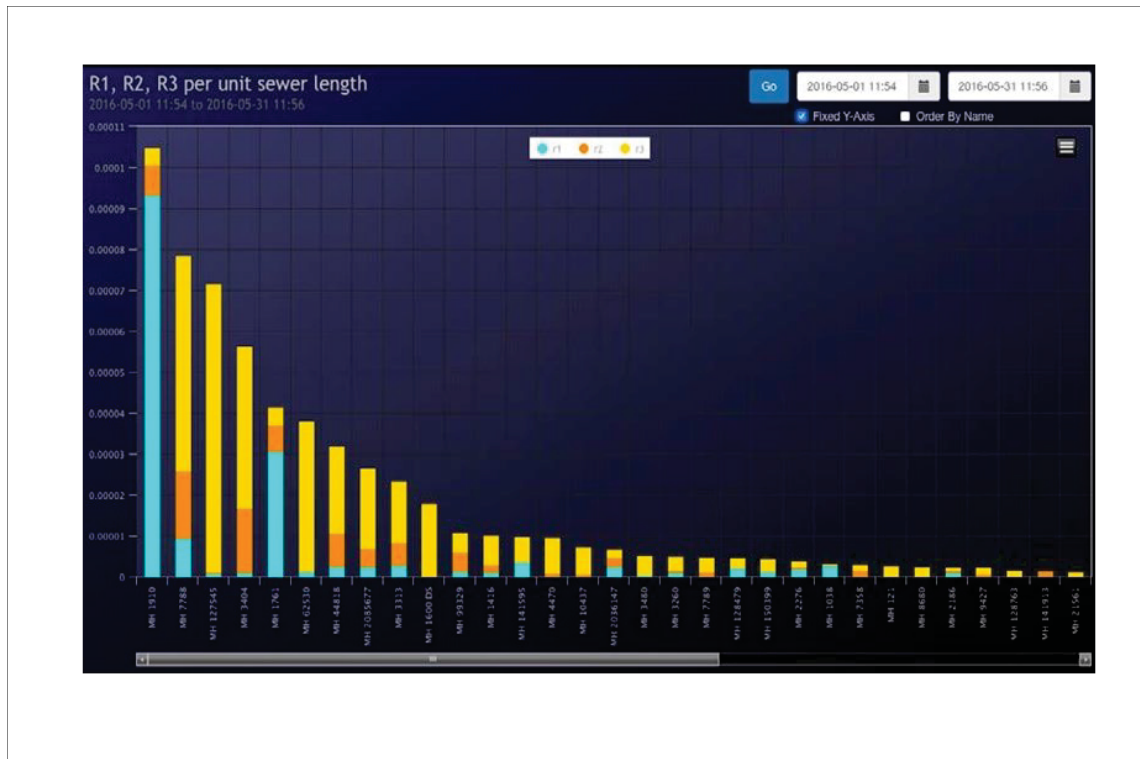


Figure 2.2 The Xylem Dashboard Platform in Grand Rapids Michigan, taken from (Xylem, 2023, p. 2)

## 2.2 Digital Twin Technologies Adoption

### 2.2.1 Digitalization Adoption Factors for Different Domains

Digitalization is a socio-technical process that focuses on transforming and adapting organizational processes into digital versions (Daniel et al., 2023). The adoption of digital twins (DTs) in the built environment, including urban water systems, has gained increasing recognition, as evidenced by a dramatic increase in publications reported by Opoku et al. (2023) in the construction field. However, the adoption process faces numerous barriers, leading to slow penetration even in developed countries. Slow adoption has been reported by Naderi & Shojaei (2023) in the UK, Bartos & Kerkez (2020) in the U.S, and Beal & Flynn (2015) in Australia and New Zealand.

According to Butler & Sellbom (2002), technology adoption rates are influenced by various factors, including innovation characteristics and economic, organizational, sociological, and

psychological variables. Understanding the adoption rate requires analyzing both factors that facilitate adoption and those that may act as barriers. The Cambridge Dictionary (2025) defines a barrier as “something that prevents something else from happening or makes it more difficult.” Conversely, a driver is “something that makes other things progress, develop, or grow stronger.” Therefore, barriers either prevent adoption or make it more difficult, while drivers promote its initiation and support its progress and development. Although these terms are often discussed together, they typically have opposing roles. Researchers have identified numerous barriers and drivers to the adoption of digital technologies like DTs; however, significant efforts are needed to classify, evaluate, assess, validate, and prioritize them across domains and applications.

Opoku et al. (2023) reviewed DT applications and identified 30 barriers to DT adoption in the construction industry. To clarify and simplify, they classified barriers into four main classes: stakeholder-oriented, construction-enterprise-related, industry-related, and technology-related. However, the study identified the top five barriers as low knowledge levels, low technology acceptance, a lack of tangible DT value, static building data, and project complexities. They insisted that a few identified barriers are practical ones, and the majority are anticipated based on researchers' expectations. Additionally, the study recommended further empirical investigation to validate the identified barriers using case studies, since most barriers are expected rather than experienced.

Broo & Schooling (2021) reviewed the adoption state of DT technology in the infrastructure industry. They highlighted three categories of barriers: digital transformation, cultural transformation, and bridging skill gaps. Cultural barriers include human factors such as the difficulty of change, cultural acceptance and transformation to a digital environment, a poor understanding of benefits and business cases, and a lack of skilled workers. Additionally, the skill gaps are magnified by an aging workforce, a limited supply of training and education courses, and the need to hire and retain talented, skilled workers in favorable conditions.

Callcut et al. (2021) reviewed the definitions, concepts, and applications of DTs across various civil infrastructure systems. The study emphasized the nascent stage of DT application and attributed some challenges to this fact. Regarding water infrastructure, respondents agreed that data transparency through open standards and API solutions is critical for DT development.

This can be maintained by providing developers and investors with access to catalyze innovation and build trust between parties. However, they believed that granting secure access to the data, especially by customers, is the major challenge, whereas maintaining up-to-date data on the systems is a minor one. Generally, the main barriers to DT implementation include output uncertainty, cybersecurity, data sharing, and data schema standardization. The results demonstrate a substantial level of awareness of DTs across the UK industry and academia, based on projected market value and the number of recent papers published on the topic. However, there is a lack of understanding of what DTs are, worsened by a plethora of vague definitions. Therefore, the study recommended that digital leaders within organizations, as well as well-recognized industry professionals, should acknowledge the workforce and asset owners for their best practices and insights on implementing innovative technologies, such as DTs. Additionally, organizations should launch programs to improve their digital maturity and workforce digital skills before adopting DT technologies. They should focus on hiring the right people in the correct positions to support the team and streamline the adoption of digital technologies. Additionally, centralized and unified monitoring and evaluation of government-funded projects and initiatives should be maintained to benefit the entire community.

Beal & Flynn (2015) discussed the digitalization of water utilities in Australia and New Zealand through smart metering technologies. They pointed out that some utilities face constraints due to a lack of overall understanding and awareness of how to develop a business case, select technology alternatives, use data, and recognize the benefits of smart metering. Social factors such as customer satisfaction and enhanced engagement, community acceptance, and trust serve as major 'social' drivers. Meanwhile, key economic drivers for successful rollouts include reducing operating costs, lowering wholesale water purchases, delaying infrastructure upgrades, enhancing meter reading accuracy, and minimizing non-revenue water. The study identified challenges in the planning phase, including difficulties establishing profitable business models, a lack of case studies demonstrating successful results, incremental implementation costs, and limited knowledge and expertise in suitable technologies. During the implementation phase, significant challenges include uncertainty about the type and timing of deployment, the appropriate technology to deploy, and compatibility among meter communication systems; the risk of technology redundancy; and the industry's limited

knowledge and experience in designing and executing rollout projects. The study also highlighted the importance of considering specific utility conditions, such as the location of value within the business case for digital transformation, describing this as a specific-utility approach.

Danielsen (2021) investigated digitalization in public organizations across various domains in Norway. The results revealed that the turbulent environment, handling of laws and regulations, existing system improvement, effectiveness improvement, resource and complexity reduction, and cost reduction are the important drivers. Outdated laws and regulations, resource and skill shortages, the complexity of existing systems, initiation costs, resistance to change, privacy and security concerns, unrealistic expectations, and time-frame constraints are the major challenges in the Scandinavian context. Tangi et al. (2020) study investigates the digital transformation of public organizations in the Netherlands. The study examined two groups of barriers and drivers to assess their impact on organizational transformation. Results suggested that only external drivers are the primary motivators for organizational transformation; hence, in public administrations, exogenous push could create a compelling environment in which barriers can be overcome. Meanwhile, contrary to expectations, barriers do not significantly affect organizational transformation, and the organization's size has an adverse impact. The study discussed external drivers, including anticipated benefits, pressure, and legal obligations. Opoku et al. (2022) review and establish a set of DT technology drivers for the construction industry. They developed a conceptual framework of 50 identified drivers to facilitate the adoption of DT technologies. A refined version grouped the drivers into four main categories: concept-oriented, production, operational success, and preservation drivers. Findings revealed that concept-oriented drivers are the primary drivers of DT adoption in the construction industry. Concept-oriented drivers include real-time data visualization, streamlining the design process, enhancing decision-making, promoting sustainability, facilitating transformation, improving design delivery, optimizing material selection, enabling smart services, ensuring effective planning, providing technical solutions, supporting social impact, and creating value. The study highlighted the low contributions of developing countries to DT technology adoption research. In contrast, developed countries like the UK, the US, and Australia are leading the global digital transformation effort toward DT adoption in construction research.

Boyle et al. (2022) reviewed digital transformation in water organizations. They found that emerging technologies, new social behavior trends, high expectations for digital progress, updated regulations, and a focus on efficiency and customer service are the main drivers. Additionally, overcoming barriers requires a corporate-wide effort to establish digital governance, skills, knowledge, and culture, along with central, unified data management. The study also highlighted the unique nature of water organizations as monopolies, focused on providing essential services rather than profit. Understanding the system's complexity, management dynamics, interdependencies, and current digital maturity is vital for successful transformation. The study concluded that digital transformation in water organizations depends on long-term strategic planning and strong commitment.

Waqar et al. (2023) investigated the drivers of DT technology adoption in the context of the smart city concept in Malaysia. Results revealed 13 highly significant barriers, grouped into four key constructs: personalization, standardization, knowledge, and operations. The most critical barriers were related to personalization, including handling uncertainty, a lack of visionary leadership, trust expectations, and privacy and security concerns. However, all other constructs are also significant for implementing DTs for smart city development. Arowoia et al. (2024) investigated the driving forces of DT adoption in construction projects in Nigeria. The most influential drivers for DT implementation are technological advancements and trends, data storage reliability, customer satisfaction, safety, and the availability and accessibility of software. The study highlighted the important role of stakeholders' desire for innovation and advancement, which can be promoted when technology meets the stakeholders' expectations.

### **2.2.2 Focal Points for Digital Twins Understanding and Adoption Success**

Many industry reports and academic articles have recently been published on the business value and projected benefits of embracing DT technology, aiming to facilitate and accelerate its adoption across sectors. In the health, manufacturing, education, cities, transportation, infrastructure, construction, and energy fields (Rasheed et al., 2019; Broo & Schooling, 2023; Callcut et al., 2021; Ammar et al., 2022). However, ongoing debates and disagreements over

the technology's features, elements, levels of sophistication, outcomes, and benefits are growing among domain practitioners (Alva et al., 2022; Ford & Wolf, 2020; ATKINS, 2017). The slow adoption and evolution of DTs are attributed to several barriers, including limited demonstration and understanding due to the technology's early stage of adoption, as well as the limited number of case studies (Bartos & Kerkez, 2020; Beal & Flynn, 2015). Additionally, the reluctant decision-makers and the lack of knowledge among the domain practitioners about the technology features, barriers, validated benefits, and key drivers to initiate adoption (Opoku et al., 2023; Ford & Wolf, 2020; Broo & Schooling, 2021; Alva et al., 2022), hinder the technology's adoption and delay its practical application. Therefore, at this stage of technological evolution, it is crucial to discuss key considerations and facts, building on early adoption efforts and prior studies. These findings from various domains, including understanding technology's features, maturity levels, capabilities, and application scales, are important in understanding the technology's potential in general. A holistic understanding and a well-selected approach are crucial for the successful adoption of technology across all domains.

DTs are data resources rather than merely 3D models that can enhance the design of new assets, support understanding of the existing, verify as-builts, run 'what if' scenarios, and deliver future digital visions (ATKINS, 2017). The report recognized the technology's potential to reduce errors and to integrate the discontinuities and fragmentation present in most traditional information management methods in the built environment. The report emphasized that creating and managing digital twins across the entire asset lifecycle is a journey, and the stage of technology adoption affects the benefits realized. Digital twins can be initiated, built, and developed at any stage; however, it is recommended to develop them early to capture sufficient data for effective long-term asset management.

Furthermore, DTs can be developed into multiple maturity-level models, in which configurations, components, capabilities, complexity, and value vary accordingly (ATKINS, 2017). The report defined a multi-level maturity scale in which the technology can be developed and linked those levels to the benefits realized. Six levels of maturity development were described in terms of elements, as shown in Figure 2.3. As the twin develops from element zero to element five, its complexity, connectivity, and value increase. The six elements

vary in capabilities and benefits, ranging from capturing real data models (as-built surveys) to fully automated operation and maintenance, where complete self-governance and control are expected by the twin. Therefore, value creation and benefits realization will be directly tied to the twin levels of maturity. Clarifying the required maturity level is expected to make the path to technology development and understanding of value clearer and easier, thereby improving adoption and expanding applications.

Maturity element (logarithmic scale of complexity and connectedness)	Defining principle	Outline usage
0	- Reality capture (e.g. point cloud, drones, photogrammetry, or drawings/sketches)	- Brownfield (existing) as-built survey
1	- 2D map/system or 3D model (e.g. object-based, with no metadata or BIM)	- Design/asset optimisation and coordination
2	- Connect model to persistent (static) data, metadata and BIM Stage 2 (e.g. documents, drawings, asset management systems)	- 4D/5D simulation - Design/asset management - BIM Stage 2
3	- Enrich with real-time data (e.g. from IoT, sensors)	- Operational efficiency
4	- Two-way data integration and interaction	- Remote and immersive operations - Control the physical from the digital
5	- Autonomous operations and maintenance	- Complete self-governance with total oversight and transparency

Figure 2.3 The Digital Twin Maturity Levels, taken from ATKINS (2017, p.11)

Different approaches have evolved for developing and applying DTs based on specific objectives (Broo & Schooling, 2023). VanDerHorn & Mahadevan (2021) emphasized that the design and implementation of the new technology should be guided by its intended outcomes. This approach helps define the necessary data, models, and processes. Clearly stating the goals and expected benefits at each stage ensures value grows throughout the project. Failing to understand the required technological resources can lead to poor decisions and an early rejection of the DT.

DT is not a one-size-fits-all solution that everyone can develop easily (Agrawal, Fischer, & Singh, 2022); nor is it a 'one-size-fits-all' technology, as Beal & Flynn (2015) discussed. Since the technology offers a wide range of configurations and capabilities (Naderi & Shojaei, 2023),

it should be evaluated on a case-by-case basis, considering each use case that operationalizes it and the benefits realized. The expected value would vary widely depending on the DT configurations chosen during the early selection process.

Hence, the selection process that precedes the decision of adoption (DOA) is crucial for successful implementation (Glaessgen & Stargel, 2012; Agrawal et al., 2022). In this regard, Agrawal et al. (2022) developed a digitalization selection framework to accelerate and facilitate the adoption of DT technology in the AEC industry. The framework helps practitioners choose the appropriate level of sophistication by weighing the pros and cons at each level, defining evaluation criteria, and assessing the implications of organizational strategies and value creation to avoid inflated benefits expectations and missed opportunities. The framework serves as a roadmap that begins by assessing the data, models, and algorithms needed, as well as the performance that can be achieved.

In addition to evaluating the current organizational environment, properly selecting stakeholders and supporters is also critical. The process should involve various stakeholders who are highly coordinated in early decision-making. A wide range of stakeholders and domain practitioners can be engaged at this stage; all must participate in determining the appropriate level of sophistication for the successful deployment of DT. They should be aware of the elements and requirements for DT developments, as well as the existing organizational practices that enable the adoption of the most appropriate technology (Agrawal et al., 2022). Ford & Wolf (2020) discussed the term “fatigue risk” in the context of DT technology development for smart city disaster management (SCDT). The term was defined as “the challenge that faces technology developers, when the supporters get tired of waiting to capture benefits and withdraw their support, preventing the complete development. Fatigue risk is identified as a threat to the development of digital twins for community-level disaster management. The study emphasized the importance of financial sponsors as the most significant community supporters; however, it also highlighted the role of officials who facilitate development, as well as the organizations and their employees who will operate the systems, and the public who are promised to reap the considerable benefits. This wide range of stakeholders is crucial for technology development at the community level, following the DOA, and vital for mitigating the effects of early rejection. Successfully managing fatigue risk

is crucial for technologies to cross the bridge from initial research to successful development in applications that deliver tangible benefits and create business value.

Furthermore, DT is a multi-scale deployment technology with high potential for advancement across various levels and scales. The technology can be applied at the city scale for urban management and planning, as reviewed by Lu et al. (2020), Schrotter & Hürzeler (2020), and Ferré-Bigorra et al. (2022), and at the district scale, as documented by Alva et al. (2022). It can also be developed on a network scale, as reviewed by Martinez et al. (2021), and on a component scale, as reviewed by Yang et al. (2022). Accordingly, the benefits realized and challenges encountered are directly dependent on the scale developed. This was emphasized by the findings of Beal & Flynn (2015), who investigated the digitalization approach of multi-scale water organizations and stated: “This highlights that the benefits and limitations are very project-utility-specific.”

Therefore, the use cases and scale of application are crucial factors in developing DTs. The reliance of DTs on their use cases and application scale leads to an extensive DT catalog, which causes confusion during development and hampers the realization of benefits, as noted by Alva et al. (2022). This contributes to the ambiguity and misunderstanding surrounding this emerging technology, including its features, components, levels of sophistication, and outcomes (Ford & Wolf, 2020; ATKINS, 2017; Alva et al., 2022). This is reflected in slow adoption rates and reluctance among stakeholders, despite documented benefits and reported improvements with technology adoption and implementation (Naderi & Shojaei, 2023; Bartos & Kerkez, 2020).

Current research on the technical implementation of DTs primarily focuses on leveraging existing technologies to build cost-effective DT solutions (Jones et al., 2020). Existing technologies like the Internet of Things (IoT), the Industrial Internet of Things IIoT, 5G, Radio-Frequency Identification (RFID), and wireless sensors are effectively used for physical-to-virtual and virtual-to-physical connections in DTs. Advances in connection technologies have enabled the development of inexpensive sensing devices that facilitate the acquisition of accurate, real-time data at low cost, thereby reducing initial investment costs (Pedersen et al., 2021; Barots & Kerkez, 2021). Additionally, BIM and GIS are two principal information technologies considered enablers of building DTs for built environments and infrastructure.

BIM plays a vital role as the central platform at the core of DT development; it represents one of the key existing modeling information technologies. In particular, as-is BIM and GIS models will serve as the central platforms, integrating with other databases and systems to accurately represent the updated models. However, it should be noted that DTs are broader than BIM and GIS models in terms of information richness and analytical capabilities; they are evolving to not only model physical systems, but also connect them by transmitting data at least in one direction to monitor the system in real-time and support analytics, simulation, and control functions (Lu et al., 2020). Thus, even though leveraging existing technologies' approaches can magnify benefits by reducing initial costs based on technology availability, concerns are raised about whether these technologies are standardized and calibrated for DT optimization (Jones et al., 2020). If so, tangible benefits will be realized through the process of improvement and cost reduction.

However, even though complex DT architectures can support advanced applications and offer multiple benefits, advanced twinning requires complex interoperability tools and is associated with higher costs. Therefore, conducting a thorough cost-benefit analysis is crucial for developing reliable models that leverage existing technology. Even a minimal discrepancy between the projected and actual project costs will pose a challenge for development (Beal & Flynn, 2015). Therefore, it is crucial to understand how far existing technologies can be improved and what advanced use cases this approach can operationalize. Similarly, Kober et al. (2023) discussed the importance of understanding DTs' fidelity levels for the realization of benefits. The authors asserted that model fidelity is an important variable and should be considered early in the design and development stages of DTs. The study referred to the DT's fidelity as the number of parameters, their accuracy, and the level of abstraction. The work aimed to improve understanding of the benefits of DTs and prevent false expectations that could lead to acceptance issues and early rejection.

To summarize, early adopters have demonstrated clearly that developing a DT is a process that requires an open mindset, characterized by curiosity and determination to learn and improve through iterations (Pedersen et al., 2021; Broo & Schooling, 2023), as well as significant time and patience (Ford & Wolf, 2020). Digitalization is more embedded in social aspects and driven by individuals, as argued by Hämäläinen (2020). This rise in the value of

stakeholders' engagement is an essential component of project management knowledge (Davis, 2017). Increasing awareness of the technology's features, application scales, maturity levels, and potential will help drive adoption and implementation. Benefits realization is a multidimensional process that is highly correlated with the selected DT capability, maturity level, embracement stage, targeted outcomes, applied use cases, and the scale of application (VanDerHorn & Mahadevan, 2021; Beal & Flynn, 2015). Inflated benefits resulting from a misunderstanding of the technology's capabilities and elements, as well as underestimated benefits due to a lack of demonstration and validation, can equally delay adoption and lead to early rejection. Early rejection, in turn, prevents a holistic understanding of the technology's outcomes and hinders its uptake.

Many perceived benefits are highlighted in the literature and industry; however, efforts to validate and quantify these benefits are lacking. Few papers document tangible improvements over current systems (Jones et al., 2020). Understanding the desired outcomes and identifying the proper stakeholders for the early selection stage of technology capabilities and maturity levels are crucial dimensions before making the decision to adopt DOA. Additionally, current organizational and technical readiness, as well as financial and public support, are essential for the successful adoption of technology. Patience and determination from all stakeholders, especially supporters, and the presence of a dedicated team to track and evaluate successful cases can inspire others to adopt the technology.

### **2.2.3 Internet of Things IoT Technologies Models**

Emerging sensing devices of the Internet of Things (IoT) and advances in communication technologies (ICT) are two major revolutions in sensor data collection and analysis (Reda Taha et al., 2021). IoT technologies provide a global network infrastructure that enables physical and virtual devices (Things) to communicate and integrate using established standards and protocols, linking them to digital platforms (Ablyazov, 2021). Inspired by the industrial Internet of Things (IIoT), which is used for component monitoring and machine fault detection in manufacturing (Boyes et al., 2018), sensing technologies in the built environment can help support informed maintenance decisions and detect anomalies by leveraging real-time data on infrastructure conditions (Bartos & Kerkez, 2020).

Sensing devices can collect, measure, and communicate data in real time, and analyze and assess asset status (Economides, 2016). ATKINS' (2017) report distinguishes multiple maturity levels of digital twin development and directly links them to their intended outcomes. Six levels of maturity development were described as the twin evolves from element zero to element five, its complexity, connectivity, and value increase. The six levels vary in capabilities and benefits, from capturing real data models (as-built surveys) to the ultimate automated operation and maintenance with complete self-governance and control. The report described level three maturity and capabilities as enabled by sensing-connected technologies, such as the Internet of Things (IoT), with data captured and viewed in a one-directional flow to support operational efficiency. This data can be analyzed to communicate and predict the behavior of built assets, facilitate informed decision-making, and update existing systems with the resulting insights. It is emphasized that to develop this level of digital twin, sensors and connected devices are required to collect data, thereby enabling operational efficiency. The report highlighted that this level is considered the starting point for developing true digital twins in the built environment.

The benefits of sensing technologies are expanding beyond understanding current-state behavior to enable a life-cycle thinking paradigm for infrastructure stakeholders (Reda Taha et al., 2021). Water systems are not an exception; IoT technologies have been applied in the water domain to enable smart water metering and real-time monitoring (Lorenz et al., 2020). In addition, for flood prediction systems in vulnerable cities based on real-time water level measurements (Perumal et al., 2015), and for reporting real-time sewer condition data for operational management in the sewer system (Edmondson et al., 2018). Accordingly, IoT technologies can enable smart water management, in which the water cycle, from sourcing to recovery, can be efficiently monitored and managed in real-time conditions (Shahra et al., 2019).

### 2.3 Urban Water Systems Context

Urban infrastructure systems provide the foundation for movement, supply utilities and services, and protect cities against hazards and disasters. These structures support community business growth and promote a safe and convenient quality of life (CIRC, 2019). Cheng et al. (2016) divided urban infrastructure facilities into five categories: transportation infrastructure, energy infrastructure, utility infrastructure, recreational facilities, and environmental infrastructure (Vilutienė et al., 2020; Bradley et al., 2016). Utility infrastructure encompasses the networks and pipelines that deliver or manage essential utilities, including electricity, natural gas, water, and sewage. According to Cheng et al. (2016), water utility (WU) infrastructure can be categorized into two central urban utility systems: water supply and water drainage. Water supply systems deliver water to urban areas, while water drainage systems carry water away from its source. Within the water drainage system, sewage systems transport wastewater to treatment facilities, and stormwater systems carry runoff away from urban areas to prevent flooding. These two types of systems are combined sewer systems (CSS) and separate sewer systems (SSS).

Urban water systems are a principal component of cities' infrastructure, deliver safe drinking water, and collect, treat, and discharge wastewater and stormwater to prevent pollution and protect public health (CIRC, 2019). However, they are poorly managed and at risk of facing various challenges (Marzouk & Othman, 2020; Joshi et al., 2016). Civil infrastructure is a vital sector of the economy; civil infrastructure projects are characterized by massive capital investments, complex interdependencies, large spatial extent, and the involvement of diverse stakeholders from multiple sectors (Cheng et al., 2016). However, management practices are criticized for being poor and fragmented, leading to reported catastrophic consequences and losses to the public, the environment, and the economy (Wang & Yin, 2022; Dao et al., 2021). This poor management stems from the lack of data on urban systems localization, characteristics, and actual conditions, and is magnified by poor data sharing and inadequate stakeholders' coordination (Tanoli et al., 2019; Marzouk & Othman, 2020; Wang & Yin, 2022; Huang et al., 2022; Dao et al., 2021; Esekhaigbe et al., 2020).

In urban water management, floods and Combined Sewer Overflow (CSO) are two major challenges associated with urban drainage systems. Floods are generated when stormwater runoff accumulates and exceeds the capacity of the drainage system (Zhi et al., 2019; UNDRR, 2019). Floods are one of the most costly and destructive natural hazards facing urban drainage management. The phenomenon has resulted in more than US\$1.28 trillion in losses for the global economy over the last 30 years (UNDRR, 2019). On the other hand, during heavy storm events, the combined streams of stormwater and wastewater are transported through the same pipe in the combined Sewer System (CSS). This can lead to system overloading, resulting in the discharge of polluted streamflow into nearby natural waterways, a phenomenon known as CSO (García et al., 2015).

Simulation models are valuable tools that hydrologists rely on to aid in forecasting and resolving stormwater-related problems, primarily floods. Those valuable tools enable the analysis and prediction of the relationship between rainfall and runoff by handling the complex hydrologic and hydraulic processes. In addition, by simulating dynamic runoff routing and transporting through waterways, storm sewers, channels, and pumps within the catchment (Maheepala et al., 2001). In the field of water modeling, various software products have been developed, including the EPA's SWMM (Storm Water Management Model) and the Watershed Modeling System (WMS) from Aquaveo. Additionally, Autodesk offers a range of BIM tools, including InfoWorks, Civil 3D, and Storm and Sanitary Analysis (SSA). Most of these models are executed in batch mode and are widely used and calibrated by professionals in the drainage field. Users place high confidence in models despite their technical limitations (Pedersen et al., 2022). Model results are used to plan, design, and upgrade water utility systems to address various challenges related to stormwater management or expansion needs (Bartos & Kerkez, 2020; Maheepala et al., 2001). As a result, municipalities and local authorities rely heavily on the models' ability to simulate water system behavior across numerous scenarios when making capital investments in networks for planning, design, and operational management.

To ensure accurate and reliable model results, calibration and validation techniques can be used (Maheepala et al., 2001). Ghaith et al. (2022) emphasized that, to rely on the selected model, it must be well-calibrated. Although vital, the calibration process can be a laborious, costly, and time-consuming task that heavily relies on the quality of the hydrological data

collected. Obtaining accurate hydrological data is challenging because it requires numerous sensing devices and staff to collect the necessary measurements. Additionally, obtaining measurements of water levels and flows across a large spatial area for an extended period can be impractical. As a result, calibration is typically conducted over short timeframes and with limited measuring points. This limitation in calibration techniques and tools stems from resource and workforce constraints, leading to increased model uncertainty (Maheepala et al., 2001). False assumptions about basin behavior also magnify model uncertainty during the simulation process, and the reliance on outdated and intermittent rainfall data records. Understanding the hydrological response of a catchment is challenging due to its complex, nonlinear relationships, as noted by Alperen et al. (2021). These relationships are influenced by the ever-changing behavior of physical systems and hydrologic conditions, as well as unpredictable natural processes, ranging from rainfall to runoff discharge (Bartos & Kerkez, 2020).

Conventional models remain limited and inaccurate in representing the catchment and in overcoming calibration challenges (Alperen et al., 2021; Ghaith et al., 2022). Consequently, models' performance sometimes shows poor representativeness and is subject to uncertainties across all rainfall events and their parameters. This prevents the interventions and investments in stormwater systems from achieving desired outcomes (Pedersen et al., 2022; Pedersen et al., 2021; Bartos & Kerkez, 2020).

On another level, conventional management processes face internal and external challenges in the context of urban infrastructure in all categories (Marzouk & Othman, 2020; CIRC, 2019). Regarding WUI systems, besides the aging and deteriorated infrastructure networks, they face the challenges of the need for expansion due to the urbanization sprawl, and the network's congestion and interdependencies being buried and invisible (Ghaith et al., 2022; Marzouk & Othman, 2020; CIRC, 2019; Lieberman et al., 2017). While systems' interdependencies can improve operational efficiency, they can also increase vulnerability, causing cascading damage. An underground sewer collapse can lead to road damage and ground subsidence, thereby polluting groundwater (Dao et al., 2021). At the same time, drainage issues caused by inefficient stormwater management and inaccurate drainage system design can adversely affect the functionality and integrity of the transportation system, potentially exposing it and the

public to major hazards (Ferrante et al., 2020). What makes things worse is that such cascading damages are disastrous and unpredictable (Lieberman et al., 2017).

All aforementioned challenges are magnified by the lack of data and the fragmentation of efforts, which together constitute the phenomenon of an “Information Isolated Island”. Integrated data across all interdependent systems on a common data platform to support well-informed decision-making is lacking (Alperen et al., 2021; Ghaith et al., 2022; Huang et al., 2022). Moreover, if the data exists, it is barely shared between stakeholders or digitally represented and saved; usually, it is documented by paperwork and gets lost over time, which results in recapturing the same data repeatedly (Tanoli et al., 2019; Esekhaigbe et al., 2020; Wang & Yin, 2022; Wang, 2021). Besides, urban drainage management faces specific challenges posed by climate change and natural disasters. A rise in storms is projected, resulting in more frequent extreme storm events that cause floods (O'Brien et al., 2008).

Condition assessment of water utility infrastructure (WUI) is crucial for effective asset management. The CIRC (2019) raised significant concerns about the condition of existing public infrastructure assets across all categories, declaring them poor and at risk. Most of the inspected assets are aging, deteriorated, and have been neglected for a long time. This means that they will continue to deteriorate if retrofitting actions are not initiated to prevent further severe deterioration and avoid costly damage.

Retrofitting actions are crucial for maintaining an acceptable level of service and preventing failure. The failure to maintain systems' serviceability has catastrophic consequences for the public, the economy, and the environment (Hawari et al., 2018). The French Standardization Association (AFNOR) defines failure of assets as “a deficiency in performance, referred to a required level of performance and result in the termination of the ability of the asset to perform a required functionality (Hawari et al., 2018). Physical (structural) and operational inspections, as well as continuous monitoring of the WUI assets, are vital for condition assessment. However, inspecting the WUI assets is a complex process that requires multi-sourced data and an effective monitoring system. Well-informed condition assessment based on accurate and relevant data will enhance decision-making for maintenance and rehabilitation work, significantly extending asset service life and avoiding substantial spending on premature replacement (Kaddoura et al., 2018). Those massive and buried networks require cyclic and

comprehensive monitoring and assessment (Wang & Yin, 2022; Moradi et al., 2019). However, the current monitoring methods, which rely on manual inspection or data interpretation, have apparent limitations.

Switching to new emerging digital tools can facilitate and improve the condition assessment by automating the inspection process and increasing the quality and consistency of data (Moradi et al., 2019). Capturing and sharing relevant, precise, and updated information on the location and status of infrastructure systems will help operators, managers, and decision-makers plan, optimize, and maintain these national systems more effectively (SWAN's 2022 Annual Recap). Moradi et al. (2019) reviewed recent computer-aided detection techniques and condition assessment in sewer systems. They indicated that a broad spectrum of defects in sewer systems (drainage systems) could be inspected, including structural defects such as cracks and deformation, operational and maintenance defects such as root intrusion, obstacles, deposits, and inflow/infiltration, and construction defects. They indicated that the Closed-Circuit Television (CCTV) method is the most widely used for recording internal conditions in buried drainage pipeline networks. The method incorporates manual revision for the results by human inspection. The manual inspection processes are slow, expensive, and labor-intensive. In human visual inspection, operators review the videos taken by the remotely controlled vehicle in a tedious, impractical, ineffective, and time-consuming process. A well-certified inspector needs to process the data, detect different defect features, and assess their level of severity, which makes the process prone to error and subjective, not forgetting that these huge buried networks are an unsafe, prone to low visibility, and difficulty of the pipe's small size, which results in many limitations in capturing videos and pictures of inner pipes, making them challenging to maintain (Wang & Yin, 2022)

## **2.4 Information Systems and Technology Acceptance**

Digital transformation is progressively altering business models, gaining significant attention, and emerging as a compelling direction in urban development (Ablyazov, 2021). However, the evolution of digitalization is “more embedded in social aspects and driven by individuals” (Hämäläinen, 2020). Recker (2021) describes the information systems IS perspective as

primarily interested in socio-technical systems involving individuals and groups who interact with the digital information and communication technologies (ICT) to accomplish tasks in their private, business, or social contexts. The IS research field centers on the societal impact of the development and use of digital ICTs. A socio-technical approach includes two components: the technological, such as digital infrastructure, systems, platforms, hardware, software, algorithms, and data, and the social (individuals and collectives), such as networks, governments, organizations, communities, groups, and teams. These two components interact as they are developed, used, and evolved in various contexts (Recker, 2021). Stakeholders' perceptions affect the acceptance of new technologies and determine their diffusion. People's initial perception and willingness to use new technology are directly proportional to its perceived benefits and ease of use, making the analysis of acceptance among potential users a vital step in promoting adoption (Najib & Fahma, 2020; Pijpers & van Montfort, 2005; Davis, 1989). In response to the influence of social factors, many studies have applied various social psychology theories to model the adoption of new digital technologies (Hewitt et al., 2019; Keller et al., 2018; Lee et al., 2015). The most common theories include the diffusion of innovation (DOI), the theory of reasoned action (TRA), and the technology acceptance model (TAM). These theories can be used to test, measure, explain, and predict acceptance by examining relationships among behavioral constructs among stakeholders regarding the adoption and use of digital technologies. Applying social psychology theories is a validated approach to exploring the technology adoption process and the factors involved in accepting and ultimately using the new technologies.

Information Systems IS researchers have investigated the technology adoption from the socio-technical perspective, as the divide between the human and technology. Based on their perspective, the adoption of new technology is questioned by society, and its acceptance is influenced by individuals' education, personal habits, and social context (Economides, 2016). Social science theories were effectively deployed by IS research to test, explain, assess, and even predict significant adoption factors. The Technology Acceptance Model (TAM) is one of the IS systems models that posits that intention to use a technology results from two internal beliefs: perceived usefulness and perceived ease of use (Davis, 1989). However, many factors shape users' intention to adopt a technology or to continue using it once it is introduced (Nikou

& Economides, 2017). A few studies have discussed water digitalization as a socio-technical issue from the perspective of public users, aiming to facilitate the utilization of advanced digital tools in the Middle East.

## 2.5 TAM Theoretical background and Application

The Technology Acceptance Model (TAM) is a theoretically grounded social science model developed by Davis (1989) as an extension of the theory of reasoned action (TRA) (Fishbein & Ajzen, 1977) and the theory of planned behavior (TPB) (Ajzen, 1985). TAM is one of the most widely used and validated models for assessing users' acceptance and use of new technology (Saylam & Ozdemir, 2022). The model is widely deployed in IS theory and research (Recker, 2021), which examines users' acceptance of new technology and its actual use. TAM defines the users' behavior intention (BI) to adopt or actually use (Actual Behavior) a technology as a dependent factor. Additionally, it presents two internal beliefs that influence behavioral intention through individuals' attitudes in modeling the acceptance process: perceived usefulness and perceived ease of use. However, the model additionally proposes that external variables directly or indirectly influence the two constructs, ultimately affecting people's intention (Najib & Fahma, 2020). This means that external variables affect the two latent constructs (perceived usefulness, PU, and perceived ease of use, PEOU); in turn, these affect attitude, which ultimately influences behavior intention, BI.

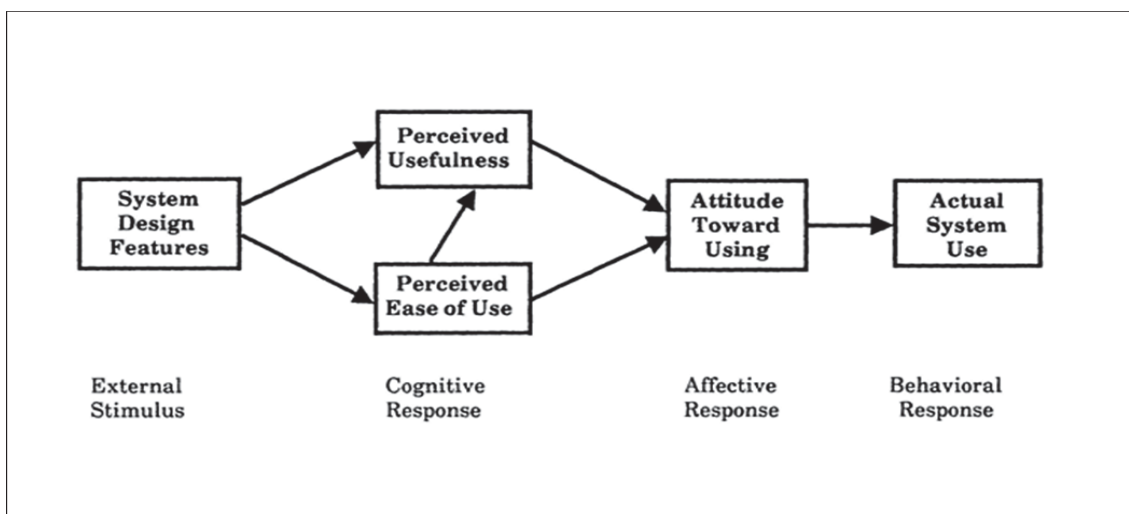


Figure 2.1 Original TAM Model, printed from Davis (1989, p.5)

The model also hypothesized that perceived ease of use PEOU influences perceived usefulness PU directly. The original TAM version is extracted in Figure 2.4.

TAM has been applied widely in many domains and contexts, in military aspects research (Saylam & Ozdemir, 2022), in digital payment acceptance (Najib & Fahma, 2020), in cloud-computing technology adoption (Ferri et al., 2021), for users' acceptance in German agriculture (Mohr & Kühn, 2021), and public users' intention to use smart home technologies in Greece (Pliatsikas & Economides, 2022), and for testing the acceptance of online learning community (Liu et al., 2010). However, TAM applications in the water domain are limited; the model was applied by Minkman et al. (2017) for Dutch citizens reporting on water quality, by Morienyane & Marnewick (2019) for local municipality employees in South Africa, by Taheri et al. (2022) for agricultural professionals in Iran, and by Madias et al. (2023), Madias et al. (2022) for applying smart water meters in households in the American context.

Each of the aforementioned studies examined different factors related to its context and the problem it addressed. Minkman et al. (2017) applied the final version of TAM, to assess citizens' intention to report water quality variables through a mobile application. The findings reveal the most important drivers: usefulness, demonstrability of benefits, and task relevance. Morienyane & Marnewick (2019) extended the TAM final version with factors that are relevant to the municipality employees' daily tasks for water service management. The results revealed that user training, facilitating conditions, and participation in interface design are significant factors that affect users' intentions. In addition to the generic TAM constructs of perceived usefulness, perceived ease of use. Madias et al.(2022) applied factors derived from the Value-Belief-Norm theory as mediators. They tested their effect on the perceived knowledge of water usage when adopting a smart water meter. Results revealed the importance of knowledge on the three aspects (values, beliefs, and norms) in relation to the intentions to use smart water meters. Taheri et al. (2022) applied the TAM extended model among agricultural professionals in Iran regarding Wireless Sensor Network (WSN) adoption. The factors of social influence, knowledge, confidence, and facilitating conditions significantly improved the explanatory power of TAM. Knowledge was the most significant influencing factor for professionals' intention to use WSN in their work. However, both perceived usefulness and perceived ease of use significantly affect adoption intention.

According to Chawla & Kowalska-Pyzalska (2019) and Chen et al. (2017), various public actions and policies can be implemented to facilitate the adoption of smart meters. Agarwal & Prasad (1998) stated that, based on studies in social psychology like that of Liska (1984), environmental and personality characteristics act as moderators in developing behavioral intentions. The relationship between users' perceptions and their decision to adopt new technology can be influenced by certain personality factors, such as personal innovativeness, as well as by demographics (Sun & Zhang, 2006). A study by Venkatesh et al. (2003) identified the role of individuals' characteristics in explaining technology usage, proposing them as moderating factors. These variables include age, gender, and previous experience with smart applications or mobile tools.

TAM, however, is criticized for being broad, not offering deep insights, focusing on the acceptance factors, and ignoring inhibitors (factors that prevent the adoption). Hence, integrating other relevant factors is necessary for context-related comprehension of the adoption of a specific technology (Dou et al., 2017). According to Flavián et al. (2022), the disruptive nature of advanced technologies and their social and economic implications make continuous research essential in this rapidly growing area. Almomani et al. (2022) reported that the literature has an insufficient understanding of IoT adoption behaviors and called for more in-depth research.

### **2.5.1 TAM Application in the UAE**

As discussed in the previous section, TAM is widely used; thus, this section reviews studies that have applied the TAM model in the UAE context.

The TAM generic model, along with its numerous extended versions, has been utilized to explain and understand the adoption of various new technologies in the UAE. (Ahmad & Khalid, 2017) investigated the predictors to adopt mobile government (m-government) services by end-users in the United Arab Emirates (UAE), a leader in m-government development. The study extended the Technology Acceptance Model (TAM) by the factors of trust, cost, social influence, variety of services, perceived usefulness in information technology, and demographics. The results confirmed trust and social impact as positively associated with end users' intention to adopt m-government services. Arar et al. (2021) studied

the preferences and needs of older adults regarding the use of smart home technologies in the UAE. The results showed that smart home technology for health management is inevitable for improving the quality of life for older adults, as 67.0% of elderly users in the UAE have severe diseases. However, elderly users in the UAE believe that smart home technology can violate their privacy; their age group and computer affinity were the most influential variables. They demonstrated that their technology anxiety negatively affects their acceptance of smart home technologies.

Alhashmi et al. (2019) tested a modified Technology Acceptance Model (TAM) incorporated with critical success factors (CSFs) to investigate the adoption of AI in the UAE healthcare sector. A literature review of TAM studies from 2015 to 2018 identified key external factors to consider in CSF studies using TAM, according to the authors. The extended (ETAM) was tested qualitatively. The results showed that managerial, organizational, operational, and IT infrastructure positively affect PU and PEU and should be considered CSFs in determining the implementation of AI in the healthcare sector. Abdool et al. (2021) tested the main factors of the original TAM model and confirmed its applicability to the adoption of telemedicine services in the UAE. The results show that users' perceptions were significantly impacted by their behavioral intention. Saira et al. (2025) examined how technology impacts UAE companies using the Technology Acceptance Model (TAM). It aimed to quantify the influence of the primary TAM constructs, perceived usefulness (PU), perceived ease of use (PEU), and attitude towards the system (ATT), on actual system use (ASU). PU was found to significantly influence ASU, which means that utility is a critical factor. Theoretically, this research advances TAM theory, and practically, it encourages UAE firms to invest in training programs and intuitive system features to make digital transformation less daunting.

Based on the aforementioned studies, it has been well demonstrated that TAM was used to examine users' intentions to use digital technologies across different domains in the UAE. However, it is lacking in digitalizing urban water systems management. A few studies have addressed water digitalization as a socio-technical issue from the public's perspective, focusing on the use of advanced digital tools in arid regions and developing countries in the UAE and the Middle East. The UAE is recognized globally for its modern, advanced cities and commitment to a high quality of life, despite facing challenges (Qureshi, 2020). Challenges

such as a harsh, dry climate, scarce water resources, and the extremely high cost of water supply due to reliance on desalination remain evident, underscoring the need for innovative solutions (Alsharhan & Rizk, 2020).

## CHAPTER 3

### METHODOLOGY

This chapter describes the research design, methods, and tools employed in this doctoral project. It presents the general aspects of research design, approach selection, study area selection, and research instruments. However, each study chapter has a methodology section that is specific and describes its approach in detail.

#### 3.1 Research Design

The primary motivation for pursuing this project is to address the slow adoption of digital technologies in urban water management. Despite the dominant trend toward digital transformation in the built environment and the projected improvements, water systems lag behind other infrastructure. Slow adoption is evident even in developed countries (Schmidt et al., 2024; Bartos & Kerkez, 2020); in developing countries, the situation is even more lagging. In both cases, given the DT technology's ambiguity, its early stage of application, and the limited number of publications in water literature, slow adoption is rooted in multifaceted knowledge gaps (Broo & Schooling, 2023; Naderi & Shojaei, 2023). Stakeholders remain uncertain about the value proposition, unaware of the technology's features, and barriers they may encounter and how to overcome them. Consequently, they have a limited understanding of the adoption mechanisms and the improved outcomes that may result from adopting the new technology.

However, digitalization and digital transformation are embedded in people and led by individuals, as established in the literature (Ablyazov, 2021; Hämäläinen, 2020). This motivated the authors to explore the situation through the lens of stakeholders' knowledge and perception as explored by Yang & Chou (2019). In addition, the author chose to focus on the Middle East, where most countries are developing and struggle with severe water challenges and management issues. Meanwhile, they are the most in need, with a dominant dry climate and scarce water resources in some (Qureshi, 2020), as well as financial constraints and

political conflicts in others (Yorke, 2013). They strive to manage their water systems while providing convenient services to their cities.

This doctorate project adopts exploratory descriptive and explanatory predictive approaches, focusing on domain stakeholders and decision-makers through “multi-methods” data collection across three distinct research studies, as demonstrated by (Chilisa & Kawulich, 2012). For research design, the thesis approach is inspired by the information system (IS) research perspective demonstrated by Recker (2021). The IS perspective addresses the issues arising at the interface between humans and technology and their interaction across various contexts. According to Recker (2021), “research designs enable researchers to systematically engage in intellectual reasoning, generating knowledge depending on data or testing knowledge with existing data, thereby advancing human understanding through extension or intention”. He argued that: “A good research question does not come out of nowhere. It is the logical, necessary, and inevitable conclusion of a set of arguments that find (1) an important problem domain with (2) an important phenomenon that deserves attention from the research community and that relates to (3) an important problem with the available knowledge about this type of phenomenon”. Additionally, “What,” “who,” and “where” questions aim to explore or describe things, phenomena, and processes about which little knowledge exists. He added that successful doctoral research is characterized by a combination of research methods, in which doctoral students learn more than one method and understand how to combine them to achieve their goals.

To fulfill the project's primary goal of identifying ways to facilitate the adoption of DT technologies in water infrastructure management, the authors target stakeholders whose roles are crucial to any change or adaptation to a new system. The adoption of digital technologies is increasingly recognized worldwide, driven by rapid advances in IT solutions. Stakeholders are essential to transformation, and their perceptions are crucial for driving change within their respective areas of influence (Schmidt et al., 2024). This approach was prioritized over theoretical abstraction to provide practical insights that are easy to understand and readily applicable in promoting the adoption and implementation of DT technologies.

This thesis presents the results of three research studies employ various methodologies and utilizing both primary and secondary data. The first research study explored the adoption

barriers currently evolving based on the current snapshot of progress in the study area regarding the design and construction of water projects. The second research utilized quantitative primary data and qualitative secondary data to complement the exploratory approach with real-world examples for triangulation. The third is an explanatory predictive user study conducted among public users. It applies the deductive approach by testing existing theory rather than developing novel ones. The theoretical extended-TAM model is used to examine factors influencing the public's acceptance and adoption of a digital tool for household water management.

### **3.2 Study Area Selection and Sampling**

Reflecting on the early stage of digitalization, selecting a suitable study area in the Middle East was challenging yet essential to guide the research. Excessive care and thorough investigation were carried out in selecting the study area and prospective sample due to the early stage of technology adoption and dominant financial constraints. After searching and reviewing, the author reached out to a personal network of key persons in the water sector and held three online meetings to explain the Ph.D. project objectives and necessary context. The author then discussed the findings and his thoughts with the project supervisors. Ultimately, the study area was assigned to be the United Arab Emirates UAE, specifically Dubai for many reasons as will follow.

The UAE, especially Dubai, is a non-financially constrained environment that has led an early wave of digitalization in the Middle East's urban environment. They pioneered the adoption of digital technologies in construction (AutoDesk, 2021) and led the region through multiple initiatives and digital policies reflecting visionary leadership (Noori et al., 2020). Primarily through building information modeling (BIM), in 2013, Dubai Municipality became the first in the region to mandate BIM. Consequently, companies began adopting BIM and other new digital tools, such as drones, for monitoring and surveillance of construction projects. In 2014, the Dubai government launched the Smart Dubai initiative, and since then, the emirate has become a leader in driving growth and innovation on the global stage. In 2019, Dubai was home to the world's first and largest 3D-printed building, and in 2021, the government

introduced the Digital Dubai initiative. This featured promising digital projects that led the way in the region's digital transformation (AutoDesk, 2021).

Additionally, while being recognized as an arid region with limited water resources and minimal rainfall, the UAE has leveraged technological advancements to achieve outstanding global performance. The country boasts visionary leadership that drives success through digital transformation. This pioneering vision ranked the UAE first in the Cloud Competitiveness Index report for the MENA region (Yaseen et al., 2023), and Dubai among the top globally in sustainable urban development and ICT maturity according to The Network Society Index (NSI) (Noori et al., 2020). Moreover, the UAE is the only Middle Eastern country to have published academic papers on DT technologies in the construction industry, as noted by Opoku et al. (2023).

This confirmed the UAE, especially Dubai, as a hub for technological innovation and advancement in the Middle East region (AutoDesk, 2021). Based on this context, it is strongly expected that water domain stakeholders in the UAE have developed a significant level of awareness of the DT technologies' features and potential. Therefore, despite the early stage of DT adoption, a group of experienced users is likely to be identified within the sample, knowing that many digital projects have already been implemented. Thus, selecting a sample from this context is considered appropriate for answering the research questions. The study population was defined as water stakeholders in the United Arab Emirates (UAE), specifically in Dubai. Building on the thesis aim, the first objective is to identify the adoption factors (barriers and benefits) of DT technologies and discuss them based on perceptions. The researcher, with the recruiters' help, applied an extensive search to identify organizations in the water sector, then, to find potential participants with relevant profiles within the firms, as recommended by Greckhamer et al. (2018) and Chan et al. (2019). The recruiters reached out to their network of public and private-sector infrastructure organizations, public utilities, and technology providers in Dubai. Additionally, the author searched the LinkedIn profiles and websites of top organizations and firms to identify relevant participants, gather their contact information for outreach, and define the study population.

For the first two research studies, the sample respondents were recruited through a two-step process: first, purposive sampling, followed by snowball sampling techniques (Chan et al.,

2019). The author identified leading consulting, contracting, and project management companies based in the UAE with experience in water infrastructure planning, design, construction, procurement, building, and management. These include KEO, Khatib & Alami, AECOM, Parsons, Al Naboodah Group, Shapoorji Pallonji Group, Metito, and many others. Then the author explored each company's website and LinkedIn profile to identify potential participants and staff across various administrative and engineering levels, primarily CEOs, DMs, senior technical, and project managers. Additionally, the author searched the Dubai electricity water authority (DEWA) website, the sole utility provider in Dubai for water, electricity, and wastewater services. Then, identified several key individuals and relevant contacts through DEWA's website and LinkedIn profile for inclusion in the sample. The third category covers technology providers. By reviewing DEWA's website and LinkedIn profile, the author identified a group of technology providers who supply smart water project applications for DEWA in Dubai, including Evoqua Water Technologies, Xylem Middle East Water, and DIEHL Metering. Triangulating these sample categories aims to include the stakeholders involved and relevant to the adoption and implementation of digital twin (DT) technologies within Dubai's water sector. In total, 160 potential participants were identified for contact, representing the entire digitally savvy population in Dubai, UAE. Detailed information about the study population is available in ANNEX I.

A different approach was applied for the third research, based on the DEWA's context in Dubai. In the UAE, Dubai faces severe water scarcity, relying on desalinating seawater as the primary source of water supply (Alsharhan & Rizk, 2020). Rapid urbanization and commitment to high living standards have further magnified the issue (Qureshi, 2020). On average, the country has one of the highest per capita water consumption rates in the world, at 550 liters per day (Al Desoukie, 2020). A steady increase in demand over 2002–2025 has led to an unprecedented rise in desalinated water production; production is projected to exceed 5.0 Bm<sup>3</sup> by 2025 (Alsharhan & Rizk, 2020). This will entail substantial costs, marine environmental pollution, and high greenhouse gas emissions. However, the country's pioneering perspective and leadership have leveraged new technological advancements to achieve a remarkable performance worldwide (Riadh, 2022).

To address water security issues at both the national and global levels, in 2017, the UAE unveiled its Water Security Strategy 2036, which aims to ensure sustainable access to water and aligns with the UAE's vision for prosperity and sustainability. The main objectives of the strategy are to reduce demand by 21%, enhance the water productivity index, decrease the scarcity index by 3 degrees, increase treated water reuse to 95%, and maintain a national water storage capacity of 2 days. The strategy focused on policy development, legislation, awareness campaigns, and the utilization of advanced technologies to improve national water security. By halving per capita average consumption and promoting sustainable practices, the strategy aims to save AED 74 billion and reduce carbon dioxide (CO<sub>2</sub>) emissions from desalination processes to 100 million metric tons (The UAE Water Security Strategy 2036, 2024).

In line with this, in 2024, Dubai launched the "Mohamed bin Zayed Water Initiative," aimed at addressing global and national water scarcity challenges. The initiative aims to raise awareness of the severity of water scarcity in the UAE and accelerate the adoption of technological innovations to address the challenges it presents (The Mohamed bin Zayed Water Initiative, 2024). In 2024 also, Dubai Hydro Insight, a project by DEWA, was awarded the Smart Water Project of the Year by the Global Water Awards. The project developed a fully automated monitoring system by utilizing digital IoT solutions to excel in water and wastewater management (Jones, 2024). In the same year, DEWA, Dubai's sole water provider, announced that it had installed over 1 million smart water meters, achieving 100% installation across Dubai. Additionally, the authority launched its Smart Living initiative through its website, providing a dashboard application to help customers monitor their water consumption digitally and proactively. The dashboard allows users to track their consumption, receive alerts for high water usage, and compare their consumption with others (Smart Living, 2023). The aims were to enhance operational efficiency and manage services digitally through integrated smart systems using disruptive technologies, thereby achieving greater savings for DEWA and its customers (DEWA, 2023).

To fulfill the initiative's goals, the households' public users should use the tool at the intended level; however, no previous efforts have been made in this regard. Adoption is still in its early stages, and users' perspectives regarding the adoption rate and acceptance of digital tools remain unknown. DEWA has made a substantial investment in installing smart meters and

offering digital tools to enable the materialization of benefits and actual consumption reduction; the public must adopt these digital tools at a corresponding level. Therefore, it is essential to investigate adoption and identify the factors that may influence the public's acceptance to adopt and use these tools.

Thus, the third research adopts an explanatory predictive approach in the study area based on theoretical foundation. It employs a socio-technical methodology using the TAM model (Davis, 1989) from information systems (IS) research, and extends it with user factors from prior studies addressing similar issues. The model was developed in accordance with Economides' (2016) study on selecting external factors, tailored explicitly to IoT adoption, and previous literature. Reflecting on the study area's context, defining the problem, and identifying relevant external factors. A conceptual model was proposed, and hypotheses were formulated based on the proposed relationships within the model, to be tested using empirical data. Then, based on the literature and the adopted theoretical TAM approach, a questionnaire was developed to gather quantitative primary data.

The study used a cross-sectional self-administered online survey among public users in the United Arab Emirates UAE, Dubai. The sample comprises public users in Dubai who are already registered with DEWA and should have access to a mobile application. The sampling technique used was a combination of convenience and snowball sampling, two common approaches in similar studies targeting public users (Al-Adwan et al., 2023; Keller et al., 2018). Those techniques are suitable when determining the target population size is difficult, and the study is constrained by time and budget limitations.

Additionally, it is important to mention that DEWA has strict confidentiality rules regarding data release, even for scientific purposes. The author officially requested data through a high-level administrative official at DEWA. Furthermore, provided all the information asked for on the project, objectives, scope of work, ethics committee approval number, the university, the supervisors, etc., the authority refused the data request. They justified this by stating that the data is highly confidential. This prevents the author from obtaining any actual information on the adoption rate or the exact number of users, or even conducting any trials or experiments. However, according to Keller et al. (2018), even though it may be difficult for participants to express their expectations and opinions about a novel technology without prior experience, the

lack of knowledge may enable unbiased responses by encouraging them to freely express their ideas without prior effects. This approach aligns with the study objectives, which investigate the influence on intention rather than actual use, and does not consider any effect of actual usage.

### **3.3 Instruments Design and Distribution**

Two questionnaires were developed to collect the primary data from three groups of stakeholders in the UAE: the digitally inclined and familiar, the experienced professionals, and the citizens.

#### **3.3.1 Ethical Considerations**

According to Recker (2021), scientific ethics describes norms for conducting research, distinguishes between acceptable and unacceptable behavior in scientific work, and reflects the main concerns and objectives of science (Resnik, 2016). Throughout the project, the researcher respected all necessary ethical considerations as essential to scientific research. The researcher did not engage in any illegal activities or incentivise any respondent to obtain a specific response. Additionally, the research studies have been conducted in intensive care to ensure no one is harmed. No one has been forced to participate in this study; it is entirely voluntary. Respondents filled out the questionnaire after acceptance. Besides, any previous work by any author, or scientific material, or production has been cited appropriately. To comply with the university requirements, the two questionnaires were submitted to the Ethics Committee for revision, reviewed, and then received their approval, each with a number. ANNEX VIII encloses the two committee decision approval documents.

#### **3.3.2 First Questionnaire**

The first instrument was developed through a literature review, and a customized questionnaire was designed to collect primary data essential to answering the research questions. The self-administered structured questionnaire was developed for quantitative data collection by a cross-sectional empirical study in the United Arab Emirates UAE. The questionnaire was

designed and tailored based on findings from the literature, with guidance from Beal & Flynn (2015), who explored digital transformation through smart metering technologies for water organizations in Australia and New Zealand.

In addition to considering the tool's face validity, three academic professors and one industry expert were contacted to read and provide feedback. They reviewed the content and suggested some modifications (removing some questions to avoid repetition and clarifying the text). After considering their recommendations and making the necessary modifications, a small sample of civil engineers participated in a pre-test trial to ensure clarity and timing. The form was then submitted by the author to the Ethics Committee for review and received the committee's approval.

The survey comprises four sections. The first section serves as an introduction, providing a brief overview of the features and capabilities of DT technologies. In this study, DTs refer to any digitalization approach, including 3D models, IoT sensing, AI deployment, and Big Data analytics, within various water systems. Respondents who chose to participate were screened by answering a question about their familiarity with any type or level of digital technologies used in water systems. Next, the awareness section poses questions about definitions of DT technology, awareness of maturity levels, benefits, and barriers. The third section, the experience section, is designed explicitly for users involved in project implementation and asks them questions to assess their agreement on the importance of the drivers for adoption and implementation. Additionally, they were asked two questions to evaluate the level of success and their satisfaction with the project's outcomes. The last two questions were drawn from the project success management domain, in which the literature defined project success as per Fazli et al. (2014). Finally, the demographic section includes questions about respondents' gender, years of experience, their organization type (consulting and contracting firms, local utilities, technology providers, or others), and their current roles within the organization.

The questionnaire is an online, structured survey with 5-point-scale items in three sections and multiple-choice questions in the demographic section. It is designed and crafted to ensure that only participants who are at least slightly familiar with digital technologies can answer the questions in all sections. Meanwhile, only participants with hands-on experience on digital projects for water systems can answer the experience section. This approach has been used

effectively to identify a group of experienced practitioners to validate the benefits and barriers based on their project experience. The criterion used to identify the experienced group was confirmation of current or past experience with digital technologies applied to water-related projects. Primary data were collected from the study sample using a combination of purposive and snowball sampling techniques (Chan et al., 2019; Chilisa & Kawulich, 2012; Hammadama et al., 2020).

After reaching out to contact prospective participants through their available contact information, the survey link was emailed to the entire population of 160 participants. The study sample frame targeted CEOs, senior-level project managers, and employees from consultancy and contracting firms, project management firms, public utilities, and technology providers. The survey guaranteed participation anonymity and ensured that the responses would be used solely for scientific purposes. The self-administered online questionnaire was distributed to participants and remained open from February, 2025, to April, 2025. A copy of the questionnaire is enclosed in ANNEX IV, and the Ethic Committee Approval enclosed is ANNEX VIII.

### **3.3.3 TAM Questionnaire**

The third study adopts a different research philosophy the “Positivism”. It applied a socio-technical approach using the TAM model theory (Davis, 1989) from information systems IS research. The IS approach relies on data collection to test hypotheses based on the research questions and a proposed conceptual model (Recker, 2021). The author extended the generic TAM with relevant factors from prior studies addressing similar issues to construct a conceptual model. Based on previous studies and the Dubai context, the author referred to the model developed by Economides (2016), which served as a guide for selecting external factors, as it was explicitly designed for IoT adoption. Reflection on reviewing the study area context, defining the problem, and identifying relevant external factors. A conceptual model was proposed, and hypotheses were formulated based on the proposed relationships within the model to be tested with empirical data. Based on the adopted theoretical TAM approach, a self-administered questionnaire was developed to collect quantitative primary data in a cross-sectional mode among public users in Dubai.

The developed survey followed the TAM model methodology, as it serves as a user study. The research design for this study is an explanatory predictive cross-sectional online survey. The sample comprises public users in households in Dubai, UAE. The form was posted across all available social networking platforms and social media channels, and sent by email to some volunteer recruiters for snowballing distribution in their networks. Sufficient time was allocated for data collection; the form remained open for more than three months, with reminders emailed to recipients and the form reposted on social networks every five days. The author and recruiters distributed around 250 forms. Given the budget and time constraints, the sample size was deemed sufficient and statistically adequate for analysis. To the best of the author's knowledge, this is the first study to apply the extended TAM model to explore and discuss users' profiles and condition requirements for adopting water-monitoring digital tools in UAE households.

The questionnaire began with an introduction section to familiarize participants with the study settings. First, a neutral brief overview of the potential of IoT technologies was provided to minimize any impact on respondents' perceptions. Then, the challenge and problem were defined and clarified so respondents could understand the study's motivation, and the objective was then outlined. The introduction included the ethics committee approval number, and participants were assured that their data would be confidential and used solely for scientific purposes. Then, with their consent, they were asked to begin the survey and answer the questions. The tool contained four sections: introduction, external variables, TAM model constructs, and demographics.

Before the development of the first version of the instrument, with the research supervisors' coordination, faculty members from a business management school were contacted to discuss aspects of the study. The professors specialize in IS research and engaged with the author in rounds of discussions that provided valuable comments and recommendations on the target sample, the theoretical approach, and the development of factors and scales. Based on their comments, suggestions, and rounds of refining, the first version of the questionnaire was developed. The form was then submitted by the author to the ethics committee for review and received the committee's approval. Thereafter, the form was tested in a pilot study to assess clarity and understanding and confirm the reliability and validity of scales in a 48-participant

pre-test. After preliminary analysis of several model specification options and comparison of the results, three out of the 24 items were removed to improve the model coherence. After obtaining confirmation from the supervisors, the form was considered ready. Selected items for each factor were adapted from pre-validated scales in previous studies, with minimal or no modifications. However, the piloting yielded 21 items across seven constructs. A copy of the TAM questionnaire is enclosed in ANNEX V, and Ethic Committee Approval is enclosed in ANNEX VIII.

### **3.4 Data Collection and Unit of Analysis**

The three research studies employed different methods to gather data; the first collected quantitative and qualitative primary data. The primary data were collected from the study sample (experienced and inexperienced stakeholders) using a survey and focus group discussion from experts. The second research employed a mixed-method approach, gathering both quantitative and qualitative data. The quantitative data consisted of primary empirical data from experienced stakeholders, while the qualitative data were secondary data from case studies. The third research relied on a theoretical deductive approach and collected primary quantitative data. The unit of analysis for the first research was the entire population of 160 digitally savvy stakeholders. For the second research, the unit of analysis was limited to experienced stakeholders and the case studies. For the third, it included public users in Dubai. This approach includes several stakeholder groups that are most likely relevant to the adoption of DT technologies in the water sector in the UAE.

The first and second research studies gathered data from February to April 2025, while the third collected data from April to late August 2025. The first research collected 63 responses from participants, including both experienced and inexperienced stakeholders, as well as six experts in the focus group. The second research employed an exploratory approach, analyzing data from 27 experienced stakeholders exclusively, and was complemented by qualitative secondary data sources from six case studies. Finally, the third research analyzed the collected data from 149 residents of Dubai.

## CHAPTER 4

### **BEYOND FINANCIAL CONSTRAINTS: BARRIERS TO DIGITAL TWINS ADOPTION IN WATER PROJECT PLANNING AND DESIGN MANAGEMENT**

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#### Highlights

- Primary stakeholders' data in a financially capable and digitally advanced context
- Assessment of stakeholders' perceptions on the adoption of DTs for water projects
- Barriers, cybersecurity issues, data quality, workforce gaps, and governance
- Focus group refinements, workforce gaps, data governance, and cultural challenges
- Recommended: policy updates, structured governance, and cultural change

#### ABSTRACT

Design and construction of water infrastructure projects are critical for water networks functionality. Water networks provide the essential water services, supporting public needs and convenience. Yet, water projects are poorly managed by fragmented legacy practices characterized by the lack of data and poor collaboration. This study investigates the application of Digital Twin (DT) technologies as an enabler of data-driven decision-making in water projects, with a focus on the design and construction in the United Arab Emirates (UAE). Although the UAE is a digitally advanced and non-financial constrained context, the adoption of DT technologies in water projects remains limited. Using a sequential mixed-methods design, the study gathered data through a questionnaire from 60 professionals. Further, it validated the findings through triangulation in focus group discussions to holistically understand adoption barriers. The results from the first stage reveal that cybersecurity, data availability and ownership, and interoperability issues are the main factors inhibiting the application of DT technologies. However, focus group discussion results confirm, refine the findings, and reveal other important barriers to DTs application increasing results' credibility. The study contributes with a refined two-level insight framework on barriers analysis with

underlying factors. Besides, it validates context-specific barriers, adding to the global discourse on digitalization in urban water management.

**Keywords:** Digital Twin; water projects; design and construction; focus group; adoption barriers.

#### 4.1 Introduction

Water infrastructure networks are critical for urban functionality, they provide public water services, and support urban sustainable management (Borah, 2025; Canadian Infrastructure Report Card, 2019). As pressure on water resources management from climate change and rapid urbanization increases, there is an urgent need for effective planning and management of water projects (Marzouk & Othman, 2020; UN-Habitat, 2022). Infrastructure projects including water projects are complex, characterized by high capital costs, complex stakeholder relations, long duration, and broad geographic extent (Cheng et al., 2016). Meanwhile, their design and construction face escalating challenges of fragmented planning, using legacy practices, information silos, and congested and interconnected subsurface conditions (Tanoli et al., 2019; Yang et al., 2021; Joshi et al., 2016). Fragmented information management, lack of data sharing, and absence of integrated digital platforms have led to poor collaboration and unclear decision-making throughout the entire life cycle (Edmondson et al., 2018; Wang, 2021; Wang & Yin, 2022; Zhi et al., 2019). This has led to reported catastrophic accidents in subsurface networks, that result in economic losses and service delivery failures (Esekhaigbe et al., 2020; Tanoli et al., 2019; Wang & Yin, 2022).

The Digital Twin (DT) technology has attracted growing attention for its potential applications for infrastructure management. DTs provide virtual simulation environments with real-time interaction analysis, emerging as integrated solutions rather than merely data connectivity models (Curl et al., 2019). Current research identifies DTs as all-around tools for infrastructure management, capable of supporting decision-making throughout the entire life cycle (Rand, 2019; Broo & Schooling, 2023; Baghdadi, 2025). During planning, design and construction, DTs can assist in advanced visualization, automated virtual inspections, multi-objective scenario simulations for future planning, improve construction supply chain management, optimize equipment scheduling, improve utility clash detection and damage prevention, and support collaboration and coordination of various stakeholders in infrastructure projects, thus

promote design accuracy, work efficiency, and overall design and construction management (Alperen et al., 2021; Conejos Fuertes et al., 2020; Ghaith et al., 2022; Pedersen et al., 2021; Bartos and Kerkez, 2020; Hasan et al., 2022; Tanoli et al., 2019; Deng et al., 2019; Wang et al., 2026). Additionally, in operational management DTs can detect leakage and network losses (Ramos et al., 2022), manage water treatment plants digitally (Curl et al., 2019; Rand, 2019), automate safety assessments of underground pipelines (Li et al., 2022), detect anomalies in water supply networks (Wu et al., 2023), and manage demand user consumption and pricing (Zekri et al., 2022).

Among new digital technologies, the Digital Twin has been attracting growing attention and recognition for its potential applications across the entire life cycle of infrastructure. Compared to traditional data connection and monitoring methods, the DT provides a virtual simulation environment for real-time interaction and analysis, emerging as an integrated solution rather than merely a data connectivity model (Curl et al., 2019). Current research identifies DTs as all-around tools for infrastructure management and planning, capable of supporting strategic decision-making throughout the entire infrastructure life cycle (Rand, 2019; Broo & Schooling, 2023; Baghdadi, 2025). During the planning and design, DTs can assist in advanced visualization and analysis, automated virtual inspections, multi-objective scenario simulations aiding in infrastructure future planning, and collaboration and coordination of various stakeholders in infrastructure projects, thus promoting design accuracy and efficiency and overall design planning and management (Alperen et al., 2021; Conejos Fuertes et al., 2020; Ghaith et al., 2022; Pedersen et al., 2021).

The DTs global demand and usage are expected to result in cost savings estimated at US\$950 million for design and construction industry (Rafsanjani & Nabizadeh, 2023). Several breakthroughs have been reported in manufacturing, transportation, and building industries (Grieves & Vickers, 2017; Rasheed et al., 2019; Coupry et al., 2021). However, their application for water systems remains low even in developed contexts (Bartos & Kerkez, 2020; Naderi & Shojaei, 2023). The current literature on the DT adoption has explored the value proposition and adoption factors for many engineering fields, yet water infrastructure is less covered. Previous research has shown that the implementation of DTs in water infrastructure

lags behind other infrastructure sectors. This can be attributed to the cost burdens barriers, the early stage of development, limited number of case studies, and the lack of practical evidence of implementation (Beal & Flynn, 2015; Waqar et al., 2023; Naderi & Shojaei, 2023).

The planning, design and construction are critical to the success of digital initiatives in infrastructure projects (Marzouk & Othman, 2020; Rafsanjani & Nabizadeh, 2023). Most of what happens in design and construction will determine the digitalization opportunities throughout the infrastructure life cycle. If barriers prevent digitizing data and engineering tasks in the early stages of design and construction, there will be a poor chance of digitalization in the operation stage (Mushtaq et al., 2026). Given that majority of the current literature are technical approaches, develop specific prototypes or proof-of-concept solutions, and do not consider practical adoption factors (Baghdadi, 2025; Opoku et al., 2023; Ge & Qin, 2025). Besides, current research concerns DT adoption in the operational stage, yet operational implementations are few (Boyle et al., 2022). Additionally, Beal & Flynn, (2015) demonstrated that each stage of a project poses its own set of adoption barriers, Mushtaq et al., (2026) established no significant impact of BIM operation and maintenance features on the quality of planning and design, and Opoku, et al., (2023) highlighted the lack of empirical studies on DTs adoption barriers. Thus, there is an evident need to empirically study DT barriers in the design and construction of water projects.

Reflecting on this background, this research explores the barriers to the adoption of DTs in water projects in the UAE, a digitally advanced and non-financially constrained environment. The UAE faces severe water security issues due to the high cost of supply and its commitment to the highest living standards. However, its visionary leadership supports early digital transformation, positions it as a regional hub of innovation for cloud computing leadership and ICT maturity (Noori et al., 2020; Yaseen et al., 2023). Additionally, in 2013 Dubai has advanced the digitalization of the architecture, engineering, and construction (AEC) industry through an early BIM mandate that resulted in adoption of other digital technologies (e.g., drones and smart monitoring systems) (Autodesk, 2021). This makes the UAE a relevant case study for investigating the adoption of digital transformation technologies beyond financial constraints.

This paper aims to empirically explore the barriers to the adoption of DTs in the design and construction of water projects. It identifies the barriers using quantitative surveys, then validate and triangulate the findings through the qualitative insights of focus group discussions. The paper adds to the existing literature on the digitalization in infrastructure projects a largely uninvestigated area. Thereby, it provides a reference for future studies and contributes empirically on the understanding of early-stage barriers of DTs adoption in the Middle East. The research makes three contributions; it presents empirical evidence on the barriers to the adoption of DTs in the design and construction of water projects. Secondly, the research establishes that beyond the financial burdens, organizational, technical, cultural, and governance barriers are crucial in a digitally advanced, non-financially constrained setting. Finally, by combining survey with focus group analysis, the multi-methodological perspective refined a two-level insight framework that increases results' credibility. The rest of the paper will proceed as follows: The body of existing research will be examined in section 4.2; the research methodology will be described in section 4.3; the results will be presented in section 4.4; and discussed in section 4.5, results implications in section 4.6 and the conclusions and limitations will follow in section 4.7.

## **4.2 Background and Literature Review**

### **4.2.1 Digital Twin Technologies Understanding**

Recently, a considerable amount of industry reports and research studies have been conducted in the realm of examining the potential benefits of digital twin (DT) technologies in various fields such as the healthcare, manufacturing, education, smart cities, transportation, infrastructure development, construction, and energy domains (Rasheed et al., 2019; Callcut et al., 2021; Ammar et al., 2022; Broo & Schooling, 2023). In sum, these research works show that digital twins have emerged as a novel approach for improved visibility, prediction, and decision-making support across various systems. However, despite the recent increase in research on this area, there is a lack of conceptual clarity about what exactly digital twin technology is (Callcut et al., 2021; VanDerHorn & Mahadevan, 2021; Ammar et al., 2022).

In the built environment, ATKINS (2017) defined DTs as systems that go beyond Building Information Modelling (BIM) and static three-dimensional models. According to this definition, DTs are dynamic, data-driven resources capable of improving asset design, confirming as-built status, facilitating scenario simulation, and supporting long-term asset management based on updated digital records of infrastructure. The definition distinguishes Digital Twins (DTs) from other digital models by emphasizing real-time data integration and decision-support capabilities. In the context of Urban Water Systems (UWS), Pedersen et al. (2021) define DTs as systematic virtual models of the physical elements of UWS, represented as a network of data links, founded on open data standards. They highlight their multiscale characteristics in terms of functionality and application across technological, organizational, and societal levels.

However, despite conceptual progress, the diffusion of DT technologies has remained at a preliminary stage, creating a ‘fuzzy’ implementation environment, particularly in the water sector (Daniel et al., 2023). The existence of a few empirical studies and the limited number of publications have obstructed the demonstration, validation, and dissemination processes (Broo & Schooling, 2023; Naderi & Shojaei, 2023). The various applications of DTs, in terms of scale of development, technologies used, functions, maturity levels, and anticipated outcomes, further exacerbate the misunderstanding (ATKINS, 2017; Alva et al., 2022; Zhang et al., 2023; Zekri et al., 2022). Thus, confusion has arisen over the distinction between partial digital models and full DT systems, leading to misconceptions about potential outcomes and the complexity of the development process. A lack of understanding of DTs' capabilities and limitations has particular implications for the DT adoption process. Misaligned expectations, combined with a lack of information about the technical, organizational, and governance aspects of DTs, may lead to the project being prematurely abandoned, restricting the development of the required infrastructure to support the DT (Ford & Wolf, 2020). In the water sector, where concerns about risk and regulation are more severe, these factors may further delay the adoption and integration of the technology into mainstream practices. Thus, the importance of improving knowledge levels and recognizing the adoption issues in the water sector has been emphasized in the existing literature.

#### 4.2.2 Barriers to DTs Adoption in Water Projects

Despite growing attention to the importance of Digital Twin technology, its uptake is limited by challenges, despite its potential for improvement (Bartos & Kerkez, 2020; Schmidt et al., 2024). The understanding of current challenges in adopting technology has long been well documented in the body of knowledge, grounded in theoretical propositions rather than practical implementations, lacking validation in practice (Opoku et al., 2023). This is especially the case in the water industry, where current academic scholarship has primarily focused on the construction/operation stages, with less focus on planning/design management (Waqar et al., 2023; Opoku et al., 2023; Arowoia et al., 2024).

Various studies have examined the barriers to adopting DTs. For example, in a detailed review of DT applications in the construction industry, Opoku et al. (2023) identified 30 key barriers, clustered into four categories based on stakeholders and industry. The most significant barriers include a lack of knowledge among stakeholders, low acceptance of technology, limited understanding of the value proposition, project complexity, and the static nature of building data. This highlights the importance of recognizing that implementing a digital twin (DT) faces challenges that extend beyond technology into the organization's culture. As highlighted by Broo and Schooling (2021), the barriers to implementing digital twins in infrastructure can be categorized into three types: digital transformation barriers, cultural transformation barriers, and skills barriers. In the cultural transformation barriers, the challenges faced in this area relate to human and organizational issues, such as the resistance to change, the challenges in changing from traditional processes to digital processes, the lack of awareness among the stakeholders regarding the benefits of digital transformation, and the lack of understanding of the business case.

The literature also points towards technical difficulties that vary from system functionality to data infrastructure readiness. Data security and ownership, interoperability issues, unawareness of enabling technologies, and data collection, storage, analysis, and management have all been identified as key barriers to implementing DTs (Broo & Schooling, 2021). On the other hand, workforce skills challenges include an aging professional population, a lack of

specialized educational and training programs, difficulties in recruiting skilled staff, and the need to maintain a supportive working environment in a competitive job market.

In addition to the construction industry, research studies that concentrated on water governance and the digital transformation in the public sector have also highlighted the importance of non-technical issues. In the context of the urban wastewater industry in the Swiss substates, research by Manny et al. (2021) revealed that individual and organizational barriers were the major factors that impede the use of data. The research finding illustrates that the lack of vision and limited organizational resources were the major factors that impeded public authorities from evaluating and using available digital big data, despite technical feasibility.

Community and system-level barriers have also been investigated in the context of smart cities and disaster relief. Ford and Wolf (2020) have listed two key limiting factors for DT development at the community level: “fatigue risk” and “data ownership”. Fatigue risk is the point of threat at which sponsors, specifically the financial supporters of a project, tend to withdraw their support if the time to reap benefits is extended, thereby preventing the development of the entire system. On the other hand, Waqar et al. (2023) found that cybersecurity and data privacy concerns are the key DTs development barriers in Malaysia, reflecting the increasing importance of data privacy in the context of public infrastructure systems. At a more general level of civil infrastructure, Callcut et al. (2021) analyzed the concepts, definitions, and uses of DT across several infrastructure areas, concluding that most difficulties stem from the early state of DT-related adoption. The most important difficulties in this area are: output uncertainty, cybersecurity issues, data-sharing challenges, and a lack of standardized data structures. Their analysis reveals substantial familiarity with DT concepts across industry and academia in the UK; however, this familiarity is often accompanied by a lack of clarity due to the use of vague definitions.

Collectively, although there is currently little literature specifically related to the adoption of DT in water infrastructure, there is sufficient existing literature that can serve as a foundation for understanding the adoption barriers commonly encountered in the planning and design phase of water infrastructure projects. Nevertheless, these barriers are not typically analyzed in an integrated, context-specific manner, and their validity is rarely tested in practical

Table 4.1 The DTs Documented Barriers Based on the Literature

Barriers to DT Adoption	Reference
BR1. The data cybersecurity issues	(Callcut et al, 2021), (Broo & Shooling, 2021), (Jones et al., 2020), (Waqar et al., 2023)
BR2. The data availability, collection, storage, and ownership issues	(Boyle et al, 2022), (Opoko et al., 2023), (Broo & Shooling, 2021), (Jones et al., 2020), (Waqar et al., 2023), (Ford & Wolf, 2020)
BR3. The lack of knowledge and interest from water managers	(Boyle et al, 2022), (Beal & Flynn, 2015), (Opoko et al., 2023), (Waqar et al., 2023)
BR4. Difficulties in integrating the various stakeholders across the organizations to work as a single team, poor coordination, and system complexity	(Boyle et al, 2022), (Opoko et al., 2023), (Ford & Wolf, 2020), (Waqar et al., 2023), (Agrawal et al., 2022), (Schmidt et al., 2024)
BR5. The lack of successful case studies of the application of DT that prove the cost-benefit effectiveness	(Beal & Flynn, 2015), (Opoko et al, 2023)
BR6. The lack of standardization and interoperability tools for technical feasibility	(Beal & Flynn, 2015), (Callcut et al., 2021), (Opoko et al., 2023), (Broo & Shooling, 2021), (Jones et al., 2020), (Waqar et al., 2023)
BR7. Misunderstanding the capabilities level required based on intended outcomes early in the selection process	(Beal & Flynn, 2015), (Callcut et al., 2021), (Opoko et al., 2023), (Broo & Shooling, 2021), (Agrawal et al., 2022), (Jones et al., 2020), (Waqar et al., 2023), (Schmidt et al., 2024)
BR8. Poor engagement of proper stakeholders early in the selection process on the proper technology	(Opoko et al, 2023), (Ford & Wolf, 2020), (Agrawal et al., 2022), (Glaessgen & Stargel, 2012)
BR9. The lack of a trained workforce and skilled system users due to poor or incomplete training programs	(Boyle et al, 2022), (Callcut et al, 2021), (Opoko et al, 2023), (Broo & Shooling, 2021)
BR10. Users' acceptance of using the new technology and the reluctance of professionals	(Boyle et al, 2022), (Beal & Flynn, 2015), (Opoko et al., 2023), (Broo & Shooling, 2021), (Waqar et al., 2023), (Schmidt et al., 2024)
BR11. The unexpected incremental cost of the development and implementation	(Beal & Flynn, 2015), (Waqar et al., 2023)
BR12. The Limited investment in innovation, limited top management support, and unwillingness to assume and support the risk associated with innovation	(Boyle et al., 2022), (Beal & Flynn, 2015), (Broo & Shooling, 2021), (Waqar et al., 2023), (Agrawal et al., 2022), (Schmidt et al., 2024)
BR13. The lack of dedicated work to track the improvement and evaluate the performance after the adoption	(Callcut et al., 2021), (Ford & Wolf, 2020), (Agrawal et al., 2022), (Hamma-adama et al., 2020)
BR14. The lack of governmental promotion and digital policies	(Boyle et al, 2022), (Opoko et al, 2023) (Manny et al., 2021), (Schmidt et al., 2024)

stakeholder engagement exercises. As such, there is a clear need to classify barriers to DTs adoption across phases and domains, and to validate these barriers in practical, contextual settings. Table 4.1 compiles the most relevant barriers identified in the existing literature on the adoption of DT across various phases and domains, with the most relevant in the planning and design phase of water projects. Although existing research has identified barriers in adopting Digital Twins (DTs) across various infrastructure domains, little attention has been paid to barriers in the planning/design phase of water projects, which is pivotal in determining future digital implementation opportunities. The analysis of existing research shows a scattered research effort regarding the use of DTs in the planning/design and construction phases of water projects. The existing research on DTs reveals that most work focuses on technical feasibility or implementation aspects rather than decision-making in the early phases of implementation strategies. In addition, the early stage of technology in the water domain, combined with a lack of reliable research in the form of validated case studies, has led to limited awareness of the challenges in adopting DTs in water projects.

### **4.3 Research Methodology**

#### **4.3.1 Research Design**

This research uses a mixed-methods approach to conduct a scientific investigation of DT adoption barriers for water projects in the UAE, a highly advanced context in the Middle East. Mixed-methods approaches combine quantitative and qualitative methods within a single investigation to capitalize on the depth and breadth of insights simultaneously and to improve the validity of empirical results through cross-validation (Johnson et al., 2007). Mixed methods have been recognized as the third methodological paradigm for scientific research reflecting its importance, according to Johnson et al. (2007). This study employs an exploratory-descriptive research design. The quantitative method is used to determine the significance of barriers to the adoption of digital technology (DT), while the qualitative approach is used to confirm the findings. Triangulation, as a methodological approach, is used to increase the validity of findings by confirming them across multiple sources (Torrance, 2012). This

methodological approach is highly significant, particularly for early adoption studies, for which there is limited scientific research (Chilisa & Kawulich, 2012; Recker, 2021).

The quantitative data were collected using an online, structured questionnaire, in which respondents were asked to rate their level of agreement with statements about the factors that act as barriers to the adoption of DT in water infrastructure projects. The structured survey technique is well known in construction studies as an appropriate approach for capturing stakeholders' opinions in the complex context in which decisions are taken (Chan et al., 2019; Hamma-adama et al., 2020). The structured survey questionnaire was developed based on barriers that exist in the literature, as shown in Table 4.1.

Later, the study employed semi-structured interviews with a focus group to collect qualitative data from experienced stakeholders in the water design and construction industry. The main reason for using focus group research in this study was the need to allow in-depth discussion among the research participants, to gain a profound understanding of the identified barriers from different perspectives. In the early stages of technology adoption, subjective validation, aimed at leveraging the empirical knowledge of expert practitioners, has been seen as appropriate and necessary for refining and validating contextual constructs (Powell, 1992; Yang & Chou, 2019). To improve methodological clarity and depict the order and integration of the research stages, a flowchart was designed to illustrate the entire research process (Figure 4.1). The figure shows the sequence of a mixed-methods study, beginning with an extensive literature review to identify potential barriers to the adoption of DT. The study proceeds to the quantitative stage, which involves a structured questionnaire to assess the perceived significance of potential barriers to DT adoption. The quantitative study's preliminary findings are followed by the qualitative stage, which involves semi-structured focus group discussions to assess the validity, interpretation, and significance of the findings. The final stage involves integrating findings from the quantitative and qualitative stages through triangulation to systematically validate potential barriers to DT adoption and develop robust conclusions for water project planning and design management.

### 4.3.2 Study Area and Sample Selection

The population was considered to be digitally savvy stakeholders involved in water infrastructure projects in the United Arab Emirates, with a focus on Dubai. Given that Digital Twin use is considered new, and that this study is exploratory in nature, purposive and snowball sampling were used to select participants with direct experience in digital/data-driven infrastructure projects, as described by Greckhamer et al. (2018). This type of sampling is considered most relevant in emerging fields such as this, where experts are few and difficult to identify using probabilistic techniques.

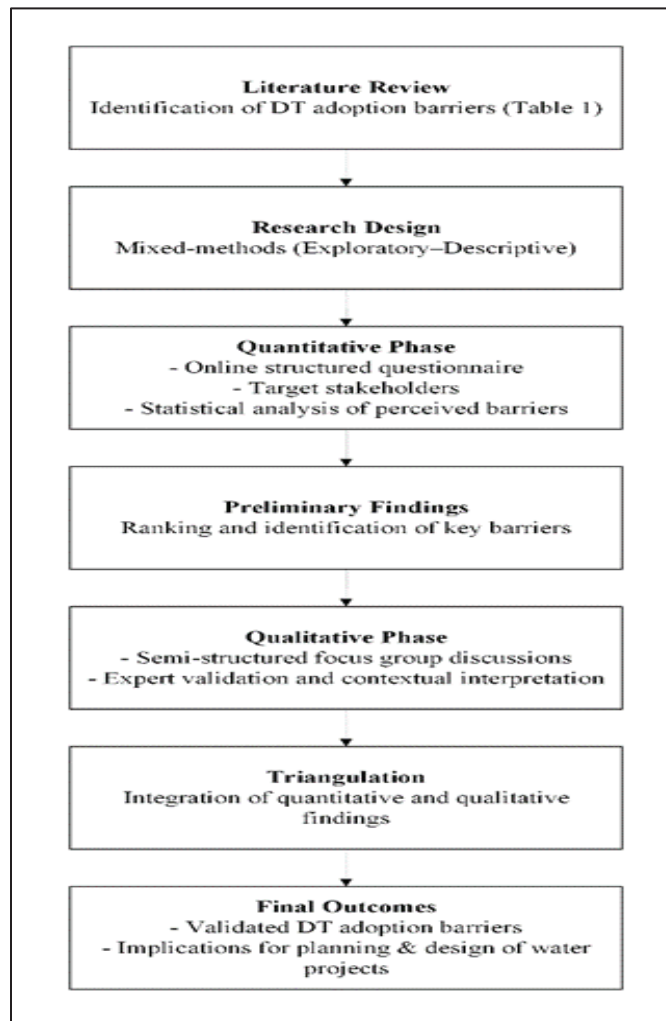


Figure 4.1 Research methodology flowchart

The targeted group included four major categories of stakeholders: (1) consultancy and project management organizations, (2) construction engineering firms, both working on water

infrastructure projects, (3) Dubai Electricity and Water Authority (DEWA), the only public utility company dealing with water services in Dubai, and (4) technology providers operating in Dubai and supplying digital solutions. The primary screening process, using professional profiles and evidence of engagement in digital projects, identified 160 respondents as representative of the effective population, as in similar studies (TaHERi et al., 2022). The sampling process primarily included chief executive officers (CEOs), direct managers (DMs), senior project managers, and engineers, ensuring that major relevant stakeholders and professionals were included.

#### **4.3.3 Questionnaire Design and Quantitative Analysis**

A structured, self-administered questionnaire was designed to collect quantitative information on barriers to the adoption of Digital Twins in water projects. The design of the proposed study's instrument was guided by Beal and Flynn (2015) for the study of digital transformation in water organizations and other studies, as described in the accompanying literature review. To establish the face validity of the study's instrument, three academics and an industrial expert reviewed the survey, and several items were removed and refined as a result. The proposed study's instrument was later reviewed by the institutional ethics committee and approved for use. The pilot test of the proposed study's instrument was conducted with a small group of civil engineers to assess the clarity of the questions, the timing, and the instrument's overall structure. The pilot test led to a few wording modifications. The proposed study's instrument was administered after participants provided consent.

The questionnaire had four sections: (1) background of the respondent and familiarity with Digital Twin technology; (2) awareness, perceived benefits of Digital Twin, and perceived barriers in the adoption of Digital Twin; (3) experience section related to digital projects; (4) demographics. The questionnaire used a five-point Likert scale, which was preferred for its simplicity, reduced respondent burden, and consistency with similar construction and infrastructure-related research. A response rate of 39.4% was achieved, and 60 responses were considered valid out of 63.

Despite its relatively small size, it is deemed sufficient, especially given that Digital Twins have only recently entered the water sector and that there is a limited number of professionals with relevant know-how and experience. Similar studies of other novel digital solutions have used similar sample sizes (Beal & Flynn, 2015; Eadie et al., 2014; Chan et al., 2019; Rapp et al., 2023). For the analysis of quantitative data, IBM SPSS Statistics software version 29.0 was used.

#### **4.3.4 Focus Group Validation**

For the purposes of triangulating and refining the results obtained from the quantitative approach, further qualitative research in the form of focus group discussions (FGDs) was employed. The focus group discussion is considered a very useful approach for validating quantitative research results and for identifying both convergence and divergence in opinions of expert respondents (Morgan & Spanish, 1984). In the current study, the qualitative approach served as a validation tool, enabling a thorough analysis of survey results.

For the focus group, participants were selected through purposive sampling from survey respondents with the necessary professional experience and willingness to participate. The focus group interviews were conducted online via video conferencing software (Zoom) and phone calls. The total time for the interviews was 270 minutes, facilitated by the researcher.

A semi-structured guide was designed to allow free participant expression and to explore all thematic areas. This was based on the quantitative study's results and aligned with Danielsen's (2021) recommendations. At the end of these group discussions, participants took part in a ranking task, in which they were required to rate themes identified as barriers on a scale of 1 to 5. Six experts agreed to take part in the focus group discussions; however, one expert could not participate in the interview and completed the ranking activity on his own. All the experts gave their consent to record the discussion. The recordings were transcribed verbatim, and the qualitative data were analyzed using content analysis.

## 4.4 Results

### 4.4.1 Reliability and Validity Results

The instrument's internal reliability was assessed using Cronbach's alpha to ensure the scale is reliable in measuring the adoption barriers of the Digital Twin (DT). The result is shown in Table 4.2. The overall Cronbach's alpha is 0.911, indicating high reliability. According to Taber (2018), Cronbach's alpha values of 0.71 to 0.91 are considered good to excellent. This indicates that the scale is reliable in measuring the adoption barriers of the Digital Twin.

Table 4.2 Results of the Reliability Analysis

Factor	Number of Items	Cronbach's Alpha
Perceived DT barriers	14	.911

To determine construct validity and understand the factorial structure of the barrier variables, a Principal Component Analysis (PCA) was used. However, before the factor extraction, the suitability of the data for factor analysis was checked. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.718, meeting the minimum requirement for factor analysis of 0.60 (Kaiser, 1974). Furthermore, the Bartlett's Test of Sphericity was found to be significant, with the value of  $\chi^2 = 1753.741$  and  $p < 0.001$ . This confirmed that the correlation matrix was not an identity matrix; hence, the data are suitable for factor analysis.

After extraction, the data were evaluated for interpretability and conceptual coherence following the procedure proposed by Keller et al. (2018). Two factors were identified as stable and conceptually meaningful, explaining a large amount of variance together. The grouping of the initial 14 barriers into two factors is consistent with other research on digital technology (DT) adoption that has previously reduced a large number of barriers into a few latent constructs (Opoku et al., 2023; Waqar et al., 2023). The two factors obtained from the analysis were named based on the thematic congruence of the items loading onto each factor.

The first component (C1) involves barriers related to data governance, resource availability, cost factors, and support at the policy level. Therefore, the first component is titled

‘Organizational and Policy Barriers.’ The second component (C2) involves barriers related to a lack of knowledge, coordination among stakeholders, implementation feasibility, available workforce skills, and learning within the organization. Therefore, the second component is titled ‘Knowledge Barriers, as shown in Table 4.3. The complete PCA results are provided in ANNEX VII.

Table 4.3 Components Results

Component	Items with loadings	Proposed label Name
C1	BR1, BR2, BR5, BR10 BR.11, BR14	Organizational and policy barriers (data, resources, cost, promotion)
C2	BR3, BR4, BR6, BR7, BR8, BR12 BR9, BR13	Knowledge barriers (organizational, technical, workforce)

#### 4.4.2 Demographic Results

Table 4.4 illustrates the demographics of the survey participants (N=60). The demographics reveal that the main gender representation in the survey consists of male participants (86.7%), followed by female participants (13.3%). The demographics reflect the current makeup of the water and construction industries in the study environment; they can be seen as a limiting factor in the study results.

Regarding professional experience in the water sector, the data indicates a high level of expertise. Some 36.7% of the group has over 11 years of professional experience, and 38.3% has 5-10 years of professional experience in water-related projects. This indicates that the group has considerable knowledge of water-related aspects. Regarding their association with organizations, most respondents (75.0%) belong to consulting, contracting, and management engineering firms. Technology providers make up 13.3%, while public utilities and academic/research institutions make up 8.3% and 3.3%, respectively.

Regarding hands-on experience in DT projects, 45.0% of respondents have experience, while the remaining 55.0% have none, despite their familiarity with the concept of Digital Twin. Because the adoption of the DT is in its infancy in the water industry, the number of

implemented digital projects is low, and experienced stakeholders are hard to identify; classifying digital experience as yes/no categories is appropriate at this stage of the analysis. To make the survey results subject to qualitative validation, a focus group discussion was held with a purposively selected group of experts.

Table 4.4 Demographic Characteristics

Variable	Category	(n = 60)	%
Gender	Male	52	86.70%
	Female	8	13.30%
Water Experience	Less than 5 years	23	38.30%
	5–10 years	15	25.00%
	11–15 years	9	15.00%
	More than 16 years	13	21.70%
Organization Type	Consultation & Contracting Engineering	45	75.00%
	Utility	5	8.30%
	Technology Providers	8	13.30%
	Research / University	2	3.30%
Digital Experience	Yes	27	45.00%
	No	33	55.00%

Table 4.5 Focus Group Subjects

Participant	Organization Type	Position Role	Years of Experience
P1	Consultation and project management firm	Digital Engineering Innovation Manager	16
P2	Consultation and project management firm	Infrastructure Manager	18
P3	International consultation, contracting, and project management firm	Construction Manager	22
P4	International consultation and contracting Management firm	Global Head of Digital Sustainability	26
P5	International Consultation firm	Infrastructure Project Director	32
P6	International Consultation and Project Management firm	Digital Practice Director, Regional BIM Strategy Leader	23

Table 4.5 presents the profile of the participants in the focus group discussion, all of whom hold key management or strategic roles in the international or regional consulting, contracting, and management firms. The participants also have significant experience in the field, ranging from 16 to 32 years, and are actively involved in digital innovation, infrastructure management, or the digital strategies of their respective firms.

#### 4.4.3 Survey Barriers Results

Figure 4.2 illustrates the average scores for respondents' views on the key barriers to the adoption of Digital Twin (DT) technology in the planning and design of water projects. The results suggest a strong focus on data-oriented barriers. Cybersecurity of data, data availability, and data ownership are identified as the key barriers, ranking first and second, respectively, with scores of 3.80-3.87. This reveals the respondents' extra caution regarding data protection and access in the scenario of adopting DT technology in a cautious water project setup.

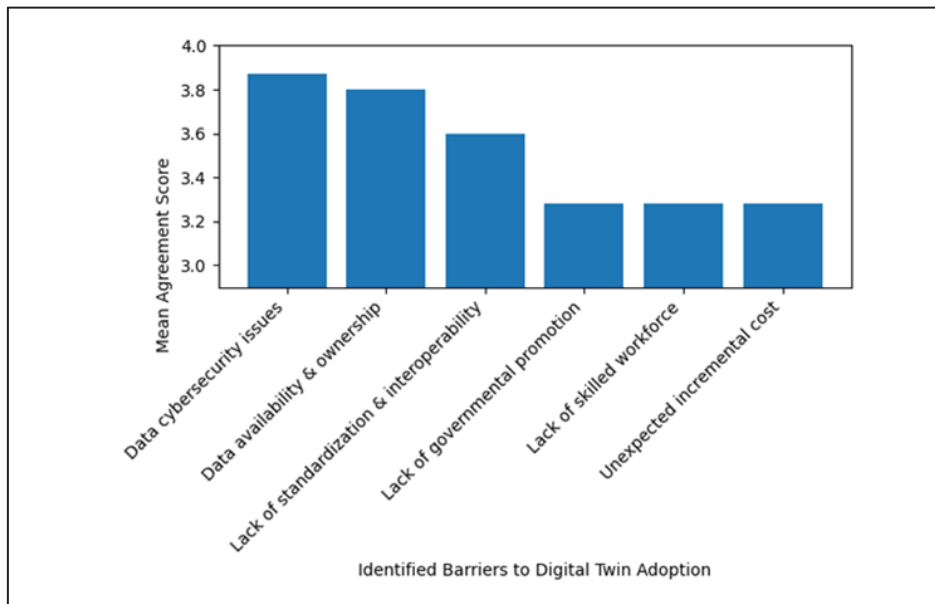


Figure 4.2 Survey results of perceived Digital Twin adoption barriers

A lack of tools for standardization and interoperability ranked third as the most problematic issue ( $M = 3.60$ ), underscoring that interoperability issues across different digital systems and formats have been a constant source of difficulty in implementing DT solutions. This finding

again implies that technical incompatibilities have been a significant source of problems. Those barriers related to the general enabling environment were considered to have a medium level of influence. The absence of government support ranked fourth ( $M = 3.28$ ), suggesting that policy guidance is important but secondary to other considerations in the DT adoption process. Similarly, the absence of trained and skilled staff and unexpected incremental development costs received similar mean scores, suggesting that human capital issues and costs are considered concerns but are secondary in importance at this juncture in DT adoption.

#### **4.4.4 Qualitative Focus Group Results**

The focus group discussions were conducted to validate and refine the survey's quantitative results and to gain insights from experienced professionals. The five experts engaged in critical reflection on the identified barriers. The final ranking task, carried out at the end of the focus group discussion, is presented in Figure 4.3 and captures the relative importance of the identified barriers from the focus group's perspective.

BR9 (Workforce Skills and Digital Capacity), as shown in Figure 4.3, was identified as the most evident barrier among all participants. The lack of digital skills and workforce readiness was cited as the major obstacle in the adoption of Digital Twins. One participant stated, “Many contractors lack qualifications and skilled people who can meet the increasing demands of digital project requirements.” Another stated that workforce problems were “the most complex barrier, as companies are unwilling to offer workforce training programs and instead look for online solutions that have been ineffective.” The need for a highly skilled workforce was also highlighted for complex tasks involving digital twins, such as “utility clash detection, data-driven modeling, and system integration.”

BR1 (Cybersecurity issues) was also considered among the most important barriers, though there were divergent views. Some experts considered data cybersecurity a major threat, especially given the dangers posed by outdated technology and cyberattacks. In contrast, others were satisfied with the regulatory frameworks in Dubai and Abu Dhabi to ensure data cybersecurity and noted similarities in data cybersecurity across the financial sector.

In relation to the availability and ownership of data (BR2), the focus group discussions added to the survey results by emphasizing the quality rather than the quantity of the available data. The participants identified the challenges of inaccurate, outdated, and disparate as-built data for utilities and digital infrastructure. The inconsistency between the project stages and the data standards is said to affect the accuracy of reverse engineering tasks, potentially leading to design errors and system malfunctions. Though participants agreed that data availability has improved in recent years, the challenges associated with data accuracy, relevance, usefulness, filtering, and analytics remain substantial.

The barrier of standardization and interoperability tools (BR11) was viewed as lessening in severity. This is because respondents felt that while compatibility issues with software and data loss in platform exchanges have not disappeared, these problems have been reduced by open data standards and client requirements. Some respondents felt that the constraints of interoperability have become less of a driving force in inhibiting DT despite some compatibility issues that require developer attention.

Likewise, the unexpected additional cost for implementing DT (BR6) was not considered a significant issue by the focus group respondents. Experts concur that cost issues can be addressed and mitigated through effective procurement practices and early-stage planning. Although DT systems with full functionality are pretty costly at present, respondents argued that efficiency gains and quality-of-work improvements make additional expenditures worthwhile for large-scale projects and public-sector projects. Additionally, market competition and regulatory compliance cannot be sacrificed for the sake of additional costs.

Regarding government and regulation (BR14), participants saw the government's role as both an enabler and a regulator in the adoption of DT as crucial. Although some participants seemed satisfied with the current regulations requiring the digital submission of documents, others advocated stricter regulations and mandates, as well as the need for structured governance of data security and privacy.

Additionally, all respondents emphasized the influence of resistance to change and the culture's mindset on DT adoption. Resistance to change is attributed to a lack of awareness, a lack of

understanding of the benefits, and a lack of case studies on successful implementation, all of which were emphasized as barriers to adopting the DTs. On the whole, the results from the focus group are primarily in line with those from the survey study, yet they offer subtle contextual information. In particular, workforce readiness and data governance have proven to be even more significant than financial considerations, thereby supporting the study's primary assumption and enhancing the credibility of the research methods used.

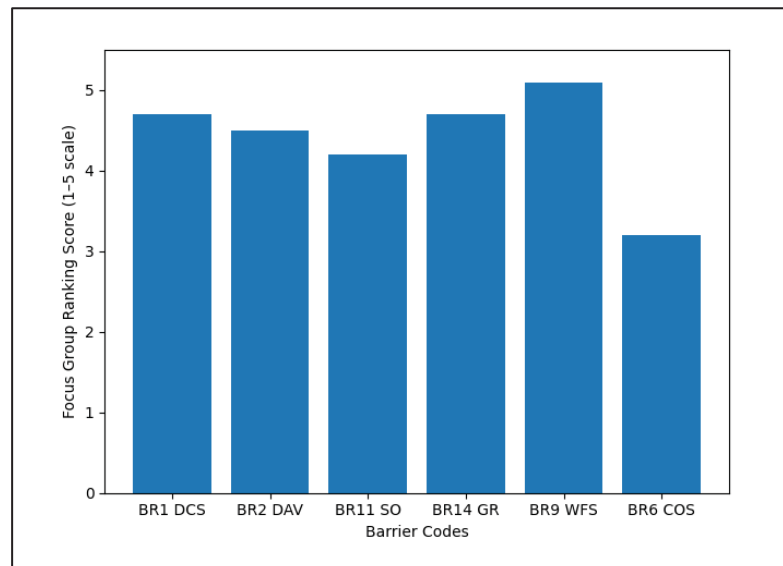


Figure 4.3 Focus group-based ranking scores of adoption barriers

#### 4.5 Results Discussion

Analysis of the findings shows that professionals in the United Arab Emirates believe that the adoption of Digital Twins (DTs) is hindered more by data- and knowledge-related factors than by costs, thus validating the underlying hypothesis of this study. At the macro level, the findings of this study indicate that respondents ranked data cybersecurity, availability, and ownership; standardization and interoperability; and digital literacy of the workforce, as well as limited government support, as the most important factors, followed by incremental costs. These findings emphasize the importance of having a strong data infrastructure and its ability to withstand risks in the water infrastructure sector.

This result supports the existing literature, which points to data governance and security-related problems as key hurdles to adopting digital technologies (DTs) and other advanced digital

solutions. Opoku et al. (2023) identify data-related problems as among the most critical for adopting DT across various construction settings. Others, such as Broo and Schooling (2023) and Ford and Wolf (2020), reported problems related to data compatibility, data ownership, and the transfer of such data within the limitations imposed by technological and organizational constraints. In the area of special focus related to the water sector, Rapp et al. (2023) find that data-related complexities pose significant hurdles to the adoption of artificial intelligence in U.S. water service organizations. Schmidt et al. (2024) also find that technological challenges, such as data-related issues, have been key in slowing digital transformations due to uncertainties about data accuracy and trust.

In addition, the constraints posed by standardization and interoperability are listed as the third most significant factor, indicating that software incompatibility issues, data loss during transfer between platforms, and discrepancies in data schema are still hampering the implementation of the DT. These results align with those of Beal & Flynn (2015), who studied smart metering implementation in Australian water services, and with those of Waqar et al. (2023), who examined DT implementation in smart cities in Malaysia. Cheng et al. (2016) also considered data standardization important for water system assets to facilitate smooth data transfer throughout their life cycles. This supports the view that the data structure in the early stages of DT implementation is important for facilitating early integration of DT and maximizing data capture, as ATKINS (2017) proposed in their report.

As far as the UAE case is concerned, Alzarooni et al. (2024) found that aligning the digitalization process in the public sector with government-initiated digital projects improves digitalization outcomes; however, concerns remain about data security, integration, costs, and return on investment. The current study supports the above observations.

Even though the survey participants listed governmental promotion, workforce skills, and the cost of incremental development as moderate rather than major factors, the relevance should not be overlooked. It is crucial to have a skilled workforce to facilitate teamwork, enhance productivity, and help in practical use, as seen in water utilities and the construction industry (Beal & Flynn, 2015; Opoku et al., 2023; Broo & Schooling, 2021; Callcut et al., 2021). Moreover, the research by Manny et al. (2021) showed that vision and resources are more

important than institutional structures for the use of digital data in wastewater management. This aligns with the views expressed by Broo and Schooling (2021).

Depictions of unexpected incremental costs were not extreme, suggesting that concerns about costs may stem from uncertainty and misunderstanding rather than a lack of financial resources. As indicated by Beal and Flynn in 2015, the costs have long been overstated because of their measurability relative to the other barriers. Current research shows that the implementation of DTs can be cost-effective if the fidelity of the system is appropriately specified (Kober et al., 2023), and there has been progress made regarding the lowering of costs for the implementation of DTs for water management (Ghaith et al., 2022; Bartos & Kerkez, 2020).

By integrating the findings from the focus group discussions, a more refined, micro-level perspective on the barriers can be achieved. As shown in Figure 4, the focus group discussions not only confirmed the survey findings but also further structured them into a two-level framework, separating confirmed, refined, and new barriers. Though some barriers, such as cybersecurity issues and the role of the government, were confirmed, others, such as the focus on data quality rather than quantity, were refined. More importantly, digital capability in the workforce was found to be the most important barrier at the micro level, even more important than data issues. Participants noted the lack of a qualified, skilled workforce, the ineffectiveness of training programs, and the unavailability of subject-matter experts to address complex issues. This again supports the view that the eventual implementation of DT is limited by the availability of human resources, even when the technical solution is available. Moreover, through focus group interviews, cultural resistance and mindset lock-in emerged as significant issues in relation to the adoption of DT. Lack of knowledge about the advantages of DT, resistance to change, and skepticism due to the absence of proven successful examples were recognized as important factors in adoption reluctance. The dissemination of success stories about the application of DT, encouraging whole-life-cycle thinking, and integrating digital technologies into the early planning/design phase were recognized as important for changing mindsets and promoting adoption.

In conclusion, the two-level analysis shown in Figure 4.4 indicates that although the macro-level survey emphasizes the importance of structural and technical aspects, the micro-level qualitative research highlights the underlying workforce factors and cybersecurity issues that influence DT adoption. Taken together, these results support the argument that the barriers to the adoption of DT in the planning of water projects are much broader than just cost constraints.

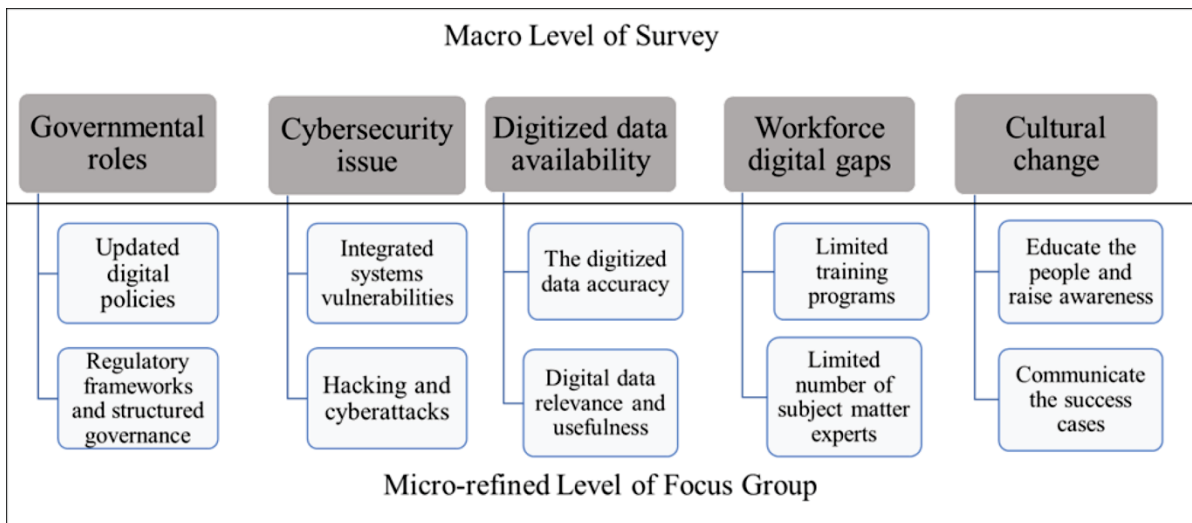


Figure 4.4 Two-level insight framework analysis of survey and focus group findings

The difference in rankings between survey and focus group approaches, as shown in Figure 4.5, provides further insight into how barriers to Digital Twin (DT) implementation change as a more refined, qualitative perspective is adopted. While the survey results ranked barriers based on data and technical limitations, the focus group discussions placed greater emphasis on workforce digital capability (BR9) as a key barrier, followed by cybersecurity and data governance.

The emphasis on workforce digital literacy factors can be explained, in part, by the lack of alignment between academic programs and industry requirements in engineering departments, particularly due to outdated curricula in educational institutions. Collaboration between industry and universities has been identified in the literature as a major approach to innovation and closing the skills gap in construction and infrastructure workforces. Various studies have indicated the need to create collaborative consortia involving universities and industry companies to facilitate knowledge sharing, enable technology transfer through empirical

studies, and support continuous curriculum updates (Lavikka et al., 2020; Ankrah & Omar, 2015; Fernandes, 2023). This approach has immense potential to advance the development of Digital Twins in water resources by increasing focus on university engineering departments and AEC companies' workers in tandem.

Cybersecurity issues (BR1) were also reiterated as ever-present risks against the adoption of DT. The integrated approach of DT systems, which combines several technologies and heterogeneous data sources, makes them more vulnerable to cyber-attacks. Cybersecurity issues also underscore the need to implement effective data protection measures. The respondents pointed out limitations in digitized data, specifically the lack of as-built data, and mismatches between the data sources and the data needed for the projects, which have led to malfunctions in engineering tasks. The focus group discussion further clarified the problem statement by emphasizing the importance of data quality over data availability. Data accuracy, usefulness, filtering, and relevance are more important and deserve greater attention. This position aligns with the views of Eggimann et al. (2017), who noted limitations in using data for urban water management due to data quality issues, data processing complexity, data ownership issues, and cost factors.

Besides, the issues related to DTs development and integration, including the enabling technologies and reliance on heterogeneous data sources, make the role of standardization and the use of standard data formats even more important. It was, however, acknowledged that while interoperability issues have reduced over time, software limitations and incompatibilities remain significant. Such issues can be intricately linked to employee competencies, as complex technologies require not only technically competent employees but also subject-matter experts in their respective domains. Water projects, which are associated with interdependencies, interconnectedness, and legacy data issues, further struggle with these challenges.

Cost-related barriers (BR6) were seen as less important than in previous stages of digital technology adoption. Understanding the objectives of DT at the beginning of the project lifecycle enables organizations to identify the required level of model sophistication and prevent the addition of unnecessary technological complexity. The importance of this has been explained by ATKINS (2017) using the definition of six levels of DT maturity and by Kober

et al. (2023) using the idea of the fidelity of DT models as the level of abstraction and precision required for the desired results.

Regulatory uncertainty and the inability to strictly enforce the regulations are also listed as barriers to the adoption of DT. The participants have strongly emphasized the importance of the government acting as both a facilitator and a regulator to foster innovation, ensure data security, and protect public interests. The additional costs associated with technology are considered a weak barrier to DT; these costs are now largely offset by the efficiency and quality gains they enable. One significant aspect of the qualitative research results is the recognition of ‘cultural resistance/mindset inertia’ as a new barrier. This is because it encompasses resistance to change, a lack of awareness of DT's benefits, and skepticism due to the absence of verified case studies. The respondents stressed that whole-life-cycle thinking, communicating successful implementation stories, integrating digital technology into the early planning/design phase of projects, and cultural change are critical to achieving digital transformation success.

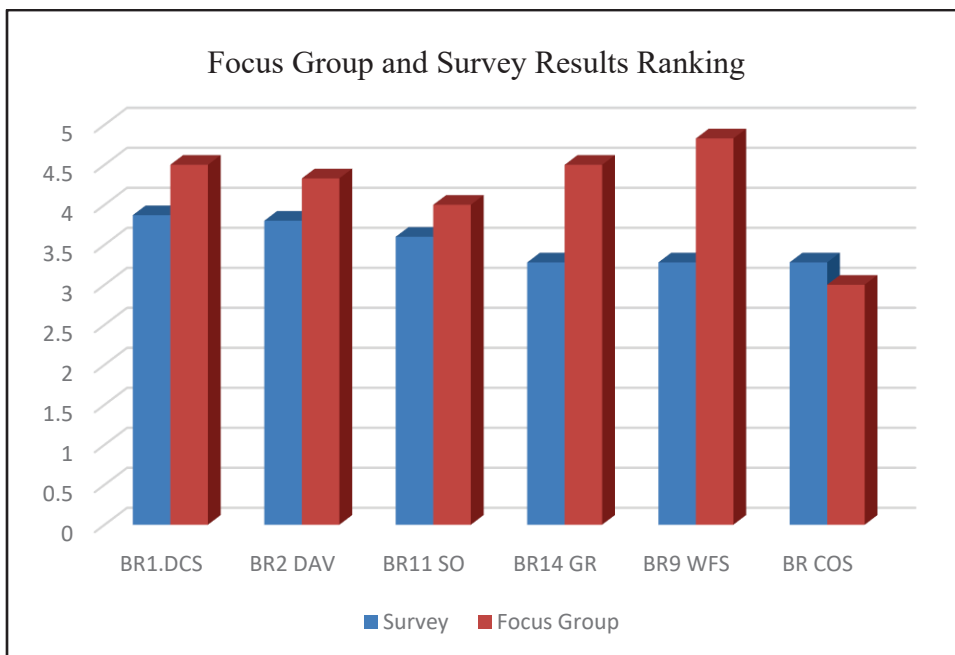


Figure 4.5 The Barriers Ranking across the Two Results

In conclusion, based on the ranking displayed in Figure 4.5, the micro-level findings obtained from the focus group sessions clearly indicate that, in addition to the barriers and limitations identified in the macro-level survey findings, workforce and cybersecurity limitations exist in the micro-level that can only be addressed through multi-faceted approaches, including organizational development, governmental interventions, and cultural change in the UAE water project management. The findings thereby support the conclusion that, beyond financial limitations, other barriers to adopting DT in the UAE water project management sector must be addressed through multifaceted approaches. Additionally, by addressing the barrier in the water sector, other sectors in the UAE might benefit from adopting DT in their operations and functions.

#### **4.6 Results Implications**

The results yield several implications for policymakers and AEC professionals regarding the promotion of Digital Twins (DTs) in the planning and design of water projects. Firstly, the prevalence of results associated with data governance issues underscores the critical and pressing need for comprehensive, effective government regulations on data cybersecurity, ownership, and compatibility (Broo & Schooling, 2023; Callcut et al., 2021; Ford & Wolf, 2020). The integration of DTs into the early planning and design stages of water projects and construction, rather than after construction, can significantly improve data quality and support the comprehensive data models (ATKINS, 2017; Cheng et al., 2016). The use of regulatory mandates and incentive-driven policies, as in Dubai's past BIM mandates, can significantly facilitate the integration of DTs and mitigate hesitation in their adoption (Bakar et al., 2020; Alzarooni et al., 2024).

Organizational-level implications of the findings include a clear indication that a water utility or AEC organization's digital capability within its workforce is a crucial enabling factor for DT implementation, often outweighing financial factors. Water utilities and AEC organizations must therefore invest in their workforce's future skills, train them, and hire experts with a deep understanding of managing complex systems (Broo & Schooling, 2021; Opoku et al., 2023). Firstly, industry-university collaborations are an effective way to address a lack of workforce

digital skills and readiness for DT implementation. This can be achieved by aligning university curricula with industry requirements and engaging in joint DT pilot implementations and validation of new and emerging DTs (Ankrah & Omar, 2015; Lavikka et al., 2020; Fernandes, 2023). This can help organizations implement DTs and achieve efficiency and sustainability goals without burdening their financial systems (Beal & Flynn, 2015; Kober et al., 2023). Secondly, collaboration between technology providers and the AEC firms in designing and conducting training programs, attending seminars, and enrolling in workshops to upgrade workforce digital capacity and fill the digital literacy gaps will be an effective approach. In sum, cross-disciplinary collaborations to upgrade workforce digital capacity, structured data governance, regulatory frameworks with clear mandates, communicating successful case studies, and educating stakeholders will be beneficial to overcome current barriers and promote the DTs adoption and integration in the water planning and design projects workflow.

#### **4.7 Conclusions and Limitations**

This study investigated the adoption of Digital Twin technologies in the planning and design of water projects in the UAE, a digitally advanced, non-financially constrained context. The research employs a mixed-methods approach that combines the findings of a survey study with insights from a focus group validation. The findings reveal that the constraints to the adoption of Digital Twin Technologies are not only budgetary; data management, workforce digital capabilities, and the organization's readiness are key barriers that need to be addressed. This is evidenced by the appearance of key constraints in the survey, including data security, data quality, ownership, and data interoperability.

When comparing the survey results and the focus group findings, it becomes clear that while data and technique issues are generally recognized at the macro level, workforce and organizational issues come into sharper focus at the micro level. Findings from the focus group enable more precise articulation of some barriers to recognizing the importance of data relevance over data availability, and to identifying cultural and mindset issues with the level of detail not easily achieved through more technique-driven approaches. Findings emphasize

the role of early-stage decision-making in planning and design in influencing the implementation of Digital Twins.

The research has several practical implications. This research pushes the frontiers of knowledge regarding DT adoption by presenting an argument against cost-focused discourses in favor of an analytical two-tier model that distinguishes between macro-structural factors and micro-constituents. From an empirical standpoint, this research represents one of the few early studies in the Middle East to examine DT adoption in water project management, drawing on knowledge from a region that leads the digital transformation agenda. It provides recommendations for government policymakers, water organizations, technology providers, and AEC companies on best practices for data governance structures and trust, employee competencies, and cultural change

This research has several limitations that should be considered when interpreting the findings. First, the number of participants is fairly small, but it targeted a particular group of professionals with sufficient knowledge of DT technologies, with a focus on the United Arab Emirates, specifically Dubai. While this targeting is valid given the exploratory nature of this research, as well as the current infancy stage of the adoption of DT technologies for water project planning and design, the findings of this study would not be generalizable over other geographical locations. Further, this study has used purposive, or snowball, sampling, even though, valid for accessing knowledgeable stakeholders in emergent technology fields, could be subject to selection bias, favoring those with prior exposure or interest in digital transformation initiatives.

Secondly, the research primarily focuses on experts' perceptions rather than on actual data on the implementation success of Digital Twins. Although the research design offered the benefits of a mixed-methods approach and validation across groups, the self-reported data could have been influenced by views shaped by personal experience, organizational settings, and personal expectations. Further, the few successful implementations of Digital Twins in the water utility space and the high confidentiality of cost data limit the scope for comparing perceptions with actual performance data. Longitudinal future studies could provide valuable insights into the

impact of barriers on the success of Digital Twin implementation over time. Next step could be a focus group to discuss and validate the benefits.

## CHAPTER 5

### **DIGITAL TWIN ADOPTION DRIVERS AND PERCEIVED PROJECT SUCCESS IN WATER INFRASTRUCTURE PROJECTS: UAE STAKEHOLDERS' PERSPECTIVE AND GLOBAL CASE EVIDENCE**

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- Explores key drivers influencing Digital Twin adoption in UAE urban water systems.
- Mixed-methods approach integrating quantitative and qualitative data.
- Optimize performance, reduce costs, and manage safety as critical drivers.
- Regulatory compliance is underrecognized in local perceptions but vital globally.
- Insights for policy and strategy makers to advance digital transformation.

#### ABSTRACT

Digital Twinning (DT) technologies are strategically promoted to enhance planning, construction, operation, and management of water projects. However, empirical adoption drivers and the project success remain unexplored, particularly in developing contexts. This study investigates these factors using an exploratory descriptive mixed-methods design. Firstly, it surveys experienced stakeholders, mainly CEOs, decision-makers, and senior technical managers in the United Arab Emirates (UAE), a non-financially constrained environment. Then triangulates by using synthesized qualitative data on global water DT implementations. The survey reveals a consensus that performance optimization, leveraging data to reduce costs, asset-risk mitigation, and public-safety management are key drivers of DT adoption. However, perceptions of cost reduction and customer service exhibit disagreement, reflecting varying organizational priorities. Triangulation with global cases corroborates the findings and highlights regulatory compliance as a more dominant driver internationally than perceived within the UAE context. Across both datasets, digital twinning initiatives are associated with positive perceptions of project success, evident in goal achievement and team satisfaction. The study provides insights for policymakers in the UAE, underscoring the need for adaptive regulatory frameworks, coordinated governance structures, and clear mandates that link DTs deployment to asset management and sustainability outcomes. The results add to the emerging literature on digitalization in critical infrastructure

by identifying empirical drivers of adoption. Besides, it offers a perspective on assessing water project success to inform stakeholders and future research directions.

**Keywords:** Drivers, Digital Twin technologies, Qualitative case studies, Project success

## 5.1 Introduction

The digitalization of urban environments is increasingly recognized, with cities adopting advanced technologies to improve operational management (Ablyazov, 2021; Hämäläinen, 2020). Urban systems cannot escape the digital approach; it has become a necessary shift rather than an optional strategy (Tang et al., 2019). Among emerging technologies, Digital Twins (DTs) have gained significant attention for their ability to replicate physical assets, systems, and processes in real time by integrating sensing into interconnected data platforms (Naderi & Shojaei, 2023; Jiang et al., 2021). DTs provide enhanced visualization, performance monitoring, and scenario-based simulation within a risk-free virtual environment. This has led to widespread applications across infrastructure planning, design, and operational management (Schrotter & Hürzeler, 2020; Ghaith et al., 2022; Grieves & Vickers, 2017). A global investment in DTs is expected to reach USD 48 billion by 2026 reflecting this momentum (McKinsey, 2022).

Despite their potential and significant investment projections, the adoption of DTs within the water sector remains relatively limited. Industries such as manufacturing, aviation, and construction have made advanced progress in DT deployment. However, design and construction of water projects and water utilities continue to lag, facing barriers in transitioning to the advanced digital tools (Piras et al., 2024; Müller-Czygan et al., 2021). Understanding what drives DT adoption is therefore crucial; prior research on technology adoption highlights that it is influenced by interacting factors, including drivers and organizational priorities (Hochscheid & Halin, 2019; Yang & Chou, 2019). Drivers, in particular, guide decision-makers and help shape expectations about the value and potential of new technologies (Arowoia et al., 2024; Opoku et al., 2022). According to Danielsen (2021), drivers are factors that motivate organizations to start digitization or digital transformation. Identifying these drivers across different domains can clarify understanding of adoption pathways and inform policy and investment decisions (Eadie et al., 2014).

Although several studies have examined factors influencing DTs adoption in the built environment and construction sectors (AlBalkhy et al., 2024; Agrawal et al., 2022; Feng et al., 2021), empirical insights in water projects remain limited, even in developed contexts (Schmidt et al., 2024). Early-stage evidence, in light of limited implementations, often relies on expert knowledge rather than full-scale application outcomes, making experienced stakeholders a vital source of information on both adoption drivers and project success evaluation (Yang & Chou, 2019). Given that project success of water projects, like other infrastructure projects, generally faces financial constraints and other technical challenges.

The United Arab Emirates (UAE) offers a relevant context for such an investigation. The UAE, especially Dubai, has led the digital transformation in the Middle East, as a non-financially constrained leader. This has been catalyzed by initiatives like the 2013 BIM mandate and the 2021 Digital Dubai program (Autodesk, 2021). Although the UAE faces severe water security challenges, it has gained worldwide recognition for digital innovation. This was demonstrated by the 2024 Smart Water Project of the Year award for Dubai Hydro Insight (Jones, 2024). The country's digital readiness and the presence of visionary leadership position UAE stakeholders well to offer valuable insights into DT adoption and implementation (Yaseen et al., 2023; Noori et al., 2020).

This study addresses literature gaps on the adoption of DTs in water projects by examining the drivers and perceived project success factors based on the experiences of UAE stakeholders. Then, triangulating these findings with global DT case evidence. The study pursues three objectives:

1. Identify the key drivers of DTs adoption based on experienced perceptions of water projects implementation.
2. Investigate the project success evaluation of early adopters in terms of delivery achievement and stakeholder satisfaction.
3. Contextualizing the findings in global real-world case studies to gain deep understanding.

The remainder of the paper is structured as follows: section 5.2 reviews relevant literature; section 5.3 presents the research methodology; section 5.4 presents the results and discussion;

and section 5.5 concludes with key findings, acknowledges the limitations, and recommends future work.

## **5.2 Literature Review**

### **5.2.1 Digitalization Adoption Drivers**

Digitalization is a sociotechnical process that attempts to transform and adapt organizational processes into digital counterparts (Daniel et al., 2023). Adopting DTs in the built environment, including urban water systems, has gained increasing recognition; Opoku et al. (2023) reported a dramatic increase in construction publications since 2021. Digital twin technologies are presented as integrated solutions for water systems, rather than merely models of data connections by Curl et al. (2019) and Callcut et al. (2021). However, the adoption process faces numerous barriers and is slowly penetrating even in developed countries, as reported by Naderi & Shojaei (2023), Broo & Schooling (2023), Bartos & Kerkez (2020), and Schmidt et al. (2024).

Cambridge Dictionary (2025) defines a driver as “something that makes other things progress, develop, or grow stronger.” Therefore, adoption drivers promote adoption, enabling it to develop, evolve, and advance (Hochscheid & Halin, 2019). According to Butler & Sellbom (2002), technology adoption rates are affected by various factors, including innovation characteristics and economic, organizational, sociological, and psychological variables. Understanding the adoption rate involves analyzing factors that facilitate or hinder adoption. Researchers have identified many drivers of digital technology adoption, like DTs, but a significant effort is needed to classify, evaluate, assess, and prioritize them across domains and applications.

Callcut et al. (2021) examined the definitions, concepts, and applications of Digital Twins (DTs) in civil infrastructure. They emphasized that DT use is still evolving, citing this barriers as a key factor. For water systems, they underscored that data transparency through open standards and application programming interfaces APIs is essential for DT growth, allowing access for developers and investors, fostering innovation, and building trust. The study

indicates that UK industry and academia are aware of DTs, but lack a clear understanding due to vague definitions.

Beal & Flynn (2015) examined the digitalization of water utilities in Australia and New Zealand, driven by social factors such as customer satisfaction, community acceptance, and trust. Besides, economic drivers include lowering operating costs, reducing wholesale water, delaying infrastructure upgrades, improving meter accuracy, and reducing non-revenue water. The study emphasized the importance of utility-specific conditions and the location of value gained from digital transformation.

Opoku et al. (2022) conducted a systematic review to identify 50 drivers of digital twin (DT) technology in construction, grouped into four categories: concept-oriented, production-driven, operational success, and preservation-driven. They found concept-oriented drivers, such as real-time data visualization, streamlining design, decision-making, promoting sustainability, digital transformation, enhancing design delivery, optimizing materials, enabling smart services, effective planning, technical solutions, supporting social impact, and creating value, were the primary drivers for DT adoption. Opoku et al. (2023) noted that developing countries contribute little to DT research, while developed nations such as the UK, the US, and Australia lead globally.

Boyle et al. (2022) reviewed the digital transformation of water organizations and indicated that it was driven by emerging technologies, social trends, regulatory updates, and the need for efficiency and improved customer service. Barriers like the need for corporate-wide digital governance, skills, knowledge, culture, and unified data management are noted. They insisted that water organizations are monopoly institutions focused on public service, and face unique challenges. Success depends on understanding organizational complexity, relationships, interdependencies, and digital maturity, necessitating long-term planning and strong commitment.

Arowoia et al. (2024) investigated the drivers of DT adoption in Nigeria's construction industry. The key drivers of DT implementation include technological progress and trends, data storage reliability, customer satisfaction, safety, and the availability and accessibility of software. The study emphasizes the crucial role of stakeholders' desire for innovation and progress, which can be fostered when technology aligns with stakeholders' expectations.

Table 5.1 Drivers to the application of DTs for Water Projects

Drivers of DT adoption	References
DR.1 Future Forecasting and benchmarking of peak floods or peak demand for best management	(Beal & Flynn, 2015), (Danielsen, 2021), (Bartos & Kerkez, 2021), (Ghaith et al., 2022), (Li, Feng & Han, 2022)
DR.2 Public safety management	(Bartos & Kerkez, 2021), (Ghaith, M., Yosri A., & El-Dakhakhni, W. 2022), (Li, Feng, & Han, 2022), (Yang et al, 2021)
DR.3 Defer new infrastructure augmentation & planning, and defer capital expenditures CAPEX	(Beal & Flynn, 2015)
DR.4 Leverage data to reduce operational costs (OPEX)	(Beal & Flynn, 2015), (Danielsen, 2021), (Boyle, et al, 2022), (Opoko et al, 2022), (Arowoiya et al, 2024), (Wu et al, 2023), (Li, Feng & Han, 2022)
DR.5 Improve simulation models, meter reading accuracy, and increase reliability in the software utilization	(Beal & Flynn, 2015), (Danielsen, 2021), (Ghaith et al, 2022), (Alperen et al, 2021), (Bartos & Kerkez, 2021)
DR.6 Reduce manual reading and the associated labor, costs, and health and safety issues (OHS)	(Beal & Flynn, 2015)
DR.7 Optimize performance and increase work efficiency	(Beal & Flynn, 2015), (Boyle, et al, 2022), (Opoko et al, 2022), (Danielsen, 2021), (Wu et al., 2023)
DR.8 Safety and risk management of the asset pipe networks	(Opoko et al, 2022), (Wu et al, 2023) (Li, Feng & Han, 2022), (Yang et al, 2021)
DR.9 Regulation compliance	(Danielsen, 2021), (Boyle, et al, 2022), (Opoko et al, 2022)
DR.10 Improve customer/client services (satisfaction, billing, community acceptance, customer trust, public engagement)	(Beal & Flynn, 2015), (Boyle et al., 2022), (Opoko et al., 2022), (Arowoiya et al., 2024)
DR.11 Keeping up with new technology and driving innovation	(Boyle, et al, 2022), (Opoko et al., 2022), (Arowoiya et al., 2024)

Based on this review, it is apparent that efforts in the water domain are still in their early stages, warranting further consideration and studies. Table 5.1 presents drivers based on academic papers, along with their respective citations.

### **5.2.2 Project Success**

Digitalization has provided practical solutions over the past five years to address the growing challenges in urban water management; however, an empirical gap remains between the solutions offered and their successful implementation (Müller-Czygan et al., 2021). The literature emphasizes the importance of project management knowledge in realizing benefits and managing successful project implementation (Fazli et al., 2014). Project management is an essential operational methodology for planning, systematically coordinating, and controlling resources, activities, and timelines to achieve defined objectives efficiently and effectively (Davis, 2017). According to Tillmann et al. (2012), the realization of project benefits should be maintained through a comprehensive lens and a holistic understanding. This extends beyond the physical asset to be understood as a means of achieving agreed-upon goals, rather than merely delivering outcomes.

Stakeholders' management is recognized as a crucial part of project management knowledge (Shaqour, 2022). Previous research on BIM adoption in the AEC industry has shown that it starts with individuals (people), then moves through processes and technologies (Eastman, 2011). Therefore, successful implementation is directly reflected in stakeholders' perceptions of project benefits and achievements, which greatly influence the adoption of digital projects (Al-Ashmori et al., 2020). According to Fazli et al. (2014), a project is considered successful if it has been delivered:

- According to its specifications
- Within budget and time
- To the satisfaction of the client, end-users, and investors
- With the help of a satisfied project team

In this context, project specifications refer to the intended outcomes outlined at the beginning and serve as the mutually agreed-upon goals for project delivery (Tillmann et al., 2012). Moreover, satisfaction is not limited to senior management; it includes all team members

involved in the project. According to Davis (2014), diverse stakeholder perceptions are essential for identifying project success factors, highlighting their central role in project management knowledge. Therefore, when success is viewed holistically, it involves not only achieving goals but also stakeholder satisfaction. Davis (2017) emphasized the critical role of stakeholder collaboration in achieving project success, noting that their individual perspectives affect outcomes and help negotiate resources and skills that are often beyond the project manager's control. Given limited access to cost information due to high organizations confidentiality regarding financial data and the difficulties in measuring benefits and identifying measurement indicators. Thus, assessing stakeholders' perceptions is considered a suitable approach for evaluating project success, especially during the early adoption phase, as discussed by Yang & Chou (2019). Additionally, literature has investigated the critical success factors in the UAE for many strategies like Public Private Partnership (PPP) for housing and infrastructure projects (Alteneiji et al., 2020; Al-Saadi & Abdou, 2016). However, this area of research lacks empirical evidence on water project management, particularly regarding the adoption of digital technologies such as DTs.

## **5.3 Methodology**

### **5.3.1 Research Design and Sampling**

This study is an exploratory descriptive investigation, essential in the early stages of adoption, that involves a limited number of water digitalization projects in the Middle East. A mixed-methods approach using primary quantitative data is triangulated with secondary qualitative data from real-world examples to contextualize and deepen the interpretation of the findings. According to Recker (2021), there are several reasons to choose a mixed-methods research design. The rationale behind this strategy is to compensate for the limitations of one method (e.g., a survey) with the advantages of another (e.g., a case study). Other reasons may include ensuring a more comprehensive observation or testing propositions that emerge inductively through another method. In general, exploratory studies involve smaller sample sizes and are limited in their ability to generalize results to a larger population. However, they can be understood as the first stage of the three-stage investigation process of exploration, description,

and experimentation, as described by Swaraj (2019). They offer preliminary insights for future investigation and help shape an informative research direction.

This study collects primary data from experienced stakeholders and then complements it with qualitative secondary data from real-world examples. Twenty-seven responses from the experienced stakeholders were analyzed for exploratory purposes. Quantitative data were collected on the perceptions of key stakeholders via a structured questionnaire in a cross-sectional mode. Purposive and snowball sampling techniques were applied to identify the targeted sample participants. The 27 responses from the experienced sample primarily comprises professionals from consultancy and contracting firms, besides technology provider companies and a utility. The self-administered online questionnaire remained open from February 24, 2025, to April 5, 2025, after distribution.

Three questions were posed to experienced participants to gather their perceptions. The questions were developed based on a literature review of digitalization drivers' studies in the construction and infrastructure, as well as project management knowledge domain. The experienced participants evaluated their perceptions on drivers' importance and the project's success, measured by goal achievement and stakeholder satisfaction. The first question asked participants to rank the importance of various drivers to influence the adoption and implementation of DTs in water projects, using a five-point scale from "not important at all" (1) to "very important" (5). Additionally, on two questions from the project management literature. The first asked stakeholders to assess the project's success in achieving its goals on a five-point scale from (1) as "not on track" to (5) as "exceeded," with an option for "not applicable at this stage" for more precise responses. The third question assessed stakeholders' satisfaction with digital water projects on a five-point scale, from 1 (least satisfied) to 5 (most satisfied), and included a "no opinion" option for flexibility and accuracy.

To triangulate the quantitative findings in a practical context and compensate for low utilities representation in the sample; a qualitative approach was used by analyzing secondary data from several case studies worldwide. The selected cases were examined in terms of business drivers, initial project objectives, and the benefits realized, as detailed in ANNEX II. After analyzing the questionnaire results, a qualitative review was carried out on six case studies involved significant effort in planning, implementing, and managing either pilot or phase

rollouts of the DTs application across various water systems. They were sourced from the websites of leading water solutions providers, such as Xylem, Bentley, KISTERS, and MOBILTEX. These case studies illustrate how drivers are applied in real-world scenarios and demonstrate the substantial benefits they generate. A links to each case example website are provided in ANNEX III

### 5.3.2 Method of data analysis

For the analysis of quantitative data, IBM SPSS Statistics software version 29.0 was used. Internal consistency was assessed using Cronbach's alpha for different components of the instrument. Descriptive statistics for demographics were analyzed to gain essential insights from the data. The assumption of normality was assessed for each item using the Kolmogorov-Smirnov and Shapiro-Wilk tests to check the null hypothesis. Then, the Kruskal–Wallis H test was used to assess significant differences in agreement among respondents' sub-groups regarding their rankings of the drivers' importance. The Kruskal–Wallis H test is a popular nonparametric rank-based test that compares more than two independent samples to test whether they come from the same distribution. This test is a powerful alternative to the one-way analysis of variance and has been shown to be effective for small samples (Siegel, 1957).

## 5.4 Results and Discussion

### 5.4.1 Reliability and Validity Results

The analysis included responses from 27 participants within the experienced group, with no missing data, resulting in a 100% valid response rate. Internal consistency reliability was assessed using Cronbach's alpha. The 11-item drivers retained high reliability ( $\alpha = .810$ ), as shown in Table 5.2. According to Taber (2018), Cronbach's alpha falls between 0.71 and 0.91 is considered good and acceptable if it ranges from 0.45 to 0.98.

Table 5.2 Reliability Results

Factor	Number of Items	Cronbach's Alpha
Perceived Drivers	11	.810

Regarding the instrument's validity, this study is exploratory and aims to initiate further discussion of the drivers of DTs adoption for water systems in the Middle East. To ensure face validity, which refers to the extent to which a tool appears to measure what it claims to measure (Leedy & Ormrod, 1980). Three academic professors and one industry expert reviewed the content and provided feedback and suggestions. After considering the recommendations and making the necessary adjustments, a small sample of civil engineers participated in a pre-test trial to ensure clarity, understanding, and timing. Additionally, to ensure the instrument's validity, the questions were derived, with slight modifications, from validated instruments in similar previous research, such as Beal & Flynn (2015), Fazli et al. (2014), and Shaqour (2022).

#### 5.4.2 Demographic Results

Table 5.3 presents the demographic characteristics of the study sample (N = 27), which reflects a strong male representation, with 88.9% identify as male and only 11.1% as female.

Table 5.3 Demographics of Experienced Participants

Demographic Variable	Category	Experienced (n = 27)	%
Gender	Male	24	88.90%
	Female	3	11.10%
Water Sector Experience	Less than 5 years	5	18.52%
	5–10 years	7	25.93%
	11–15 years	4	14.81%
	More than 16 years	11	40.74%
Organization Type	Consultation & Contracting Engineering	17	62.96%
	Utility	2	7.41%
	Technology Providers	8	29.63%
Position / Role	Project Manager or Senior level	11	40.74%
	CEO or Main Director MD	9	33.33%
	Junior to Mid-Career Engineer	2	7.41%
	Technology Provider Professional	5	18.52%

Notably, the largest share (40.7%) had more than 16 years of experience. The largest group of experienced participants works for consultation and contracting firms (62.96%), followed by technology providers (29.63%), and a relatively small percentage (7.41%) for utilities. More importantly, it is worth noting the high-level roles held by the majority of participants; they are mainly CEOs, main directors, MDs, or senior project managers, with a (74.0%) ratio. This demonstrates that the sample included not only experienced stakeholders of digital water projects, but also experts and decision-makers in their respective domains, given their years of experience and managerial roles. Not forgetting that 18.52% of the sample are technology provider professionals.

#### **5.4.3 Normality Test Results**

For scale questions, normality should be tested; the assumption of normality was assessed using the Kolmogorov-Smirnov and Shapiro-Wilk tests, testing the null hypothesis.  $H_0$  (Null Hypothesis) is: The data for the drivers is normally distributed. Results indicate that all the drivers have p-values  $< 0.05$  for both the K-S and the Shapiro-Wilk tests. Therefore, the data significantly deviated from normality, confirming non-normality. Hence, a non-parametric statistical test (e.g., the Kruskal-Wallis test) was used in further analysis of the data.

#### **5.4.4 Drivers Ranking Importance Results**

The ranking results indicate that participants emphasize operational efficiency and cost-related factors Table 5.4. Specifically, the highest-rated driver was "optimize performance and increase work efficiency" ( $M = 4.41$ ,  $SD = 0.84$ ), highlighting the crucial role of DTs in improving work performance. This was closely followed by "Leverage data to reduce operational costs" ( $M = 4.26$ ,  $SD = 0.66$ ), suggesting that financial savings from data-driven operations constitute a major motivator. The third most supported driver was "Safety and risk management of asset pipe networks" ( $M = 4.11$ ,  $SD = 0.7$ ), underlining the importance of operational factors, followed by "Public safety management" ( $M = 4.04$ ,  $SD = 0.65$ ). On the other hand, the lowest-rated driver was "Improve simulation model and meter reading

accuracy" ( $M = 2.74$ ,  $SD = 1.06$ ), indicating that while technical precision is valued, it may not be perceived as the most pressing factor in decision-making about DT adoption.

Table 5.4 Top Ranking Drivers

Driver	Mean	SD	Min	Max	R
DR7 Optimize performance and increase work efficiency	4.41	0.84	1	5	1
DR4 Leverage data to reduce operational costs	4.26	0.66	2	5	2
DR8 Safety and risk management of asset pipe networks	4.11	0.7	2	5	3
DR2 Public safety via early flood warning systems	4.04	0.65	2	5	4

Similarly, "Defer new infrastructure augmentation and capital expenditures" ( $M = 3.44$ ,  $SD = 1.19$ ) showed a wider spread in responses, suggesting varying levels of agreement among participants regarding its importance. These findings underscore that the primary drivers for DT adoption in this context are those that cause perceived improvements in operational efficiency, cost reduction, and safety management. While following the innovation and regulatory compliance lack enough support from the study sample. Conversely, the respondents are more motivated by economic and operational factors, as well as community safety management, which serve as primary drivers for adopting and implementing the digital water project.

#### 5.4.5 Agreement among the Experienced Participants

The responses from experienced participants were categorized into three sub-groups based on the organization type. These groups included leading organizations adopting digital twins (DTs) for water project applications, such as consulting and contracting firms, utilities, and technology providers. Consultation and contracting firms are responsible for planning, designing, building, and executing infrastructure projects. Local utilities or water organizations primarily handle water supply services and operations, including planning, management, and other related tasks. Technology providers develop and supply software products that deliver digital solutions. The perceptions of these three parties are crucial to the adoption and implementation of new digital technologies, given the early stage of technology penetration.

To assess their agreement on the importance of various drivers of DT adoption in water projects, the Kruskal-Wallis test was used (Siegel, 1957). The Kruskal-Wallis test is a robust nonparametric test that compares variance across more than two independent samples and is particularly suitable for small sample sizes. The Kruskal-Wallis test determines whether the samples have significant agreement and whether they originate from the same distribution. It was applied to the sample to evaluate whether there are statistically significant differences in mean ranks among drivers for experienced participants ( $n = 27$ ), segmented by organization: consultants/contractors, utilities, and technology providers.

Results in Table 5.5 show that there is a significant difference in participants' mean ranks for two drivers; first the driver "Leverage data to reduce operational costs" among the subgroups at ( $\alpha=.05$ ), with  $H(2) = 7.506$ ,  $P = .023 < .05$ , where the consultants & contractors ( $n=17$ ) subgroup reported the lowest mean rank (mean rank = 11.53). However, professionals in utilities management and technology providers recognized the role of DR.4 more than the others. This can be attributed to differences in their roles and interests, with utilities more focused on operational costs and issues (Daniel et al., 2023). Technology providers are concerned with marketing and assuring their clients of the return-on-investment ROI that can be achieved by reducing operational expenses through utilizing the data. Hence, those two groups are more aware and can recognize the role of leveraging data to reduce costs effectively.

Table 5.5 Kruskal-Wallis Test Results of Significant Differences

Drivers	Expert Company Type (Mean Rank)			Kruskal-Wallis Test	
	Consultancy/ Contractor ( $n=17$ )	Utility ( $n=2$ )	Technology provider ( $n=8$ )	Test Statistic ( $H$ )	$P$ - value
DR.4 Leverage data to reduce operational costs	<b>11.53</b>	<b>23.00</b>	<b>17.00</b>	<b>7.506</b>	<b>0.023</b>
DR.10 Improve customer service	<b>15.76</b>	<b>19.00</b>	<b>9.00</b>	<b>5.994</b>	<b>0.050</b>

In addition, there is a statistically significant difference in participants' mean ranks for the business driver "Improve customer /client services" among the three subgroups at ( $\alpha=.05$ ), with  $H(2) = 5.994$ ,  $P = .05$ , where the technology providers subgroup reported the lowest and utilities

the highest mean rank, 9.00 and 19.00, respectively. This supports the previous research findings which show that utilities prioritize customer engagement and satisfaction (Beal & Flynn, 2015; Daniel et al., 2023). For the remaining drivers, differences among subgroups were not statistically significant ( $p > .05$ ), and the ranking agreements were accordingly confirmed. This indicates that the sample subgroups concurred on the importance of the remaining drivers that include optimized performance, public safety management, and asset risk management.

#### 5.4.6 Project Success Assessment

The concept of project success is widely discussed in project management literature. Two questions from previous literature on project management success, as well as the Beal & Flynn (2015) study, were used to gather data from experienced stakeholders. The respondents' expertise in the water sector, their managerial roles (CEOs, DMs, and senior managers), and their involvement in digital projects and familiarity with project management and success evaluation, gained through decision-making roles. This supports their relevance and suitability for evaluating project achievement, making them well-suited for assessing project success. The sample reported their perception of how goals were achieved and their level of satisfaction with the outcomes.

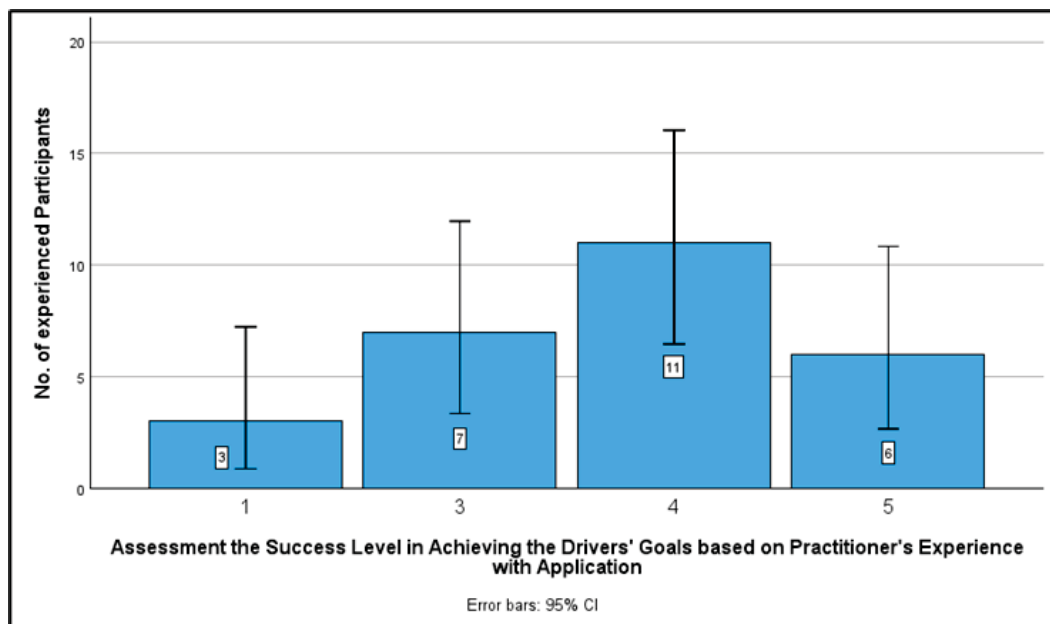


Figure 5.1 Distribution of Assessment for Goals' Achievement

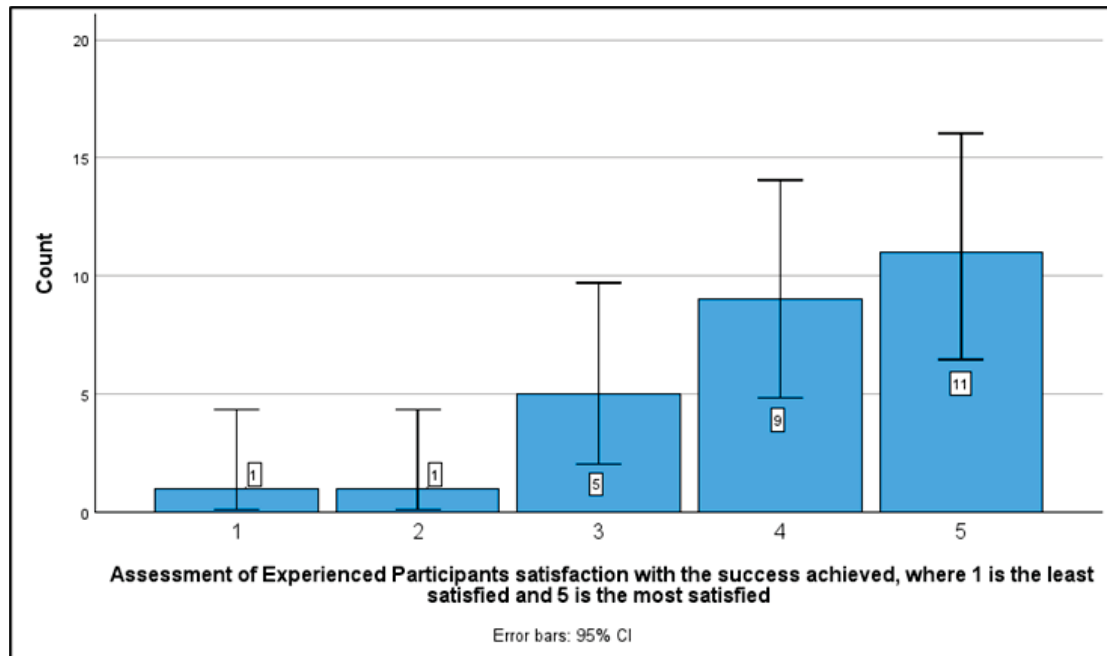


Figure 5.2 Distribution of Assessment for the Satisfaction Level

As shown in Figure 5.1, (62.3%) of respondents perceived successful implementation: (11) participants reported that the goals were “Achieved”, and (6) reported “Exceeded”. While only (3) participants (11.1%) believed the project’s success was “Not on track”. Responses to satisfaction ratings closely mirrored the previous perception results. Twenty participants (74.0%) reported high satisfaction, selecting levels 4 or 5, with eleven participants (40.7%) giving the highest possible satisfaction rating. In contrast, only two participants (7.4%) expressed low satisfaction, selecting ratings of 1 or 2. Figure 5.2.

#### 5.4.7 Case Studies Analysis

To contextualize our results in a real-world context, six digital water examples from utilities' real projects were selected and analyzed across three main areas of interest: business drivers, initial objectives, and the benefits achieved after implementation. Some of these cases involved full rollouts, while others were pilot studies applied to actual systems with plans to expand in the future. Several key drivers emerged from the case study analysis, primarily environmental protection agency EPA federal consent, regulatory compliance, keeping up with technology,

environmental commitment, and managing with advanced digital tools, as well as participating in the municipalities or cities' initiative program.

Additionally, other drivers include improving customer service, optimizing performance, reducing OPEX and CAPEX, mitigating flood impacts, and other areas, as discussed in this section. Table 5.6 presents the survey's significant drivers and their frequency of appearance in real-world utilities examples.

Table 5.6 Drivers supported by real-world examples against survey results

Rank in survey	Drivers of the Survey Analysis	Frequency in Case Studies					
		CS 1	CS 2	CS 3	CS 4	CS 5	CS 6
1	DR 7 Increase network operational efficiency and optimize performance	×	×	×	×	×	
2	DR 4 Leverage data to reduce operational costs	×	×	×	×	×	×
3	DR 8 Safety and risk management of asset networks	×		×	×		×
4	DR 2 Public safety via early flood warning systems	×	×		×		×
5	DR11 Keeping up with technology and driving innovation.		×		×	×	×
6	DR10 Improve customer service.		×	×	×	×	×
8	DR 9 Regulation compliance	×	×	×	×		×

Regulatory compliance appears as a shared driver across several cases. In the CS 1 Cincinnati case, the DT application was motivated by an EPA consent decree aimed at eliminating sanitary sewer overflows (SSOs) and mitigating combined sewer overflows (CSOs). In CS 3, Grand Rapids focused on regulatory compliance with the Department of Energy mandate, while in CS 4, Philadelphia specifically linked the Online Water Quality Monitoring project to environmental regulations. This pattern suggests that policy and environmental regulations are strong drivers of digital water innovation. This demonstrates that utilities primarily adopt advanced digital technologies when driven by compliance requirements and their related environmental goals.

Cost savings from leveraging data, including capital expenditure (CAPEX) and operating expenditure (OPEX), are evident in all cases and are strongly supported by the survey. For

example, CS 1 Cincinnati aimed to avoid capital costs while achieving over 90% in cost reductions; CS 2, DC Water, aimed to cut non-revenue water and operational costs; CS 3 Grand Rapids avoided costs up to USD 1 billion through predictive monitoring; and CS 6 Calgary highlighted cost savings and better asset management through automated corrosion monitoring. These examples demonstrate the importance of financial efficiency and cost reduction in driving digital transformation within water organizations.

Several cases demonstrate the importance of organizational readiness and strategic planning, highlighting key drivers at both levels. CS 2 DC Water committed its digital twin to a five-year strategic plan, emphasizing innovation, customer service, and the importance of strategic planning by setting both short and long-term objectives. CS 5 Philadelphia linked online monitoring with improved utility performance and better customer service. CS 3 Wessex (UK) streamlined digital asset management into a long-term operational strategy. This indicates that institutional commitment and leadership vision are essential for scaling digital innovation, alongside financial and regulatory requirements.

Technological innovation is also a significant driver; all six cases involved advanced technological systems, ranging from real-time sensors and SCADA integration to AI-driven decision support and digital twins. CS2 DC Water and CS4 Wessex (UK) implemented full digital twin models for operational and financial optimization. CS5 Philadelphia used an advanced data management system (WISKI) for automated quality control, and CS6 Calgary developed on a secure cloud platform for automated corrosion monitoring and reporting. Therefore, technological innovation and keeping up with new technologies serve as cross-cutting enablers rather than drivers; they support regulatory compliance, help reduce costs, and enhance operational resilience. Noteworthy is that the different capabilities reported in each case related to various technological complexities confirm ATKINS (2017) report earlier findings regarding the DT's six maturity levels, their varying levels of sophistication and outcomes.

When analyzing the initial objectives against the realized benefits, it was reported that the benefits exceeded the expectations in all cases. However, no cost information was included,

except for two cases: first, CS 3, the city of Grand Rapids, Michigan. The report noted that investing \$30-50 million would save up to \$1 billion, which could be allocated to capital investments in a new asset network. The other is CS6, Calgary, Canada, which states that “Dollar for dollar, the Cost of protecting 10 km of pipe equals the cost of replacing one km.” In the same case, CS 6 Calgary reported that team satisfaction has increased, with the team becoming smarter and able to focus on other tasks, stating, “Real-time monitoring has made our team smarter, giving us the time to explore new ways to improve and optimize.”

Notably, in all cases, it was not only a single driver that contributed to the adoption of digital transformation. In contrast, many drivers resonate across all cases concurrently, emphasizing that multiple drivers are motivating utilities to embark on the digital adoption journey. Besides, although the technologies adopted differ in type, scale, and use cases (real-time control, full digital twins, corrosion monitoring), their functions share similar objectives and collectively serve the big aims of the drivers, such as regulatory compliance, cost reduction, performance optimization, and improved services. This supports our earlier discussion that technological innovation plays the role of enabler rather than a driver.

Therefore, it is evident that both results (quantitative and qualitative) align with each other for drivers and perceived project success. However, the sole difference lies in regulatory compliance and mandate requirements; this driver is evident and strong in real-world cases but lacks sufficient support in the quantitative data. This suggests that government entities and environmental agencies in the UAE should place greater emphasis on developing updated regulations, standards, mandates, and guidelines for compliance. Additionally, they should communicate digital initiatives and strategies to stakeholders and the public to enhance their awareness and understanding of the value of adopting new technology and supporting strategic plans. Despite triangulation with quantitative findings from exploratory surveys, which may suggest the generalizability of the drivers across contexts, generalization should be approached cautiously. The findings may inform countries with similar contexts and economic capacities; however, generalization is not granted in the Middle East, given varying digital maturity and the regional focus.

## 5.5 The Findings, Limitations, Recommendations

This study explored and identified the key drivers of digital technologies in water projects in the UAE's urban water systems, addressing a notable gap in both literature and practice. The analysis evaluated experienced stakeholders' perceptions of the importance of drivers to adoption, perceived project success on implementation, and tested variations in agreement. A triangulation with qualitative analysis of global digital water cases corroborated the survey findings, ensuring their credibility.

Quantitative analysis revealed that the most influential drivers include performance optimization, data-driven cost reduction, improved asset safety, and improved public safety management. Subgroup analysis indicated consensus on the importance of the drivers, with minor divergence in the importance of cost reduction and customer service. Most participants described their project outcomes as achieved or exceeded expectations and reported satisfaction with the implementation, underscoring improvements resulting from digital transformation in water management.

The case study findings reinforced the quantitative results, except for regulatory compliance, which appeared more salient in real-world examples. This informs the need for the UAE to establish adaptive regulatory frameworks, audit mechanisms, and transparent communication strategies to ensure compliance and increase stakeholder awareness.

The findings offer important insights for water industry stakeholders and policymakers on what empirically drives digital twins (DTs) adoption. Organizations should enhance their workforce's digital skills, strengthen leadership, and implement structured digital maturity programs before deploying large-scale DT. Government-initiatives are encouraged to mitigate the perception of high-cost investments and foster stakeholders' willingness to adopt the new tools. This work adds to the understanding of the drivers of DT adoption in water infrastructure management, representing one of the first empirical studies in the Middle East. It bridges a critical gap in empirical engineering management literature, highlighting the importance of organizational, technological, and regulatory dimensions of digital transformation. While the findings may inform similar economies with comparable digital maturity, generalization should be approached cautiously due to contextual variations. The study provides a reference

for guiding digital transformation strategies in the UAE water systems, contributing to both regional sustainability goals and global discourse on digital infrastructure management.

For limitations, this study is exploratory and represents the first empirical effort in the Middle East to investigate the drivers influencing digital twin (DT) adoption within urban water infrastructure. While the findings provide preliminary insights, confirmatory studies with larger and more diverse samples are required to validate and generalize the results across broader populations and contexts. The study focused on identifying significant adoption drivers but did not examine their causal interrelationships. Future research can integrate the identified drivers into a system dynamics framework to model feedback loops, simulate potential interventions, and explore the temporal evolution of DT adoption processes in the UAE and similar contexts. Given the early stage of DT implementation and the limited number of relevant case studies in the region, the relatively small sample size was deemed acceptable. Particularly as participants held senior managerial positions and had extensive water experience, including hands-on experience with digital water projects.

Although purposive sampling was justified by the technical depth and specificity of the study topic and requirements, random sampling would become more feasible once DT adoption matures and broader user engagement is established. Furthermore, project success was assessed using two indicators; however, it is a broad category in project management literature. Future studies might incorporate a more comprehensive set of success metrics, such as sustainability outcomes, innovation performance, time, and budget commitment, to capture a holistic understanding of digital project success. Similarly, expanding stakeholder representation beyond the three groups examined in this study will allow for more nuanced insights into cross-sectoral perceptions and collaboration dynamics. Future research could also examine the moderating roles of organizational size, project scale, and DTs maturity level to better understand how contextual and technological readiness influence adoption success. Besides, advancing this line of research through longitudinal, cross-regional, and theoretical model-based studies will be beneficial for establishing a more generalizable and causally understanding of digital twin adoption in urban water system



## CHAPTER 6

### WATER MONITORING MANAGEMENT USING HOUSEHOLDS' DIGITAL TOOLS: AN EXTENDED SOCIO-TECHNICAL ACCEPTANCE MODEL

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- An extended socio-technical framework to explore digital tools adoption in the UAE
- Technology Acceptance Model (TAM) is a strong validity predictor in water management
- Behavioral factors: efficacy, anxiety, policy support, and water security concerns
- Insights for policymakers, utilities, and technology providers for water digitalization
- Theoretically positions TAM in governance, sustainable, socio-technical systems in arid regions.

#### ABSTRACT

The digital twinning of urban water systems has attracted attention for its promising potential to improve service delivery through citizen engagement. Internet of Things (IoT)-integrated models enable timely alerts for high water usage via user applications, supporting efficient water monitoring. Utilities in digitally advanced contexts make substantial investments to provide suitable interfaces; however, user acceptance remains a significant obstacle. This study extends the Technology Acceptance Model (TAM) to examine users' acceptance. It integrates TAM with personal, governmental, and environmental variables. Empirical data were collected using a cross-sectional survey of public users in Dubai, United Arab Emirates (UAE), a digitally advanced context. The WLSMV-SEM structural equation modeling (SEM) in R was used for analyzing data from 149 users. The study identifies water security concern WSC and perceived usefulness PU as principal enablers of behavioral intention (BI). Mobile self-efficacy MSE and mobile device anxiety (MDA) presents significant relation to perceived ease of use PEOU, yet oppositely. Government policy (GP) also proved significant to (PU). In line with the theoretical TAM, perceived ease of use (PEOU) strongly predicts perceived usefulness (PU), which, in turn, drives behavioral intention (BI). The extended TAM framework evidenced a substantial predictive power for behavioral intention. Limitations were acknowledged, actionable recommendations and future research were proposed. The study's implications offer a valid predictive framework for planning the implementation of digital water tools, and extending TAM into governance and sustainability settings. Further, it paves

the way for future experimental testing of the framework and studies on post-implementation settings.

**Keywords:** Internet of Things IoT, governance, water monitoring, interface acceptance, public users.

## 6.1 Introduction

Water supply management struggles with incremental costs due to uncontrollable service network losses (Ramos et al., 2022). To address these challenges and improve network efficiency, suppliers are reevaluating their strategies and adopting new digital solutions (Yang et al., 2022). Digital twinning with Internet of Things (IoT) monitoring tools enables real-time data to support informed decisions for network efficiency (Schmidt et al., 2024; Bartos & Kerkez, 2020). The rapid evolution of digital applications offers opportunities for improving service delivery through citizen engagement. However, citizen engagement with these tools remains slow, primarily due to socio-technical barriers, including user acceptance issues (Naderi & Shojaei, 2023).

IoT systems connect physical devices to digital platforms through standardized protocols, enabling system-wide monitoring (Ablyazov, 2021). Their effectiveness largely depends on the platform; the human-machine interface (HMI), which allows user interaction to support decision-making (Li et al., 2022). Despite technological advancements, user perceptions remain crucial for successful technology implementation (Jetter et al., 2018). Socio-technical theories highlight that users' adoption is influenced by user characteristics, system design, and broader contextual factors (Greenhalgh & Stones, 2010). Consequently, comprehensive frameworks are needed to explain the acceptance of emerging digital water platforms, including IoT-enabled tools.

The technology acceptance model (TAM) provides a solid theoretical foundation for modeling acceptance through behavioral intention (Davis, 1989; Recker, 2021). TAM's methodology has been validated across a variety of technologies, including mobile payments (Rabaa'i et al., 2022), cloud computing (Ferri et al., 2021), and autonomous vehicles (Hewitt et al., 2019). In the water sector, it has been applied to IoT municipal water management (Moriényane & Marnewick, 2019), water resource reporting through citizen engagement (Minkman et al.,

2017), and smart metering (Madias et al., 2023). However, sustainability-focused technologies, like water technologies, offer opportunities to incorporate environmental, institutional, and personal factors into TAM extension.

The UAE provides a relevant setting for such analysis. Despite severe water scarcity and security challenges, the country, as a non-financially constrained context, invests heavily in digital transformation (Qureshi, 2020; Al Desoukie, 2020). Dubai Electricity and Water Authority (DEWA) has gained worldwide recognition for digital innovation, as evidenced by Dubai Hydro Insight being named the smartest water project in 2024 (Jones, 2024). The authority has finished installing over one million IoT-enabled smart meters and developed a mobile app to monitor household water use (Smart Living, 2023). However, the factors influencing households' adoption of the tool remain unexplored, given the limited socio-technical research in the Middle East.

This study extends TAM by incorporating personal factors (self-efficacy, device anxiety), environmental concerns (water security), and institutional influences (government policy). It uses survey data from Dubai citizens to analyze behavioral intentions to adopt an IoT-enabled water-monitoring tool in an arid, digitally advanced environment. Digitalization has become an inevitable shift, as evidenced by the UN Sustainable Development Goals, particularly (SDG 9). The goal aims to promote innovation and resilient infrastructure by increasing investment in ICTs (UN-The Sustainable Development Goals, 2023). This study is novel; it is the first proposal of an extended TAM to address the adoption of digital water tools through citizen engagement in the UAE, offering new insights for digital water governance and sustainability-focused user behavior.

## **6.2 Literature Review and TAM Conceptual Model Development**

This section presents a literature review of TAM studies and the factors used to develop the conceptual model.

### 6.2.1 Information Systems and Technology Acceptance

The evolution of digitalization is “more embedded in social aspects and driven by individuals,” as noted by Hämäläinen (2020). Recker (2021) describes the information systems IS perspective as primarily interested in socio-technical systems involving individuals and groups who interact with the digital information and communication technologies (ICT) to accomplish tasks in their private, business, or social contexts. The IS research centers on the societal impact of the development and use of digital ICTs. A socio-technical approach includes two components: the technological, such as digital infrastructure, systems, platforms, hardware, software, algorithms, or data, and the social (individuals and collectives), such as networks, governments, organizations, communities, groups, and teams (Recker, 2021). These two components interact as they are developed, used, and evolved in various contexts. Stakeholders are vital to the acceptance of new technologies; their perceptions shape adoption and determine diffusion. This makes the analysis of acceptance among potential users a vital step in promoting adoption (Najib & Fahma, 2020; Pijpers & van Montfort, 2005; Davis, 1989). According to Economides (2016), the adoption of new technology is questioned by society, and its acceptance is influenced by individuals’ education, personal habits, and social context.

Social science theories were effectively deployed by IS research to test, explain, assess, and even predict significant adoption factors. The Technology Acceptance Model (TAM), widely applied in IS, posits that intention to use a technology result from two internal beliefs: perceived usefulness and perceived ease of use (Davis, 1989). At the same time, these internal beliefs may also be affected by various exogenous determinants (Venkatesh, 2000). However, many factors shape users' intention to adopt a technology or to continue using it once it is introduced (Nikou & Economides, 2017). TAM has been applied to examine users' intentions to use digital technologies across different domains in the UAE (Alhashmi et al., 2019; Ahmad & Khalid, 2017; Arar et al., 2021); however, it is lacking in digitalizing the urban water system. A few studies have discussed water digitalization as a socio-technical issue from the perspective of public users, focusing on the use of IoT-advanced digital tools in arid regions and developing countries. Additionally, according to Flavián et al. (2022), the disruptive nature of advanced technologies and their social and economic implications make continuous research

essential in this rapidly growing area. Almomani et al. (2022) reported that currently, there is a limited understanding of IoT adoption behaviors, highlighting the need for more in-depth research. This underscores the rationale for the study's approach and the choice of the UAE context; a digitally advanced and financially unconstrained environment. At the same time, it seeks to manage the high costs of service supply while maintaining high living standards and meeting sustainability requirements.

### **6.2.2 Mobile Self-Efficacy**

Self-efficacy, defined by Bandura (1986) as individuals' judgments of their ability to perform tasks using technology, plays a key role in technology-related behaviors. Mobile self-efficacy has been extensively studied in social and behavioral research, especially in mobile learning, where higher self-efficacy consistently predicts greater acceptance and usage (Nikou & Economides, 2017; Mahat et al., 2012; Bettayeb et al., 2020). Within TAM, Venkatesh and Davis (1996) demonstrated that perceived ease of use (PEOU) is anchored in users' self-efficacy. Computer self-efficacy also affects performance expectations, emotional responses like anxiety, and actual use, as highlighted by Compeau & Higgins (1995). Similar patterns are observed in virtual reality VR contexts, where confidence increases perceived ease of use and engagement (Kwok et al., 2021). It is believed that users with higher self-efficacy will perceive the tool as easy to use and be more willing to use it repeatedly to accomplish the required tasks. Accordingly, based on the literature and following Nikou and Economides' (2017) work, the following hypothesis is proposed:

H1: Mobile self-efficacy (MSE) positively predicts perceived ease of use (PEOU).  
Measurement items were adapted from Compeau and Higgins (1995).

### **6.2.3 Mobile Device Anxiety**

Information communication technologies (ICT) use is often associated with heightened anxiety, especially among inexperienced users (Mac Callum & Jeffrey, 2014; Barbeite & Weiss, 2004). Computer anxiety reflects a fear that engaging with technology may result in negative outcomes, such as damaging the device or looking foolish (Mac Callum & Jeffrey,

2014). Later, Nikou and Economides (2017) define mobile device anxiety (MDA) as the apprehension people feel when using mobile technologies. This anxiety diminishes perceptions of ease of use and negatively influences attitudes toward and intentions to use technology. Research consistently shows that technology-related anxiety negatively impacts perceived ease of use and usefulness. MacCallum and Jeffrey (2014) demonstrated that ICT anxiety reduces both perceived ease of use (PEOU) and perceived usefulness (PU) in mobile learning. Similar negative effects are observed across various contexts, including mobile learning (Nikou & Economides, 2017; Mac Callum & Jeffrey, 2014), smart home technologies among older adults (Arar et al., 2021), and public mobility systems (Götzenbrucker et al., 2025), where personal control and social can help mitigate anxiety. Thus, it is demonstrated that anxiety negatively affects the tool's usability and hinders users' attempts to try it. This can be attributed to a lack of experience and knowledge in using new digital tools. Based on this literature and the work of Nikou and Economides (2017), the following hypothesis was proposed: H2: Mobile device anxiety (MDA) negatively predicts perceived ease of use (PEOU). Measurement items were adapted from Venkatesh et al. (2003).

#### **6.2.4 Governmental Policies**

The Fourth Industrial Revolution (IR4.0) has transformed how governments develop public-sector policies, fueled by rapid advances in digital technologies (Faria et al., 2021). Digitalization has become a key government priority and an instrument for economic and development progress in both developed and developing contexts (Ali et al., 2021; Kurmangali et al., 2024). According to Bakar et al. (2020), governments have the authority, resources, and strategic leverage to promote the adoption of emerging and sustainable technologies.

Policy formulation, regulatory frameworks, public awareness campaigns, and financial incentives are consistently recognized by governments as key drivers of technology adoption. Policy support has enabled sustainable technology adoption in Malaysia (Bakar et al., 2020), industry 4.0 initiatives in Portugal (Faria et al., 2021), cloud computing adoption in Australian governments (Ali & Osmanaj, 2020), and m-commerce in Jordan (Alrawabdeh, 2014). Clear policies and financial subsidies often strongly influence attitudes toward adoption (Bakar et al., 2020), whereas ambiguous policies or limited support hinder it (Jonathan, 2019). Effective

policies should address digital literacy gaps, strengthen infrastructure, and eliminate structural barriers. In addition, national strategies that ensure affordability, reliability, and equitable access demonstrate a higher level of digital readiness, thereby enabling adoption (Kurmangali et al., 2024). Similarly, transparent regulations and sufficient infrastructure promote adoption behaviors, including e-government (Alrawabdeh, 2016) and m-commerce (Alrawabdeh, 2014) in Jordan.

This factor is highly relevant in the UAE, where strong digital leadership and DEWA's ambition to become the first AI-native utility have accelerated policy initiatives. Additionally, the country leverages digital technologies to enable digital transformation and be recognized globally as a technological hub. Besides, its scarce water resources challenges and water security issues are apparent in the national water strategy 2036. Understanding whether the public's awareness of these policies and the government's commitment to sustainability shape their perceptions of the usefulness of digital tools could be informative. Based on this evidence, the following hypothesis is proposed:

H4: Government Policies (GP) positively predict perceived usefulness (PU). Measurement items were adapted and slightly modified from Bakar et al. (2020).

### **6.2.5 Water Security Concerns**

Water security concerns reflect individuals' awareness of and worry about water scarcity and the broader environmental risks (Huijts et al., 2012). Although not originally part of the TAM, these concerns have become increasingly relevant for sustainability-focused technologies, including smart metering and digital water tools (Chen et al., 2017; Bugden & Stedman, 2019). Environmental concern is influenced by personal, cognitive, and social factors, such as awareness of resource degradation, perceived effectiveness of solutions, and the long-term consequences of human activities (Gifford & Nilsson, 2014). However, concern alone does not directly lead to action; encouraging pro-environmental behavior often depends on contextual factors like trust and perceived efficacy (Tam & Chan, 2018).

Empirical research shows that incorporating environmental concerns and awareness into behavioral models enhances their predictive power. In Malaysia, increasing awareness of sustainability and energy-saving practices improved the acceptance of smart meters and

strengthened the link between intention and use (Alkawsi et al., 2020). Shen and Varis (2000) similarly observe that awareness of water security supports social acceptance of water infrastructure investments. Awareness campaigns also encourage water-saving behaviors and promote pro-environmental attitudes (Seelen et al., 2019). In the water sector, environmental concern has been shown to positively influence attitudes and intentions to adopt IoT smart meters (Madias et al., 2022).

This relationship is particularly important in the UAE, where severe water scarcity and high per capita consumption intensify pressure on water security (Al Desoukie, 2020). Dubai's strategic initiatives, including the Mohamed bin Zayed Water Initiative 2036, focus on raising public awareness on security concerns and advancing technological innovation to tackle water issues. Therefore, understanding how water security concerns influence behavioral intentions toward digital water tools is timely and imperative. Based on this discussion, the following hypothesis is proposed:

H5: Water security concerns (WSC) will positively predict behavioral intention (BI). Measurement items were adapted from Bamberg (2003).

### **6.2.6 Perceived Usefulness, Perceived Ease of Use, and Behaviour Intention**

Within the Technology Acceptance Model (TAM), behavioral intention (BI) represents users' willingness to adopt or continue using a technology (Davis, 1989). BI is influenced by two central beliefs, perceived usefulness (PU) and perceived ease of use (PEOU), which shape attitudes toward the technology (Davis et al., 1989). PU represents the extent to which a technology improves performance, while PEOU pertains to its perceived simplicity (Davis, 1989). Since TAM's development, these constructs have demonstrated strong explanatory power, with external factors influencing PU and PEOU (Venkatesh & Davis, 1996). Previous research supports these relationships empirically. PU and PEOU have both predicted IoT adoption among municipal workers (Moriényane & Marnewick, 2019) and influenced citizens' perceptions of mobile water-reporting apps (Minkman et al., 2017). Taheri et al. (2022) found PU significantly affected attitudes toward adopting wireless sensor networks in agriculture, with PEOU also remaining important. Davis et al. (1989) further confirmed PU's strong impact

on intention over time. Recent studies indicate PEOU is a strong predictor of actual system use, with PU also playing a role (Saira et al., 2025).

TAM also suggests that through an individual linkage, PEOU increases PU (Venkatesh, 2000). These core constructs (PU, PEOU) are influenced by external factors such as intrinsic motivation, emotions, self-efficacy, and facilitating conditions, especially during early stages of interaction (Venkatesh, 2000). Based on these well-established theoretical and empirical insights, the following hypotheses are proposed:

H3: Perceived ease of use (PEOU) will positively predict perceived usefulness (PU).

H6: Perceived usefulness (PU) will positively predict behavioral intention to use the application (BI). Measurement items were adapted from Davis (1989).

Figure 6.1 presents the conceptual model, annotated with the constructs and their corresponding hypotheses. All hypotheses were tested at a significance level ( $\alpha = .05$ ) and *t*-values exceeding 1.96. Table 6.1 presents the items for each factor, along with their corresponding reference sources.

The conceptual model will contribute a novel perspective to the regional water management literature and highlight the strategic role of environmental risk communication in accelerating public uptake of smart water technologies.

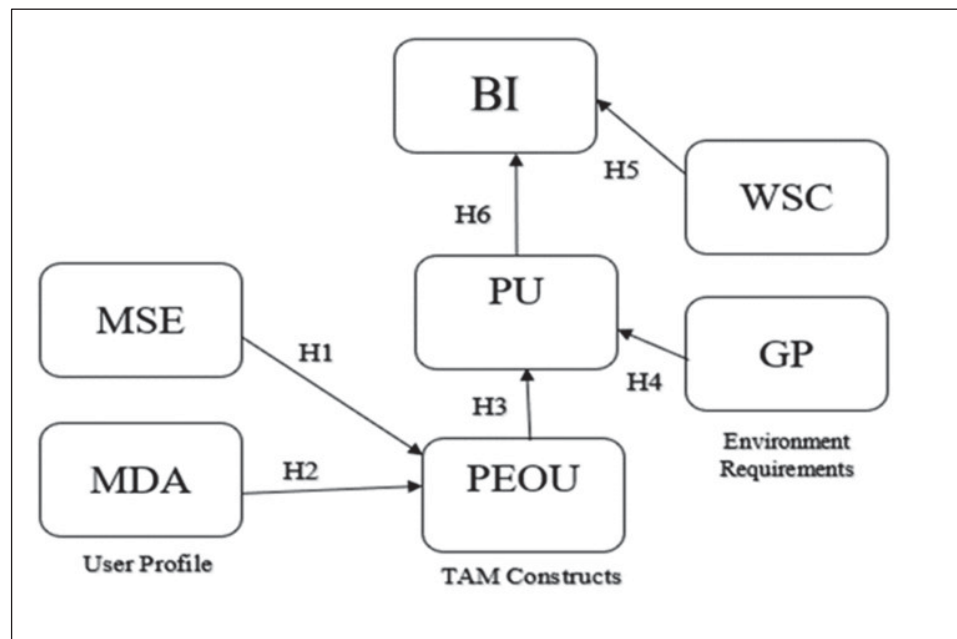


Figure 6.1 TAM Conceptual Model

Table 6.1 Items of the Final Model with Associated References

Factor	Reference
Government policies	Bakar et al. (2020)
GP1 I am aware of government initiatives that promote water conservation and sustainability.	
GP2 Governmental policies influence my decision to use the application to monitor my water consumption.	
GP3, I feel a personal responsibility to support the policies' goals by using digital tools like the application.	
Mobile Device Anxiety MDA	Venkatesh et al.(2003)
MDA1. I feel anxious about using the application	
MDA2. It scares me to think that I could lose a lot of information by hitting the wrong key	
MDA4. The application is somehow frightening to me	
Mobile Self-Efficacy MSE	Compeau & Higgins (1995)
MSE1 I could complete a task using the application	
MSE2 I could complete a task using the application if someone showed me how to do it first.	
MSE4 I can navigate easily through the Web using a mobile device to find any information I need	
Water Security Concerns	Bamberg (2003)
WSC1. I am concerned about the water security issues for my community.	
WSC2. News that concerns water security issues makes me worried.	
WSC3. If we continue as before, we will soon approach a water shortage catastrophe	
Perceived Ease of Use	Davis (1989)
PEOU1 The interaction with the application is clear and understandable	
PEOU2 It is easy to become skilled at using the app.	
PEOU3 The application is easy to use	
Perceived Usefulness	Davis (1989)
PU1. Using the application enhances my effectiveness in water preservation.	
PU2. The application is useful for monitoring my consumption.	

Table 6.1 Items of the Final Model with Associated References, continued

PU3. Using the application increases my knowledge of my water consumption	
Behavior Intention to Use (BI)	
BI1. I intend to use or continue using the application in the future.	Davis (1989)
BI 2. I plan to use or continue using the application in the future.	
BI 3. I predict I would use or continue using the application in the future.	

### 6.3 Methodology

#### 6.3.1 Research Design

This study applies an explanatory-predictive SEM research design, using a deductive approach to empirically test hypotheses derived from an extended Technology Acceptance Model (TAM) (Davis, 1989; Recker, 2021). The conceptual model includes personal, environmental, and governmental factors informed by Economides (2016) and previous studies. A structured, self-administered questionnaire was developed based on this framework and distributed through an online cross-sectional survey targeting residents of Dubai, UAE.

#### 6.3.2 Study Area Context and Sampling

Dubai provides an appropriate context for examining the adoption of digital water tools, given its national commitment to digital transformation as a leader in the Middle East and globally. Despite being in an arid climate region with severe water scarcity (Riadh, 2022), Dubai has been recognized globally for its innovative smart water solutions (Jones, 2024). The Dubai Electricity and Water Authority (DEWA) has made a massive investment in deploying IoT-enabled smart meters. It provides customers with a digital water-usage monitoring tool, making household users a relevant target population. DEWA does not disclose customer data or allow field access due to high confidentiality, which prevents the formation of a sampling frame and the collection of any information on the population size. Thus, convenience and snowball

sampling were employed, which are suitable when the sample is difficult to define and are consistent with prior technology adoption studies (Al-Adwan et al., 2023; Keller et al., 2018). This approach was appropriate given the study's investigatory nature and its focus on behavioral intention rather than actual system use. As noted by Keller et al. (2018), users without prior experience may offer less biased perceptions when intention, rather than usage, is modeled and questioned. To the authors' best knowledge, this is the first study that discusses the adoption of digital water tools among citizens in the UAE and the Middle East as a socio-technical approach.

### **6.3.3 Study Instruments and Data Collection**

Data were collected using an online survey over four months. The link was shared via email and social media channels and was regularly reshared to increase visibility. A total of 149 complete responses were obtained from approximately 250 distributed questionnaires (response rate = 59.6%). Although modest, the sample size aligns with similar TAM-based studies (e.g., Taheri et al., 2022; Indarsin & Ali, 2017; and Nikou & Economides, 2017) and WLSMV-based SEM, suitable for small samples (Beauducel & Herzberg, 2006). The survey opened with an introductory statement describing the study's purpose, outlining ethical approval, and assuring data confidentiality. Informed consent was obtained before participants proceeded to the questions. All construct items were adapted from validated prior studies, with minimal wording changes to ensure relevance and construct validity. Preliminary analysis of piloting the survey with 48 participants, including reliability, validity, and fit measures for various modeling alternatives, was conducted. The results revealed that dropping three items (GP4, MDA3, MSE3) due to weak loadings or high correlations yielded a more stable 21-item instrument organized across seven constructs, as presented in Table 6.1.

### **6.3.4 Data Analysis Methods**

All analyses were conducted in the R programming environment. The procedure followed Anderson and Gerbing's (1998) two-step approach: (1) confirmatory factor analysis (CFA) to assess measurement reliability and validity, and (2) structural modeling to test hypothesized

relationships. Descriptive statistics (means, standard deviations) were calculated, and Q–Q plots were examined to evaluate normality. The lavaan 0.6–19 package in R was used for both CFA and SEM. Given the ordinal nature of data and the modest sample size, the Weighted Least Squares Mean and Variance-adjusted (WLSMV) estimator was employed. WLSMV provides robust parameter estimates for ordinal data and performs well under small-to-moderate sample conditions (Beauducel & Herzberg, 2006). A significance level of  $p < 0.05$  was adopted for all hypothesis tests.

## **6.4 Results**

### **6.4.1 Demographic Results**

A total of 149 public users participated in the study. Males represented a slight majority (56.1%), while females made up 34.9% of the sample. The age distribution showed that the largest group was in the 35–44 age range (37.6%), followed by those aged 25–34 (30.2%). Then 13.4% in the range of 45–54, and 12.8% older than 55. Regarding educational attainment, the sample was relatively well educated: 62.4% reported holding a bachelor's degree, and 14.1% had completed a master's degree. Notably, no respondents reported being uneducated. Participants were also asked about their prior experience with smart applications. The majority (75.8%) had used smart applications before, while 24.2% reported no prior experience Table 6.2.

### **6.4.2 Preliminary data analysis**

Preliminary data diagnostics were performed in R to evaluate the dataset's suitability. It begins by detecting multivariate outliers using Mahalanobis distance at a 0.001 significance level. Next, it computes the polychoric correlation matrix to visualize the relationships in a heatmap, providing a preliminary inspection for ordinal variables. Finally, it evaluates the adequacy of factor analysis using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity.

Table 6.2 Demographics Results

Demographics	Type	Number	Percentage
Gender	Male	97	0.651
	Female	52	0.349
Age	< 25	9	0.06
	26-34	45	0.302
	35-44	56	0.376
	45-54	20	0.134
	55 <	19	0.128
Education	Uneducated	-	-
	High school	9	0.06
	Diploma college	21	0.141
	Bachelor degree	93	0.624
	Master's degree	21	0.141
	PhD degree	5	0.034
Experience	Yes	113	0.758
	No	36	0.242

Results indicate no significant number of outliers; additionally, the overall KMO value was 0.70, within the acceptable range of 0.70–0.80, indicating an adequate sample for factor analytic procedures (Kaiser, 1974). Additionally, all individual items exhibited MSA values above the recommended minimum threshold of 0.50. The results of Bartlett's test were significant ( $\chi^2 = 18,637.46$ ,  $df = 378$ ,  $p < 0.001$ ), confirming that the correlation matrix was not an identity matrix and thus the data is appropriate for factor extraction. Multivariate normality was further assessed using Mardia's test, which indicated that the data met the normality assumption across all constructs. Collectively, these diagnostic results provide strong evidence that the dataset meets the conditions for proceeding with confirmatory factor analysis and subsequent structural modeling.

### 6.4.3 Measurement Model Analysis

Following the preliminary diagnosis, confirmatory factor analysis (CFA) was conducted to evaluate the measurement model using the lavaan 0.6–19 package in R, along with the psych and semTools libraries. The measurement model comprises 21 items across seven constructs

and exhibits acceptable fit indices (Table 6.3). The model was estimated using the Weighted Least Squares Mean, and Variance Adjusted (WLSMV) estimator, and the psychometric properties (internal consistency and convergent validity) were assessed using Cronbach's alpha, Composite Reliability (CR), and Average Variance Extracted (AVE) (Hair et al., 2010). The results demonstrated strong psychometric properties and excellent incremental fit (CFI = 0.998, TLI = 0.997), as well as acceptable residual fit (SRMR = 0.076). Although the RMSEA value (0.101) exceeded the cutoff, RMSEA is known to be highly sensitive to small sample sizes and can mislead results with limited observations (Kenny et al., 2015).

Table 6.3 Model Fit Indices

Index	chisq	df	P-value	CFI	TLI	RMSEA	SRMR
Value	374.856	176	0.000	0.998	0.997	0.101	0.076

Table 6.4 Internal and Convergent Validity Assessment

Factor	Item	Loading	Alpha	CR	AVE
GP	GP1	0.771	0.833	0.768	0.651
	GP2	0.781			
	GP3	0.866			
MDA	MDA1	0.897	0.959	0.905	0.844
	MDA2	0.907			
	MDA4	0.951			
MSE	MSE1	0.880	0.912	0.836	0.784
	MSE2	0.854			
	MSE4	0.922			
BI	BI1	0.811	0.905	0.862	0.855
	BI2	0.993			
	BI3	0.959			
WSC	WSC1	0.908	0.871	0.884	0.822
	WSC2	0.914			
	WSC3	0.898			
PU	PU1	0.864	0.901	0.884	0.842
	PU2	0.973			
	PU3	0.914			
PEOU	PEOU1	0.925	0.902	0.873	0.835
	PEOU2	0.876			
	PEOU3	0.939			

Given the good performance across most fit indices and the high reliability and validity of the constructs as shown in Table 6.4, this model was deemed the most appropriate representation of the data. Table 6.4 presents the internal reliability, convergent validity, and item loadings. Composite reliability values were above 0.70 for all constructs, with Cronbach's alpha values above 0.7 (Taber, 2018), indicating they are internally consistent. Convergent validity was also confirmed; the average variance extracted (AVE) for all constructs exceeded 0.50.

Discriminant validity was evaluated using the Fornell–Larcker criterion, with Average Variance Extracted (AVE) values on the diagonal for each construct, as shown in Table 6.5. The results satisfy the criterion of Fornell & Larcker (1981), since no cross-loadings were identified higher than the correlation with that construct. These findings confirm the validity of the constructs and the robustness of the measurement model, indicating that multicollinearity is not an issue. Then, multi-collinearity was checked using the variance inflation factor (VIF), where values must be  $< 3$ . This was confirmed for all main constructs; MSE and MDA 1.67, PEOU and GP 1.92, and WSC and PU 1.88.

Table 6.5 Discriminant validity

Fornell–Larcker Criterion (Diagonal = $\sqrt{\text{AVE}}$ , Off-diagonal = Correlations)							
Factor	GP	MDA	MSE	BI	WSC	PU	PEOU
GP	<b>0.807</b>	-0.527	0.732	0.721	0.723	0.67	0.582
MDA	-0.527	<b>0.919</b>	-0.579	-0.536	-0.515	-0.508	-0.543
MSE	0.732	-0.579	<b>0.886</b>	0.791	0.83	0.719	0.775
BI	0.721	-0.536	0.791	<b>0.925</b>	0.782	0.934	0.808
WSC	0.723	-0.515	0.83	0.782	<b>0.907</b>	0.633	0.648
PU	0.67	-0.508	0.719	0.934	0.633	<b>0.918</b>	0.822
PEOU	0.582	-0.543	0.775	0.808	0.648	0.822	<b>0.914</b>

#### 6.4.4 Structural Model Results

After identifying the best-fitting measurement model, the structural model was estimated to test the hypothesized relationships. Table 6.6 and Figure 6.2 show the standardized path coefficients ( $\beta$ ), significance levels, and hypothesis testing results. The findings indicate that mobile self-efficacy (MSE) is a strong and significant predictor of perceived ease of use

(PEOU) ( $\beta = 0.693$ ,  $p < 0.001$ ), supporting H1. Mobile device anxiety (MDA) has a significant adverse effect on PEOU ( $\beta = -0.142$ ,  $p = 0.034$ ), supporting H2. Government policies (GP) have a significant positive effect on perceived usefulness (PU) ( $\beta = 0.290$ ,  $p < 0.001$ ), supporting H4. Water security concerns (WSC) significantly and positively predict behavioral intention (BI) ( $\beta = 0.318$ ,  $p < 0.001$ ), supporting H5.

Consistent with the generic TAM and supporting the theoretical proposition, PEOU significantly influences PU ( $\beta = 0.653$ ,  $p < 0.001$ ), supporting H3, and PU strongly predicts BI ( $\beta = 0.732$ ,  $p < 0.001$ ), supporting H6. The model demonstrates strong explanatory power, with  $R^2$  values of 0.607 for PEOU, 0.727 for PU, and 0.932 for BI, indicating that the extended TAM accounts for a substantial portion of the variance in users' behavioral intentions. All codes are enclosed in ANNEX VI.

Table 6.6 Path Coefficient Results

Dependent	Predictor	Estimate $\beta$	Std. Error	Z-value	P-value	Std. All ( $\beta$ )	R2	Adj_R2	Hypothesis	Result
PEOU	MSE	0.728	0.063	11.583	0	0.693	0.614	0.607	H1	S
PEOU	MDA	-0.147	0.069	-2.124	0.034	-0.142	0.614	0.607	H2	S
PU	PEOU	0.61	0.053	11.539	0	0.653	0.732	0.727	H3	S
PU	GP	0.326	0.076	4.309	0	0.291	0.732	0.727	H4	S
BI	WSC	0.285	0.046	6.192	0	0.318	0.933	0.932	H5	S
BI	PU	0.688	0.04	17.274	0	0.732	0.933	0.932	H6	S

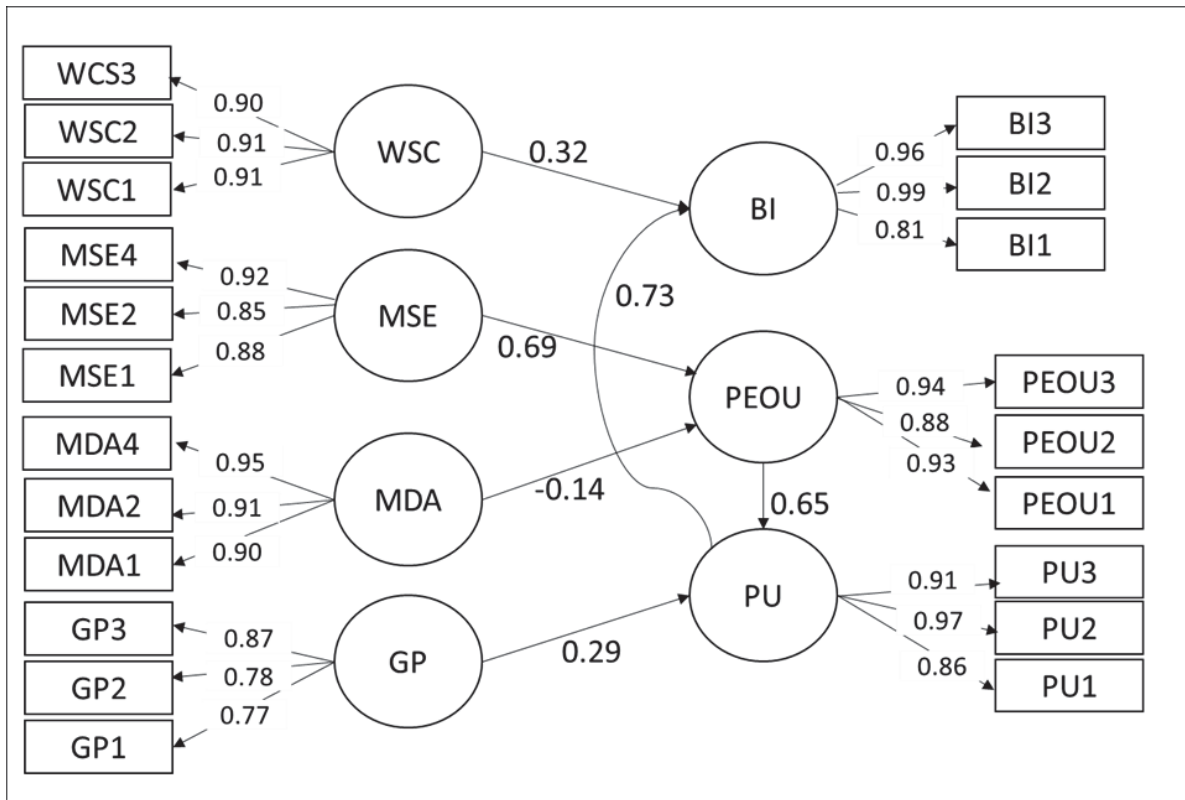


Figure 6.2 Extended TAM model Path analysis Results

### 6.5 Discussion of the Results

Results shown in Table 6 reveal that mobile self-efficacy (MSE) is a strong and significant positive predictor of perceived ease of use (PEOU) ( $\beta = 0.693, p < 0.001$ ), confirming H1. This aligns with existing research, including Venkatesh and Davis (1996), Kwok et al. (2021), and Compeau and Higgins (1995). They demonstrated that self-efficacy influences users' attitudes toward technology and improves perceptions of its usability. Venkatesh and Davis (1996) argued that perceived ease of use is rooted in self-efficacy beliefs, and Kwok et al. (2021) found similar results in virtual reality VR-based crisis-management training. The earlier study by Compeau and Higgins (1995) also highlighted the central role of self-efficacy in shaping expectations, emotional reactions, and actual computer technology use. These findings suggest that users who feel confident in their ability to operate technology tools are more likely to see them as intuitive and functional.

Conversely, mobile device anxiety (MDA) significantly decreases PEOU ( $\beta = -0.142$ ,  $p = 0.034$ ), supporting H2. This shows that anxiety actively weakens perceptions of ease of use within the study context. This finding is consistent with earlier research by Nikou and Economides (2017) and MacCallum and Jeffrey (2014), who found that ICT anxiety negatively impacts ease of use, intention, and perceived usefulness. Similar results have been observed in smart home adoption among the elderly (Arar et al., 2021) and digital mobility applications (Götzenbrucker et al., 2025), highlighting the broader significance of digital anxiety as a barrier to technological acceptance.

Taken together as psychological (personal) factors linked to interface design and usability, MSE and MDA exert opposite effects on PEOU: self-efficacy acts as an enabler, while anxiety functions as an inhibitor. The effect of MSE is substantially greater, highlighting the central role of user confidence in shaping perceptions of technology. This aligns with the well-established inverse relationship between self-efficacy and anxiety by previous research, which discussed the impact of experience as well. Liu et al. (2010) demonstrated that individuals with more prior experience report higher self-efficacy and lower anxiety, thereby increasing their intention to use digital tools. This pattern is relevant in this study, as 75.8% of respondents had experience with smart applications, likely reinforcing the strong MSE-PEOU link. However, the significant impact of anxiety, even in a digitally advanced context like the UAE, indicates that psychological barriers still exist, suggesting that users remain sensitive to tool features and design elements.

Government policies (GP) had a noticeably positive impact on perceived usefulness (PU) ( $\beta = 0.29$ ,  $p < 0.001$ ), supporting H4. This is consistent with earlier research emphasizing the important role of government intervention in technology adoption (Bakar et al., 2020; Alrawabdeh, 2016). For sustainability-focused technologies, policy measures such as regulations, incentives, awareness campaigns, and infrastructure support serve as key facilitators of public acceptance. When people see strong government commitment to water security and digital water programs, they are more likely to see these technologies as useful. Therefore, government credibility and transparent engagement lead to increased perceptions of technological benefits.

Conversely, unclear policy communication or restrictive regulatory environments hinder adoption, as noted by Ali et al. (2021), Jonathan (2019), and Ali and Osmanaj (2020). These studies stress that policies must be transparent, well-designed, and continuously communicated to effectively shape users' perceptions. Alrawabdeh (2016) also found that supportive government frameworks are vital in developing countries, where institutional conditions heavily influence adoption. In the UAE context, the significant GP-PU effect indicates that water security initiatives and national digitalization strategies enhance the perceived value and relevance of digital water-monitoring tools. Overall, the findings highlight that proactive policy actions and strategic communication are key to accelerating the adoption of sustainable technologies.

Water security concerns (WSC) had a substantial positive impact on behavioral intention (BI) ( $\beta = 0.318$ ,  $p < 0.001$ ), supporting H5. This emphasizes the importance of water risk awareness in motivating users to adopt digital tools to save resources. The result aligns with Alkawsii et al. (2020) and Shen and Varis (2000), who found that incorporating environmental and water security awareness into smart metering initiatives enhances user acceptance and strengthens the intention-use connection. Similarly, Seelen et al. (2019) and Madias et al. (2022) demonstrated that public awareness campaigns and knowledge about water consumption are key to encouraging water-saving behaviors and the adoption of smart metering technologies. Together, these studies show that awareness of environmental concerns can lead to stronger intentions to adopt sustainability-focused digital tools.

Consistent with TAM, perceived ease of use (PEOU) significantly predicted perceived usefulness (PU) ( $\beta = 0.653$ ,  $p < 0.001$ ), supporting H3, and PU strongly predicted behavioral intention (BI) ( $\beta = 0.732$ ,  $p < 0.001$ ), supporting H6. These findings reaffirm TAM's core proposition that ease of use increases perceived usefulness, which, in turn, influences the intention to adopt a technology. Previous research also shows that intuitive and user-friendly systems boost users' comfort, confidence, and perceived benefits (Davis, 1989; Venkatesh & Davis, 1996; Liu et al., 2010). The significant impact of PEOU on PU and PU on BI paths observed here underscores TAM's internal consistency and its effectiveness in explaining the cognitive processes underlying adoption. The results confirm the model's robustness and

ongoing relevance for understanding user acceptance of new digital tools, especially when perceived utility is a key factor in adoption.

## **6.6 Implications of the Results**

A socio-technical perspective provides a nuanced understanding of how social and technological factors interact within a specific environment. The results indicate that aligning social, environmental, and governmental drivers with the functional features of digital tools can significantly increase users' intention to adopt them. In the UAE, a non-financial constrained context where digital transformation is a national priority and visionary leadership acts as a strong motivator, it is essential to identify strategic management early on, based on key factors, to ensure successful implementation and sustained user engagement. Overcoming barriers that reduce intention, while enhancing enablers such as water security concerns, self-efficacy, and perceived usefulness, can accelerate adoption toward clear benefits, including improved water conservation, increased operational efficiency, reduced uncontrolled losses, and better sustainability outcomes. This is essential, particularly in the UAE, a harsh dry country facing severe water scarcity and extremely high supply costs, while committed to the highest standards of living and quality of life.

The emergence of water security concerns (WSC) as an important predictor of behavioral intention underscores key policy and educational implications of this study. This finding presents an opportunity for universities, educational institutions, and local authorities a chance to enhance water-related environmental knowledge through curriculum integration, practical learning, and public engagement efforts. Furthermore, institutional stakeholders such as water utilities and government agencies can leverage these behavioral insights by collaborating to develop targeted awareness campaigns and community outreach programs that link individual actions to national water security goals. Such coordinated efforts can increase civic participation, promote pro-environmental behavior, and support the broader national agenda for sustainable water management in the UAE. This finding is particularly significant in the UAE, where extreme climate conditions, scarce resources, and ongoing water security

challenges heighten the need for effective water management solutions. In time, the technology is in place and is not impeded by financial constraints.

Additionally, the findings highlight the crucial role of government policy design in shaping public perceptions of the usefulness of digital tools. The substantial positive impact of Government policies (GP) on perceived usefulness (PU) indicates that policy frameworks do more than regulate the deployment of technology; they actively influence how citizens assess the value and relevance of new digital tools. This emphasizes the need for adopting flexible, relevant, and performance-focused policies that foster innovation and encourage public participation. The objective-oriented policies that establish clear performance standards and ensure accountability through mechanisms such as periodic audits, impact assessments, and compliance checks serve as practical enablers. When citizens see that the government is committed to robust governance, responsible implementation, and long-term sustainability aims, their confidence in the usefulness of digital water-monitoring solutions grows. As a result, well-designed regulations and digital policy measures help streamline digital practices that support national goals for water conservation and resource management, while also boosting technology adoption.

The results for personal factors, mobile self-efficacy (MSE), mobile device anxiety (MDA), and perceived ease of use (PEOU) further highlight their contrasting influences. They also emphasize the importance of human-centered interfaces in shaping adoption outcomes. Improving users' digital self-efficacy through targeted training programs, intuitive user-focused design, and structured exposure to digital systems can significantly improve perceptions of usability. Conversely, lowering mobile device anxiety, especially among novice, elderly, or digitally marginalized users, requires supportive strategies such as specialized learning environments, accessible interface designs, and responsive technical support. Therefore, fostering digital self-efficacy with well-designed interventions can both reduce anxiety and increase confidence. These strategies help navigate IoT-enabled tools and close the digital skill gaps that might otherwise hinder technology adoption. Overall, these approaches highlight the importance of human-centered design and digital skill development

as complementary strategies to improve perceived ease of use and encourage wider adoption of smart water monitoring technologies.

These findings provide clear guidance for technology providers, emphasizing the importance of designing interfaces that are intuitive, visually simple, and easy to navigate cognitively. Reducing user burden through proper design can improve perceptions of ease of use. Additionally, complementary outreach strategies such as leveraging public figures, participatory demonstrations, and hands-on trials can further increase public confidence in the technology. For utilities, the results highlight the importance of co-developing training workshops and simulation-based demonstrations to enhance both public digital awareness and the workforce's technical skills. These initiatives help close the socio-technical gap that often hinders digital transformation efforts. Furthermore, maintaining service reliability and ensuring transparency in supplier selection, data management, and system performance can strengthen public trust, which is crucial for encouraging the adoption of smart water technologies.

These targeted interventions, evident in the study's empirical insights, underscore the importance of combining technological innovation with human-centered capacity-building and awareness. Such strategies enhance public engagement and support the UAE's broader goals for sustainable water management and smart urban development. The findings highlight the need for a coordinated, multi-stakeholder approach involving government agencies, utilities, technology providers, and community organizations to align on the regulatory, technical, and social aspects of digital adoption. The study validates a socio-technical framework that provides policymakers with a strategic foundation for planning and implementing emerging digital water technologies. By incorporating user-focused, environmental, and governmental factors, the framework illustrates the interactions between technological systems and social behavior, offering valuable insights for digital water planning, especially in a context like the UAE, where digitalization efforts are intertwined with severe water scarcity and sustainability challenges.

Practically, the findings highlight the importance of key behavioral factors, such as users' anxiety, efficacy, water security concerns, and perceptions of government support, in shaping the acceptance of digital water technologies. Incorporating these socio-behavioral insights into public engagement strategies and policy development can improve user readiness and encourage widespread adoption. This directly supports the UAE's national water strategy and DEWA's sustainability goals by promoting efficient water use, reducing water losses, and improving service delivery. Given the country's reliance on energy-intensive desalination, such informed interventions offer a cost-effective and environmentally sustainable path to long-term water security management.

Theoretically, the study expands socio-technical thinking in urban water management, an area where theory has been limited. By extending the Technology Acceptance Model (TAM) to include environmental, governmental, and personal contextual factors, the research offers a strong, flexible model for managing water infrastructure. The proposed framework demonstrates high predictive ability for behavioral intention, underscoring the importance of incorporating contextual variables to enhance adoption theory and extend its applicability beyond traditional information systems research. Additionally, it paves the way for further studies to test the framework experimentally and conduct post-implementation research. The approach can be transferred to other cities in the UAE or applied in other contexts to test its credibility and external validity. To the best of the authors' knowledge, this is the first attempt in the UAE, and the broader Middle East opens avenues for more studies.

## **6.7 The Study Conclusions and Limitations**

This study employed a socio-technical perspective, utilizing the Technology Acceptance Model (TAM) to forecast users' intentions to adopt IoT-enabled smart water tools in the UAE. The TAM is extended and validated within a sustainability-focused, policy-oriented framework by incorporating psychological (MSE, MDA), environmental (WSC), and governmental (GP) factors. The use of SEM with the WLSMV estimator was chosen to rigorously handle ordinal data and small samples (149 data points). The model's high explanatory power ( $R^2 = 0.93$ ) indicates strong predictive ability for behavioral intention. The

results contribute to TAM-based theory in several ways; the significant effects of self-efficacy and device anxiety on perceived ease of use highlight the importance of users' readiness in shaping digital technology adoption. Additionally, the traditional PEOU, PU, and BI relationship is confirmed, reaffirming TAM's robustness. Notably, the emergence of water security concern (WSC), a novel factor, as a direct and significant predictor of behavioral intention, introduces an environmental-behavioral aspect rarely addressed before. Similarly, the positive influence of government policies (GP) on perceived usefulness underscores the strategic role of governance, regulations, and policy awareness in promoting public engagement with digital transformation efforts.

In practice, the results offer insights for government agencies, highlighting the need for integrated policy frameworks that combine technological literacy initiatives with clear communication on environmental responsibilities and digital governance awareness. For technology providers and utilities, the findings emphasize the importance of user-focused design and transparent communication to reduce anxiety and increase user acceptance. Theoretically, this research expands the applicability of TAM by integrating contextual environmental and institutional factors relevant to sustainable resource management. In line with the UAE's Water Security Strategy 2036 and DEWA's Smart Transformation Vision, the proposed framework provides a solid foundation for decision-makers aiming to accelerate the adoption of digital tools through improved citizen engagement to support sustainable urban water management.

Despite its theoretical and methodological strengths, several limitations should be acknowledged. First, the modest sample size, although sufficient for WLSMV-SEM, limits generalizability and reflects common challenges in recruiting participants for studies on emerging technologies. Therefore, findings should be interpreted as context insights rather than as broad generalizations. However, the approach can be replicated and scaled up to include other cities in the UAE for broader generalization. The cross-sectional design also limits causal conclusions; future longitudinal or experimental studies could effectively examine how perceptions change over time. Although validated scales and diagnostic checks were employed, self-report bias may exist. The focus on the UAE, a digitally advanced but uniquely

positioned setting, further limits the applicability of results elsewhere, highlighting the need to test the extended model in different socio-technical contexts.

Furthermore, demographic control variables (e.g., sex, age, and education) were not analyzed, and the model excluded TAM's attitude construct as well as trust and cost factors, all of which may influence acceptance. Future research might examine these dimensions and employ larger, more diverse samples to enhance external validity. Overall, these limitations underscore the study's exploratory and contextual nature while outlining clear directions for refining and validating the model in broader digital water management contexts.

## CONCLUSIONS

This section presents the main conclusions drawn from the three studies, which aim to achieve the main objective. The thesis addressed the slow adoption of emerging DT technologies in urban water management practices by analyzing adoption mechanisms in a digitally advanced, non-financially constrained area. Literature indicates that slow adoption among stakeholders is attributed to several knowledge, awareness, and empirical gaps regarding the technology's potential, value propositions, barriers, and user acceptance issues. Stakeholders are a vital pillar for change and adaptation to the new digital era. Therefore, this thesis investigated various aspects of the digitalization of water management through DT technologies among key stakeholders in the UAE, a leader in digitalization in the Middle East and globally.

Reflecting on the early adoption stage of digital twin DT technologies, even in developed countries, the UAE, particularly Dubai, has made recognized efforts, establishing itself as a hub of technological advancement in the Middle East and globally. This confirms Dubai as a relevant area for examining digitalization mechanisms. This thesis presents the work through three studies that target the decision-making levels of relevant stakeholders to provide insights into water DTs adoption, for the first time in the Middle East. Thus, the thesis provides a coherent body of knowledge that offers both evidence-based and predictive insights to guide well-informed digitalization efforts. The following are the collective main conclusions revealed from the three studies summarized in points:

1. The empirical results indicate that digitalization of water infrastructure management can not be explained or tackled by one model or single factor; it requires understanding the project-organizational settings, motivational strategies, and citizen engagement, each discussed and refined to collectively address the slow adoption among stakeholders. This insists that digitalization is a multi-actor phenomenon and ensures the role of stakeholders' perceptions.
2. The major barriers to DTs' adoption in the design and construction of water projects are: cybersecurity, data availability and ownership issues, as well as the lack of standardization and interoperability tools, the absence of a trained and skilled workforce, lack of

governmental promotion, and the incremental development costs. Thus, data-technical, workforce, governmental, and economic barriers still dominate stakeholders' perceptions, even with project experience.

3. However, a nuanced lens of focus group discussion revealed that the workforce skills gap is the most challenging, followed by cybersecurity issues, the digitized data quality concerns (accuracy, usefulness, relevance), weak regulatory enforcement, the need for structured governance, and cultural resistance continue to be major obstacles requiring attention.
4. Government roles are the primary enablers; the empirical results advocate stricter regulations and mandates, as well as a data governance structure to ensure data security.
5. The refined views additionally noted that standardization and interoperability tools, and uniform data schemas issues are less challenging than before. Besides, the incremental costs are not major concerns; they have been alleviated over time, knowing they will be offset by work efficiency and organizational competency.
6. The results suggest that actively mitigating barriers is prioritized to promote the adoption of DTs in water infrastructure projects. This emphasizes the importance of raising awareness, long-term strategic planning, upgrading workforce digital skills, formulating effective digital policies, and establishing regulations for data security implementation and governance.
7. In addition, promoting the DTs' benefits by communicating the successful case studies and reported improvements in the current workflow will enhance understanding of the technology's potential and value. Moreover, initiating cultural shifts and changing mindsets, along with lifecycle-oriented thinking and planning, are essential for successful digital transformation in water infrastructure projects.
8. The empirical results revealed that the key drivers of DTs' adoption in water projects were to optimize work performance, leverage data to reduce operational costs, enhance safety and risk management of asset networks, and improve public safety. Thus, operational performance, economic, and safety management are the key drivers.

9. A shared consensus among stakeholders on empirical drivers' importance was reported, except for two: leveraging data to reduce operational costs and improving customer service, reflecting the variation in organizational priorities.
10. It is highly important to set policies and regulations and design mandates that can audit performance and ensure compliance implementations in the UAE water management. Case study analysis results align with the quantitative results, except for regulatory compliance. The driver is dominant in real-world utility examples as a primary driver, but lacks sufficient support in UAE-experienced perceptions.
11. Additionally, it is important to communicate the policies, initiatives, and regulations to the stakeholders and link the DTs deployment to broad objectives such as asset-management and sustainability outcomes.
12. Digital water projects are associated with high success evaluation based on perceptions. The majority of the participants assessed their goal achievements as achieved or exceeded. Additionally, they reported a high satisfaction level with the adoption and implementation of digital water projects.
13. The empirical drivers and project success results can serve as reference points and lessons learnt for similar contexts in the Middle East and globally, that aim to digitalize urban water management; however, generalization should be handled with strict caution due to differences in digital maturity and contextual settings.
14. Water industry stakeholders and academia should commit more efforts to adopting, testing, and evaluating new technologies across various areas, especially in developing countries that struggle with water security issues.
15. The mixed methods approach was beneficial and effective to contextualize the quantitative findings, complement them, and provide a profound understanding of barriers and drivers of DTs adoption for digital water projects and initiatives.
16. The extended TAM framework confirmed applicability and robustness to predict the determinants of users' intentions to adopt digital tools for managing household water consumption. The  $R^2$  value in behavioral intention (BI) is 0.932, indicating substantial predictive power. Thus, TAM is capable of predicting users' intention to use the water digital tools.

17. The mobile self-efficacy (MSE) is a strong predictor of perceived ease of use (PEOU), supporting the idea that self-confidence in using mobile devices enhances perceived system usability.
18. Mobile device anxiety (MDA) is a deterrent to PEOU, suggesting that anxiety around digital tools play an adverse role in the usability of tools even in a digitally advanced region like the UAE.
19. Water security concern (WSC) is an enabler to behaviour intention BI among public users in the UAE, significantly predicting BI. This indicates that citizens' concerns about water security issues may directly impact their intention to use the digital water tool. Additionally, the results enforce the effectiveness of citizen engagement as a new approach for urban governance.
20. The users' awareness of the supportive policy frameworks plays a vital role in promoting technology acceptance by influencing the tool's utility. Government policies (GP) significantly affect perceived usefulness (PU).
21. The proposed conceptual model can serve as a valid predictive framework for planning the water digital tools implementation. Thus, pre-implementation or concurrent strategies should take place to equip the public users with the essential knowledge and awareness of water security and governmental commitment to sustainability practices. Besides, address the digital tool's features that promote users' self-confidence and mitigate their fears towards tool usage. This can secure better acceptance and widespread adoption among potential users, thereby ensuring successful implementation. As the first attempt of the approach in the UAE and the broader Middle East, the research opens avenues and paves the way for more studies.
22. By raising the awareness, educate the workforce and the public, cross-disciplinary collaboration between all relevant stakeholders for building workforce digital capacity, revising and upgrading the educational programs and course outlines to integrate digital knowledge, setting a structured governance for data security, updating current policies to keep up with the requirements of emerging digital tools and setting regulations and mandates for compliance and environmental commitment, digitalization by DTs adoption

can be promoted among diverse stakeholders, and benefits can be realized in a water-stressed context like the UAE.



## RECOMMENDATIONS

This section suggests recommendations for future research that build on the limitations encountered and the new perspectives gained during the research. However, each manuscript includes a section that reports the limitations, justifies the concessions, and proposes recommendations accordingly. Therefore, this section provides the overall recommendations from all studies as follows:

1. For future studies, it is recommended to include a diverse sample (more utility and academic representation), with varying experience levels and more members of the new generation workforce, to explore new generational perspectives on technology adoption, rather than focusing on the CEOs and MDs. The results may be biased by managerial-level perceptions and non-random sampling techniques; however, purposive sampling was justified and inevitable, given the early stage of adoption, the lack of demonstrations, and the deep technical level required to answer the questions. Random sampling and larger sample size can be maintained in the future, once the DTs are established, to provide a generalizable perspective on DT technology adoption and gain deeper insights into perceptions.
2. Adopting a more detailed 7-point agreement scale could detect subtle variations in responses, resulting in more interpretable results, and is recommended for future research.
3. Confirmatory studies are recommended in the future to validate the empirical results and generalize them to larger populations in the Middle East. Further investigation is recommended to explore adoption factors using qualitative primary data, thereby gaining a deeper understanding of the Middle East context.
4. Other studies are encouraged to apply the same approach to other locations in the region; they may also apply it to the component scale and include more water systems, such as dams, detention basins, and treatment plants, to validate more specific benefits and barriers.

5. More research is recommended on specific maturity levels of DTs in urban water systems. The thesis discussed the digital twin technologies regardless of their maturity levels or capabilities. More level-specific research can target the multi-maturity levels to explore the specific adoption factors and project success associated with each level. This thesis operates on a macro level and explores DTs in general.
6. Furthermore, it is recommended that future researchers conduct cost analysis to monetarily establish the value of adoption, as this study was limited in its ability to access monetary data for quantification due to the early stage of the application and the high confidentiality requirements in the UAE.
7. The adoption factors identified and validated by the studies can be integrated to develop a system dynamics model. The systems dynamics methodology can simulate and assess intervention by modeling factors over time and explaining the cause-and-effect feedback loops in the UAE case. Thereby, policy interventions can be analyzed and evaluated early to provide well-informed simulated decisions on the adoption and implementation of DTs for urban water management.
8. Many measurement dimensions can be integrated and tested in future research to establish perceived project success and its enabling factors other than delivery achievements and stakeholders' satisfaction.
9. The study focused on considering three categories of stakeholders; however, many other stakeholders can be identified and consulted for future research. The literature defines a broad spectrum of stakeholders within the field of project management and the adoption of digital tools.
10. Due to the continuous changes in public behavior and the dynamic nature of social systems, the proposed extended TAM can be tested experimentally in longitudinal studies. By actually addressing the strategies that the framework provides to enforce its temporal causality predication and external validity.
11. Including demographic variables analysis within the TAM model is recommended for future investigation, which could act as control variables and might influence the model's predictive power.

12. Moreover, while the hypotheses were based on previous studies, many others causal relationships could also be proposed and tested to explain and predict various effects.
13. Additionally, cost and trust factors have proven important roles in influencing the intention to buy and use smart water meters in previous research. Future studies may incorporate cost-related and trust factors, along with other variables, to evaluate their impact on user intention.
14. To generalize findings from studies involving public users, the sample size must be carefully managed, requiring significant resources in terms of time and budget, which is not feasible within this thesis's scope. Future research could involve larger sample sizes and a post-implementation approach to investigate more influential factors, once the technology has been more widely adopted or achieved broader penetration, thereby enabling better generalization of the findings for both practical application and theoretical development. Cautions should be exercised when generalizing given differences in contextual settings and digital awareness across Middle Eastern countries.



## ANNEX I

### Population Information

The identified population of digitally-engaged or familiar stakeholders in the study area, the UAE, Dubai

### Water Utilities

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3. Maria Isabel Igrata, Senior Assistant at Dubai Electricity & Water Authority, **DEWA**, United Arab Emirates, [Maria.Igrata@dewa.gov.ae](mailto:Maria.Igrata@dewa.gov.ae)
4. Shahul Hameed, Digital Transformation Expert, Program Management Specialist, Dubai Electricity & Water Authority, **DEWA**, UAE, [Shahul.Hameed@dewa.gov.ae](mailto:Shahul.Hameed@dewa.gov.ae)
5. Eng.Abdallah Alqahtani, Network Engineer, **Water Authority SWA**, [aalq020@gmail.com](mailto:aalq020@gmail.com)
6. Wael Tawfiq Yahya, Data | Strategy | Research, **TRANSCO**, United Arab Emirates, [https://www.linkedin.com/in/wael-tawfiq-yahya-3931b616?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BQ1uLnew2R9yffOrbklnCCQ%3D%3D](https://www.linkedin.com/in/wael-tawfiq-yahya-3931b616?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BQ1uLnew2R9yffOrbklnCCQ%3D%3D)
7. Dr Jarrah AlZubi, Senior Manager at Dubai Electricity & Water Authority – **DEWA**, Dubai, UAE, [https://www.linkedin.com/in/dr-jarrah-alzubi-01b4335?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BwETktMEwQMyyv6q3apx9nA%3D%3D](https://www.linkedin.com/in/dr-jarrah-alzubi-01b4335?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BwETktMEwQMyyv6q3apx9nA%3D%3D)
8. Dr. Mamoon Atout, Senior Specialist at **DEWA**, Dubai, UAE, [https://www.linkedin.com/in/dr-engr-mamoon-atout-f-ciob-e-ipmo-safe-361aa4a?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BqBVP6WZRKeUJF8r7rku8g%3D%3D](https://www.linkedin.com/in/dr-engr-mamoon-atout-f-ciob-e-ipmo-safe-361aa4a?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BqBVP6WZRKeUJF8r7rku8g%3D%3D)
9. Bruce Stedall, Chief Operating Officer, **Transco** water and electricity distribution utility, <https://www.linkedin.com/in/bruce-stedall->

- [662b28b6?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3Bhq9xbBqpQMmSWWD2mPVwig%3D%3D](https://www.linkedin.com/in/surendra-singh-chhajta-61018527?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3Bhq9xbBqpQMmSWWD2mPVwig%3D%3D)
10. Surendra Chhajta, O&M Director, **Transco** water and electricity distribution utility, [https://www.linkedin.com/in/surendra-singh-chhajta-61018527?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3B7RI5P00CS0uK2Uv74Fr0gA%3D%3D](https://www.linkedin.com/in/surendra-singh-chhajta-61018527?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3B7RI5P00CS0uK2Uv74Fr0gA%3D%3D)
  11. Stefano Lagna, Chief Financial Officer, **Transco** water and electricity distribution utility, [https://www.linkedin.com/in/stefanolagna?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BhDgHm47mQWC7BhPwwbP8Ww%3D%3D](https://www.linkedin.com/in/stefanolagna?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BhDgHm47mQWC7BhPwwbP8Ww%3D%3D)  
<http://www.enel.com/>
  12. Omar ALAWNEH, Instrument supervisor at Abu Dhabi Transmission and Despatch Company (**TRANSCO**), United Arab Emirates, [https://www.linkedin.com/in/omar-alawneh-89036928?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BMmWR4OEtRWuAIGZmTexDeg%3D%3D](https://www.linkedin.com/in/omar-alawneh-89036928?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BMmWR4OEtRWuAIGZmTexDeg%3D%3D)
  13. Hamzeh AbuZaid, Senior Executive Director, Strategy, Execution & Operation, **Saudi Water Authority SWA**, KSA, [https://www.linkedin.com/in/hamzeh-abuzaid?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3B7oDLXTSkRCmwIkaUzS393g%3D%3D](https://www.linkedin.com/in/hamzeh-abuzaid?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3B7oDLXTSkRCmwIkaUzS393g%3D%3D)
  14. Dr. Afif Saif Al Yafei, Chief Executive Officer, **Transco** Water and Electricity distribution utility, [https://www.linkedin.com/in/dr-afif-al-yafei-83242238?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BUnfA%2FpHtS8CmvqDC9Griwg%3D%3D](https://www.linkedin.com/in/dr-afif-al-yafei-83242238?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BUnfA%2FpHtS8CmvqDC9Griwg%3D%3D)
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  17. Abdulla Mohamed AlNuaimi, Water Asset Division Manager -Asset Management |Investment Management|Strategic Planning |Project Management, **TRANSCO**, Abu Dhabi, UAE, [https://www.linkedin.com/in/abdulla-mohamed-alnuaimi?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BmPnAchQGSkqCFYg%2BGZ9JA%3D%3D](https://www.linkedin.com/in/abdulla-mohamed-alnuaimi?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BmPnAchQGSkqCFYg%2BGZ9JA%3D%3D)
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20. Hesham Saber, Operations Engineer at Dubai Electricity & Water Authority – DEWA, Dubai, UAE, [https://www.linkedin.com/in/hesham-saber-34a98911a?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3B5pS0gZS4RnaSXXg0TyKIFw%3D%3D](https://www.linkedin.com/in/hesham-saber-34a98911a?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3B5pS0gZS4RnaSXXg0TyKIFw%3D%3D)
21. Ahmad Al Wahedi, Asset Information Department Manager at TRANSCO, Abu Dhabi, UAE, [https://www.linkedin.com/in/ahmad-al-wahedi-215854a3?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3Bc9pNILDvTfOHUtzPNPDNQg%3D%3D](https://www.linkedin.com/in/ahmad-al-wahedi-215854a3?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3Bc9pNILDvTfOHUtzPNPDNQg%3D%3D)
22. Hamad Ahmed Alzaabi, Water Asset Performance Section Manager, TRANSCO, [https://www.linkedin.com/in/hamad-ahmed-alzaabi-76254984?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3B9%2FABD%2FNTQHimgOLAP5log%3D%3D](https://www.linkedin.com/in/hamad-ahmed-alzaabi-76254984?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3B9%2FABD%2FNTQHimgOLAP5log%3D%3D)

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24. Sami Al Masri, PMP, Senior Technical Program Manager (EMEA) at Oracle Cloud Infrastructure (OCI) | Ex-Amazon | Ex-IBM, Dubai, United Arab Emirates, [https://www.linkedin.com/in/sami-al-masri-pmp-0143a729?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3B%2FW9zXACRQYC12BBsB7EDBg%3D%3D](https://www.linkedin.com/in/sami-al-masri-pmp-0143a729?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3B%2FW9zXACRQYC12BBsB7EDBg%3D%3D)
25. Laith Najjar, Strategy & BD @ Oracle | Digital Transformation Strategist | INSEAD, Dubai, United Arab Emirates, [https://www.linkedin.com/in/laithnajjar?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3Bf5vqlFusTSalcBhB9Sq0JQ%3D%3D](https://www.linkedin.com/in/laithnajjar?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3Bf5vqlFusTSalcBhB9Sq0JQ%3D%3D)
26. Tania Chadah, Technology Consultant @ Oracle | Driving Digital Transformation & Innovation | Expertise in Digital Transformation, Dubai, United Arab Emirates, [https://www.linkedin.com/in/tania-chadah?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BX0Rt4DxMRBGfbwxi6z68Lw%3D%3D](https://www.linkedin.com/in/tania-chadah?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BX0Rt4DxMRBGfbwxi6z68Lw%3D%3D)
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29. Ahmed El-Zaalik, Regional Sales Manager at **Evoqua Water Technologies**, Evoqua Water Technologies, Saudi Arabia, [https://www.linkedin.com/in/ahmed-el-zaalik-49217779?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3Bp0NTY%2F2rT%2FO1vWBwgLG8Jg%3D%3D](https://www.linkedin.com/in/ahmed-el-zaalik-49217779?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3Bp0NTY%2F2rT%2FO1vWBwgLG8Jg%3D%3D)
30. Shaik Abdullah, Service Engineer at **Xylem Middle East Water Equipment Trading & Rental LLC**, United Arab Emirates, [https://www.linkedin.com/in/shaik-abdullah-5b1795a4?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3Biqyl5DRARBSvC%2F7u6rKDHg%3D%3D](https://www.linkedin.com/in/shaik-abdullah-5b1795a4?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3Biqyl5DRARBSvC%2F7u6rKDHg%3D%3D)
31. Ivan Sedov, Senior Key Account Manager, Aftermarket & Service Sales Expert | Life Cycle Services, **Xylem**, Dubai, United Arab Emirates, [https://www.linkedin.com/in/ivan-sedov-6b4bb8263?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3Bq6lSXeZQOa02Z%2BnihuoVA%3D%3D](https://www.linkedin.com/in/ivan-sedov-6b4bb8263?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3Bq6lSXeZQOa02Z%2BnihuoVA%3D%3D)
32. Maya Ayoub, Senior Regional Sales & Business Development Manager at **Diehl Metering**, Diehl Metering, Dubai, United Arab Emirates UAE, [https://www.linkedin.com/in/maya-ayoub-60b18736?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BMHkvayhSQ%2BW9ugzaOxDcKA%3D%3D](https://www.linkedin.com/in/maya-ayoub-60b18736?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BMHkvayhSQ%2BW9ugzaOxDcKA%3D%3D)
33. Tarek Khairallah, Senior Sales & Business Development Manager, **Diehl Metering**, Dubai, United Arab Emirates UAE, [https://www.linkedin.com/in/tarek-khairallah-a668086?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BuzsneQ5bSdiQqBiKJpVUhQ%3D%3D](https://www.linkedin.com/in/tarek-khairallah-a668086?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BuzsneQ5bSdiQqBiKJpVUhQ%3D%3D)
34. Mohamed Alayat, Regional Sales Manager at Diehl Metering, **Diehl Metering**, United Arab Emirates UAE, [https://www.linkedin.com/in/mohamed-alayat-451412ba?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3B8I%2BUh3U5RBGNTyYsGTLAOA%3D%3D](https://www.linkedin.com/in/mohamed-alayat-451412ba?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3B8I%2BUh3U5RBGNTyYsGTLAOA%3D%3D)
35. Rami Jamous, Technical Manager at Diehl Metering, **Diehl Metering**, Dubai, United Arab Emirates UEA, [https://www.linkedin.com/in/rami-jamous-38b516b4?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BKlHKQJUzQoajjPU5IEuxJg%3D%3D](https://www.linkedin.com/in/rami-jamous-38b516b4?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BKlHKQJUzQoajjPU5IEuxJg%3D%3D)
36. Ali Badran, Head of Customer Solution Center Middle East Region, **DIEHL Metering**, United Arab Emirates UAE, [https://www.linkedin.com/in/ali-badran-a3929596?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3BpJLVS39pR5%2BRnau1MQulRg%3D%3D](https://www.linkedin.com/in/ali-badran-a3929596?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3BpJLVS39pR5%2BRnau1MQulRg%3D%3D)

### **Consultation and Contracting Firms**

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[https://www.linkedin.com/in/yousef-altartouri-41264aa9?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3B%2Fts41SOSQAe%2FAQmj8Y8%2BAw%3D%3D](https://www.linkedin.com/in/yousef-altartouri-41264aa9?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3B%2Fts41SOSQAe%2FAQmj8Y8%2BAw%3D%3D)
159. Araz Awakian, PMP, Project Manager, **AECOM**, United Arab Emirates,  
[https://www.linkedin.com/in/araz-awakian-pmp?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3B%2Fdtjt35fQDqOCCTt79x3uA%3D%3D](https://www.linkedin.com/in/araz-awakian-pmp?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3B%2Fdtjt35fQDqOCCTt79x3uA%3D%3D)
160. Yahya Kaddoura, Designing Cities of the Future, **Atkins**, United Arab Emirates,  
[https://www.linkedin.com/in/yahyakaddoura?lipi=urn%3Ali%3Apage%3Ad\\_flagship3\\_profile\\_view\\_base\\_contact\\_details%3B%2F0Rz1R%2BSMyekI5ZRoZxxw%3D%3D](https://www.linkedin.com/in/yahyakaddoura?lipi=urn%3Ali%3Apage%3Ad_flagship3_profile_view_base_contact_details%3B%2F0Rz1R%2BSMyekI5ZRoZxxw%3D%3D)

## ANNEX II

### Water Digital Project Cases

Table-A II-1 Water Digital Project Cases

Case Studies	Business Case Drivers	Project Initial Objectives	Benefits Realized
<p><b>1. Metropolitan Sewer District of Greater Cincinnati</b></p> <p>Cincinnati, Ohio, U.S. City-scale rollout of sewers</p> <p>Technology provider</p> <p><b>GoAigua's</b> from <b>Xylem</b> sensors weather data artificial intelligence RTC decision</p>	<p>EPA federal consent decree on elimination SSO &amp; mitigation of CSO into receiving Waterways.</p>	<p>Maximize existing capital assets (Storage interceptor, pumping, treatment facilities)</p> <p>Avoid massive capital investments</p> <p>Reduce overflows</p> <p>Optimal watershed operations</p>	<p>Real-time decision Support system</p> <p>Automated optimized asset control (RTC)</p> <p>Reduce sewage overflows</p> <p>Maximize storage</p> <p>Maximize treatment</p> <p>90% Cost reduction</p> <p>Reductions CPEX &amp; OPEX</p> <p>CSO mitigated</p> <p>Output can be viewed. in a browser-based App making it accessible on any device, by any authorized User.</p> <p>Environmental regulations compliance</p>
<p><b>2. DC Water's Digital Twin Solution Columbia</b></p> <p>Improving Operational readiness and Financial Resilience by implementing a Water Infrastructure Digital Twin</p> <p>Technology Provider</p> <p><b>Bentley</b></p> <p>Bentley's OpenFlows</p>	<p>District strategic plan leveraging technological innovation</p> <p>High-quality customer services through five-year strategic plan</p> <p>DC water distributes DW &amp; collects &amp; treats WW for 670,000 residents &amp; 17.8 M visitors</p>	<p>Short-term</p> <p>Improve reliability, Increase efficiency,</p> <p>Reduce cost</p> <p>Drive innovation</p> <p>Enhance the customer experience.</p> <p>Mitigate service disruptions</p> <p>Reduce nonrevenue water</p> <p>Improve customer service.</p> <p>Leverage data to reduce operational and capital expenditures</p>	<p>A browser-based common environment visible across the enterprise</p> <p>Reduce OPEX &amp; CAPEX &amp; non-revenue water</p> <p>Improve the customer's</p> <p>Improve water quality operation pressure</p> <p>operational responses</p> <p>SCADA-integrated hydraulic model data output</p> <p>conduct "what if"</p>

Table-A II-1 Water Digital Project Cases, continued

<p>WaterSight™</p> <p>a real-time, cloud-managed water infrastructure “Digital twin.”</p> <p>GIS, asset data, operational Maximo work order hydraulic simulation models, SCADA</p>	<p>ongoing pilot test WDS</p>	<p>Automate nonrevenue audits</p> <p><b>Long-term objectives</b></p> <p>tracking water consumption all the pumps data &amp; operational functions visibility in enterprise</p>	<p>scenarios for informed decisions</p>
<p><b>3. City of Grand Rapids Michigan, U. S</b></p> <p>Sewer system city scale</p> <p><b>Xylem</b></p> <p>deployed a sensor network (flow meters &amp; rain gauges) to collect real time data from the Sanitary lines.</p> <p>SCADA</p> <p><b>Vue</b> powered by <b>GoAigua's</b> SSO/CSO Prediction &amp; Prevention applications</p>	<p>Regulations compliance with DOE mandate</p> <p>Certify performance</p> <p>invested 30-50 M SAVES up to \$1 BILLION</p> <p>Installed and commissioned 90 Flow meter 10 rain gauges to collect real-time data on sanitary lines</p>	<p>Understand sewer behavior Modeling the performance in a computer environment for better prediction</p> <p>Predict how the system</p> <p>Avoiding costly Improvements to exist infrastructure.</p> <p>Solve I/I issue represented by flood and surcharge</p>	<p>Collected, organized, analyzed served data via dashboards,</p> <p>Visual tool to understand and regulate the operation of their sewer systems</p> <p>High-accuracy model Sensor data integrated</p> <p>Identifying critical areas need improvement solved with low cost</p>
<p><b>4. Philadelphia Water Department Online Water Quality Monitoring (OWQM) Project PWD</b></p> <p><b>KISTERS</b></p> <p><b>WISKI</b> (Water Information Systems KISTERS)</p>	<p>keep up with technology</p> <p>Environmental Commitment</p> <p>Improved customer service and utility performance</p> <p>Fully automate data management</p>	<p>Acquire and store water quality sensor measurement and sensor state data (calibration/maintenance status)</p> <p>Perform automated data validation based on sensor state status.</p> <p>Analyze data to assess</p>	<p>Fully automated data management processing.</p> <p>Data validated in real-time for reporting and sourcing</p> <p>WISKI performs data quality management notifying them by SMS or email of any scenarios</p>

Table-A II-1 Water Digital Project Cases, continued

<p>OWQM data management system</p> <p>SCADA, Sensors proven data management platform integrates numerous application modules for analysis statistical calculations, and visualization</p>	<p>system</p> <p>Control water quality</p> <p>Leverage data to improve performance and management</p> <p>A network of 3,100 miles water main</p> <p>3,700 miles of sewers</p> <p>6 treatment facilities</p> <p>34 pumping stations</p>	<p>water quality and sensor states.</p> <p>Generate and terminate alarms based on sensor states and water quality thresholds.</p> <p>Achieve 99.9% availability.</p>	<p>require further attention</p> <p>Web service users can view &amp; download information with ease.</p> <p>Enable multi-parameter monitoring from the watershed</p> <p>Alarm announcement sms &amp; email notification.</p> <p>Optimize the time for data processing.</p>
<p><b>5. Advancing Digital design to Digital Twin on Durliegh Water Treatment Centre</b></p> <p><b>Wessex, UK</b></p> <p><b>AECOM</b></p> <p><b>INVICARA</b></p> <p>cloud computing</p> <p>real-time sensors</p> <p>SCADA</p> <p>Edge computing</p> <p>3D revit</p> <p>Civil 3D</p> <p>plant 3D</p> <p>point cloud scan</p> <p>GPR surveys</p> <p>Drinking water treatment trial project</p> <p>Wessex district</p>	<p>Manage the center in digitally advanced way</p> <p>Response to client growing demand</p> <p>Utilize the assets at the full treatment capacity</p> <p>Improve the service quality</p> <p>Enable best operation &amp; asset management</p> <p>Future optimized performance</p> <p>Reduce energy</p> <p>Reduce cost, chemicals</p> <p>consumption</p> <p>unplanned shutdowns</p>	<p><b>Asset Twin</b></p> <p>cloud supported</p> <p>3D model tagged with all information</p> <p>help operators to quick identification</p> <p><b>Performance Twin</b></p> <p>Operational SCADA data visualized through the common platform</p> <p>Provide the asset operation and the management team access to all information digitized and visualized</p> <p>Data-driven decision making in advance on early intervention</p>	<p>Digitalized asset information accessed easy and available</p> <p>Real-time data visualization for Data driven decision making</p> <p>The \$68M Durliegh WTC upgrade enable treatment of 30 ML/ day</p> <p>Wessex Water covers 10,000 SK</p> <p>Supplies 1.3 M people</p>
<p><b>6. THE CITY OF CALGARY</b></p> <p><b>water main</b></p> <p><b>city-scale water-main feeders</b></p> <p><b>MOBILTEX®</b></p>	<p>Municipality plan</p> <p>City initiative program to invest in technology smart performance for monitoring</p>	<p>To manage corrosion in Calgary's water network</p> <p>City employs cathodic protection systems which helps mitigate</p>	<p>Monitoring performance for corrosion protection in watermains</p> <p>Better decision with</p>

Table-A II-1 Water Digital Project Cases, continued

<p><b>data-driven Tech.</b>          population of 1.24 million          5,000-kilometre          water mains network          Since 1982, reduced breaks          by 85%          Annual investment in corrosion          protection more than 2M/year          Calgary monitors more than 121          km of steel feeder mains</p>	<p>metal water mains          corrosion management          Smart corrosion          management          Protect the system          and the public.</p>	<p>damage to metallic pipes          and lengthen          their lifespan.</p>	<p>real-time data          Shared collected data          with departments          and asset managers          Optimize timelines &amp;          budgets for O&amp;M and          replacement          Benchmark system          performance          Accurate data collection          A central point of access          CorView          (Secure web interface)          cloud platform          Immediate notifications          Benchmark performance          Prioritize critical issues          for field inspections.”          Optimize lower costs          Minimize public complaints          Optimizing staff and          financial resources,</p>
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## ANNEX III

### Online Qualitative Data Resources

1. CS 1 Metropolitan Sewer District of Greater Cincinnati Cincinnati, Ohio, the U.S  
[https://www.xylem.com/en-za/resources/case-studies/digital-twin-technology-helps-city-reduce-combined-sewer-overflow-volume-by-247-million-gallons-and-save-\\$38-million-in-capital-project-work/#:~:text=Xylem%20worked%20with%20MSD%20to,maximize%20treatment%20during%20wet%20weather](https://www.xylem.com/en-za/resources/case-studies/digital-twin-technology-helps-city-reduce-combined-sewer-overflow-volume-by-247-million-gallons-and-save-$38-million-in-capital-project-work/#:~:text=Xylem%20worked%20with%20MSD%20to,maximize%20treatment%20during%20wet%20weather)
2. CS2, DC Water's Digital Twin Solution, Columbia, the U.S, chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/ <https://it.bentley.com/wp-content/uploads/ar-dc-water-digital-twin-journey-ltr-en-lr.pdf#:~:text=The%20team%20will%20now%20be,or%20just%20improving%20operational%20response>
3. CS 3 City of Grand Rapids, Michigan, the U.S [https://www.xylem.com/en-us/resources/case-studies/grand-rapids-michigan-saves-one-billion-dollars-intelligent-urban-watershed-technology-solves-infiltration-and-inflow-problem/#:~:text=To%20satisfy%20regulators%2C%20Grand%20Rapids,the%20original%20\\$1%20billion%20estimate](https://www.xylem.com/en-us/resources/case-studies/grand-rapids-michigan-saves-one-billion-dollars-intelligent-urban-watershed-technology-solves-infiltration-and-inflow-problem/#:~:text=To%20satisfy%20regulators%2C%20Grand%20Rapids,the%20original%20$1%20billion%20estimate)
4. CS 4 Philadelphia Water Department Online Water Quality Monitoring (OWQM) Project <https://www.kisters.net/success-story/securing-drinking-water-supplies/>
5. CS 5, Advancing Digital design to Digital Twin on Durliegh Water Treatment Centre, Wessex, the UK, <https://digital.aecom.com/project/durleigh-water-treatment-centre/>



## ANNEX IV

### First Questionnaire

#### **Digital Twin Technologies Adoption for Water Systems, Awareness, Perceived Benefits, Barriers, and Drivers: The Case of the United Arab Emirates.**

##### **Introduction**

Digital Twin (DT) technologies are gaining attention for promising benefits and improvements in all sectors. However, the adoption and implementation of DTs in the water sector are lagging even in developed countries. Proper awareness, validated benefits and barriers, and users' acceptance are vital for decision-makers and water stakeholders to adopt the new systems. This survey investigates a sample of decision makers of water sector stakeholders in the United Arab Emirates UAE.

We refer here to Digital Twin (DT) technologies as common digital platforms, Internet of Things IoT integrated models, real-time control models, and integrated hydrological and hydraulics simulation models, BIM or GIS, smart metering technologies, or any digital or smart integrated representation of assets or projects for any water system.

This questionnaire collects data to benefit the main research objective of facilitating the digitalization of urban water infrastructure using Digital Twin DT technologies. A PhD research project that is conducted by Inas Abuawad, directed by Prof. Assaf, and co-directed by Prof. Katsanis in the Ecole de Technologie de Supérieure ETS construction department. The reference number of the approval decision of the Ethics Research Committee is H20230903. Your participation is highly appreciated as a contribution to the scientific community. The estimated time to complete the survey is 10-12 minutes, you can stop anytime and opt to leave. Your responses are anonymous and will be used solely for scientific research purposes. If you agree to participate, please start the survey.

To what extent are you familiar with any form of Digital Twin (DT) technologies?

- 1) Not Familiar at all   2) Slightly Familiar   3) Moderately Familiar   4) Familiar   5) Familiar very well

##### **Technology Awareness Section**

1. Listed below are common DT technology definitions, assess your agreement with the representativeness of the following definitions on a 5-point scale where:
- 1) Fully disagree   2) Disagree   3) Neutral   4) Agree   5) Fully agree

- a. “DT is a near-real-time digital image of a physical object or process that helps optimize business performance”.
- b. “DT is the virtual and computerized counterpart of a physical system”.
- c. “DT is a systematic virtual representation of the elements and dynamics of the physical system, with a set of features connected by data links that are based on standards for open data”.
- d. “DT is a virtual replica of a physical asset with bi-directional data flow (between virtual and physical worlds) that, solely or in integration with other DTs as a part of system-of-systems.”
- e. I don’t know

2. Digital Twins development involves integrating many technologies and, built into multi-maturity levels, assess your awareness regarding the DT maturity levels on a 5-point scale, where:

1) Not aware at all   2) Slightly aware   3) Moderately aware   4) Aware   5) Aware very well

3. Listed below are documented benefits of DT technologies' applications for water projects. Based on your awareness and/or experience, assess your agreement on each one of the following statements on a 5-point level scale, where:

1) Fully disagree   2) Disagree   3) Neutral   4) Agree   5) Fully agree

1. Multi-objective simulation models (e.g., running what-if analysis at any time and performing experimentation in digital form before implementation)
2. Improved decision-making on engineering tasks and functions
3. Malfunction detection and localization
4. Improved level of customer (client) service and engagement through a participatory approach and online services
5. Reduced operational cost (OPEX) through better cost estimation
6. Defer capital expenditure (CAPEX) in network upgrades or expansions and reduce long-term expenses.
7. A unified comprehensive output securely accessible to authorized users on any device
8. Reduced compliance issues with environmental regulations and standards
9. Enhanced transparency and collaboration across sectors and departments
10. Knowledge retention for new workforce generations.
11. A Proactive workforce adaptation and better allocation of resources
12. A near-holistic real-time connection between the physical and the digital world for future forecast planning or virtual inspections
13. Improved visualization for better planning
14. Improved safety and reduced risk on the community, staff, and asset level.

15. Improved accuracy and reliability (simulation models or software accuracy).

4) Listed below are 14 defined barriers to DT technologies adoption and implementation. Based on your awareness and /or experience, assess each barrier on a scale from 1 to 5 where 1 is the least challenging and 5 is the most challenging.

- |     | 1  | 2 | 3 | 4 | 5 | I don't know |
|-----|--|---|---|---|---|--------------|
| 1.  | The data cybersecurity issues (e.g., protocols for data encryption, access privileges, addressing device vulnerabilities, and the need for routine security audits) (Technical barriers)     |   |   |   |   |              |
| 2.  | The data availability and ownership issues (e.g., the need for massive amounts of data to be collected, the availability of digitized data, and data ownership issues) (Technical barriers). |   |   |   |   |              |
| 3.  | The lack of interest from water managers due to the reasons that might affect the legacy paradigm in the water industry (Cultural barriers)  |   |   |   |   |              |
| 4.  | Difficulties in integrating the various stakeholders across the organizations to work as a single team, and poor coordination (Organizational barriers).                                     |   |   |   |   |              |
| 5.  | The lack of successful case studies application of DT that prove the cost-benefit effectiveness for the water sector (Economic barriers)   |   |   |   |   |              |
| 6.  | The lack of standardization and interoperability tools for technical feasibility (Technical barriers)  |   |   |   |   |              |
| 7.  | Misunderstanding the capabilities level required based on intended objectives early in the selection process (Organizational barriers)   |   |   |   |   |              |
| 8.  | Poor engagement of proper stakeholders early in the selection process on proper technology (Organizational barriers)   |   |   |   |   |              |
| 9.  | The lack of a trained workforce and skilled system users due to poor or incomplete training programs (Workforce barriers)  |   |   |   |   |              |
| 10. | User's acceptance to use the new technology and the reluctance of professionals (Social barriers)  |   |   |   |   |              |
| 11. | The unexpected incremental cost of the development and implementation (Economic barriers)  |   |   |   |   |              |
| 12. | The Limited investment in innovation, limited top management support, unwillingness to assume and support the risk associated with innovation (Organizational barriers)                      |   |   |   |   |              |
| 13. | The lack of a dedicated team to follow up on the improvement and evaluate the performance after the adoption decision and implementation (Organizational barriers)                           |   |   |   |   |              |
| 14. | The lack of governmental promotion (e.g., digital initiatives, proper policies and strategies, and governance regulations for the new technology (Regulation barriers)                       |   |   |   |   |              |
| 15. | If you have any barriers not included, please specify.   |   |   |   |   |              |

- 5) Do you have current or previous experience with any form of DT technologies project for water systems?
- a) Yes
  - b) No

### Technology Experience Questions

This section asks questions for participants with hands-on experience of any DT level for water projects. It asks about the key drivers, achievement, and level of satisfaction based on the experience.

1. Listed below are pre-defined drivers for adopting DTs in water projects. Based on your project experience, assess their importance for adopting DT technologies on a 5-point level scale, where;

- 1) Not important at all    2) Slightly Important    3) Fairly important    4) Important    5) Very important    6) No opinion

1. Future Forecasting and benchmarking for best management planning.
  2. Public safety management.
  3. Defer new infrastructure augmentation and capital expenditures (CAPEX).
  4. Leverage data to reduce operational costs (OPEX).
  5. Improve simulation models' and meter reading accuracy and increase reliability in the software utilized.
  6. Reduce manual reading and the associated labor, costs, and health and safety issues (OHS).
  7. Optimize performance and increase work efficiency.
  8. Safety and risk management of asset pipe networks.
  9. Regulation compliance with (governmental regulations and environmental organizations' mandates).
  10. Improve customer (client) services (satisfaction, community acceptance, customer trust, public communication & engagement through the interface platform).
  11. Keeping up with new technology and driving innovation.
  12. Others, please specify
2. Based on your experience with the application, assess the success in achieving the drivers' goals on the following scale. If you have more than one answer, select accordingly:
- a) Exceeded    b) Achieved    c) Partially achieved    d) On track    e) Not on track
  - f) Not applicable at this stage
3. On a scale from 1 to 5, assess your satisfaction with the success achieved, where 1 is the least satisfied and 5 is the most satisfied.

1                      2                      3                      4                      5                      No  
 opinion

### **Demographic Section**

This section asks questions about the respondents' years of experience, organization type, and current positions.

1. Years of experience in the water sector
  - a. Less than 5 years
  - b. 5-10 years
  - c. 11-15 years
  - d. More than 16
2. What is your organization's type?
  - a. Utility
  - b. Consultation and engineering management
  - c. Contracting engineering
  - d. Technology providers
  - e. Others, please specify
3. What is your position (role)
  - a. Work as Chief Executive Officer CEO or Main Director MD
  - b. Work as Project Manager PM or Senior technical manager
  - c. Work as mid-career or junior-level engineer
  - d. Work as technology provider professional
  - e. Others, please specify
4. Please, if you give consent to future contact regarding this survey or want to be informed of the study results, provide your preferred contact information



## ANNEX V

### TAM Questionnaire

#### TAM Model and the Acceptance of Water IoT-Digital Twin Technologies in the UAE

Adopting IoT technologies is an emerging approach for water management. Despite gaining attention for their promising benefits and improvement in all sectors, the adoption and implementation of IoT technologies in the water domain are lagging even in developed countries. By integrating IoT sensors, every asset in a network acts as a data source, sending real-time updates to be centrally analyzed, even from remote areas. The output is smart dashboards that visualize the insights through unified data platforms. Those tools revolutionize how water systems are monitored and managed by the users in their households. User acceptance is a well-documented challenge; many factors at multiple levels are crucial for synthesizing users' acceptance. This survey asks questions based on an extended Technology Acceptance Model TAM, to understand what factors shape the public users' acceptance of IoT technologies in their households' water management by using a dashboard application.

The questionnaire collects data to benefit the main research objective of facilitating the digitalization of urban water infrastructure using Digital Twin DT technologies. A PhD research project that is conducted by Inas Abuawad, the researcher, directed by Prof. Assaf, and co-directed by Prof. Katsanis in the Ecole de Technologie de Supérieure ETS construction department. The reference number of the approval decision of the Ethics Research Committee is 25087. Your participation is voluntary and highly appreciated as a contribution to the scientific community. The estimated time to complete the survey is 10 minutes. You can stop anytime and opt to finish. Your responses are anonymous and will be used solely for scientific research purposes. If you consent to participate, please start the survey.

#### EXTERNAL VARIABLES

In all the following questions, assess your agreement on the statements regarding the effect on your acceptance to use or continue using IoT tools, on a five-point scale, where

- a. Fully disagree    b. Disagree    c. Moderately agree    d. Agree    e. Fully agree

#### **1. Government policies (PG)**

GEPI I am aware of government initiatives that promote water conservation and sustainability.

GEP2 Governmental policies influence my decision to use the application to monitor my water consumption

GEP3I feel a personal responsibility to support sustainability goals by using digital tools like the application.

GEP4 Government campaigns encourage people to use the application to track and reduce water usage.

## **2. Mobile Device Anxiety (MDA)**

MDA1 I feel anxious about using the application.

MDA2 It scares me to think that I could lose a lot of information by hitting the wrong key.

MDA3 I hesitate to use the application for fear of making mistakes I cannot correct.

MDA4 The application is somewhat frightening to me.

## **3. Mobile Self-Efficacy (MSE)**

MSE1 I could complete a task using the application

MSE2 I could complete a task using the application if someone showed me how to do it first.

MSE3 I could use the mobile device before I began using the application.

MSE4 I can navigate easily through the Web using a mobile device to find any information I need

## **4. Water Security Concerns (WSC)**

WSC1. I am concerned about the water security issues for my community.

WSC2. News that concerns water security issues makes me worried.

WSC3. If we continue as before, we will soon approach a water shortage catastrophe

## **TAM VARIABLES**

In this section, assess your agreement on the statements regarding your perceived usefulness, ease of use, and intention to use or continue using IoT tools, where

- a. Fully disagree    b. Disagree    c. Moderately agree    d. Agree    e. Fully agree

### **5. Perceived Ease of Use (PEOU)**

PEOU1 The interaction with the application is clear and understandable

PEOU2 It is easy to become skilled at using the app.

PEOU3 The application is easy to use

### **6. Perceived Usefulness (PU)**

PU1 Using the application enhances my effectiveness in water preservation.

PU2 Application is useful for my consumption monitoring.

PU3 Using the application increases my knowledge of my water consumption

### **7. Behavior Intention to Use (BI)**

BIU1 I intend to use or continue using the application in the future.

BIU2 I plan to use or continue using the application in the future.

BIU3 I predict I would use or continue using the application in the future.

## DEMOGRAPHICS INFORMATION

### Demographics Section

1. Your gender
  - a. Male            b. Female            c. Prefer not to say
2. Your age is
  - a. Less than 25
  - b. 25 -34
  - c. 35- 44
  - d. 45-55

e. More than 55

3. Your highest level of education

a. Uneducated

b. High school

c. College Diploma

d. Bachelor's degree

e. Master's degree

f. PhD degree

4. Do you have experience with any smart application usage?

a. Yes      b. No

## ANNEX VI

### SEM MODEL Code File

#### SEM MODEL\_17\_09

This code is designed to import data from a CSV file and examine its structure by displaying the variable names and their count. It then checks for missing values and handles them by replacing each missing entry with the mode (the most frequent value) of its column. A custom function is defined to calculate the mode, since R does not provide one by default. Finally, the first six rows of the cleaned dataset are displayed to verify that the missing values have been properly handled, ensuring the dataset is ready for further statistical analysis.

```
file_path <- "C:/Users/MSI/Desktop/DATA12.csv"
data <- read.csv(file_path, header = TRUE, sep = ",", stringsAsFactors = FALSE)

# 1. Display variable names and their count
print("Variable names:")
print(names(data))
cat("Number of variables:", ncol(data), "\n")

# 2. Check for missing values
print("Number of missing values in each column:")
print(colSums(is.na(data)))

# 3. Function to calculate the most frequent value (mode)
get_mode <- function(x) {
  uniq_x <- na.omit(unique(x))
  uniq_x[which.max(tabulate(match(x, uniq_x)))]
}

# Replace missing values with the mode for each column
for (col in names(data)) {
  if (any(is.na(data[[col]]))) {
    mode_val <- get_mode(data[[col]])
    data[[col]][is.na(data[[col]])] <- mode_val
  }
}
```

```

}
}
# 4. Display the first 6 rows after replacing missing values
print("First 6 rows of the data after handling missing values:")
head(data)

```

This code specifies and estimates a Structural Equation Model (SEM) that integrates both the measurement and structural components. The measurement part defines latent factors (e.g., GP, MDA, MSE, BI, WSC, PU, PEOU) through their observed indicators, while the structural part specifies causal relationships among the latent constructs. The model is estimated using the WLSMV estimator, suitable for ordinal Likert-scale data, and allows correlated errors between similar items to address potential estimation issues. Model fit is assessed using key indices ( $\chi^2$ , df, p-value, CFI, TLI, RMSEA, SRMR). Standardized path coefficients are extracted to evaluate hypothesized relationships, and standardized factor loadings are reported to assess item contributions. The reliability of each construct is evaluated using Cronbach's Alpha, Composite Reliability (CR), and Average Variance Extracted (AVE), providing a comprehensive assessment of the model's validity and reliability.

```

# 1. Load libraries
# =====
library(lavaan)
library(semTools)
library(psych)
library(dplyr)
library(knitr)

# =====
# 2. Define SEM model with correlated errors
# =====
sem_model <- '
# Measurement model
GP    =~ GP1 + GP2 + GP3
MDA   =~ MDA1 + MDA2 + MDA4

```

```

MSE  =~ MSE1 + MSE2 + MSE4
BI   =~ BI1 + BI2 + BI3
WSC  =~ WSC1 + WSC2 + WSC3
PU   =~ PU1 + PU2 + PU3
PEOU =~ PEOU1 + PEOU2 + PEOU3

# Structural model
PEOU ~ MSE + MDA
PU   ~ PEOU + GP
BI   ~ WSC + PU

# Allow correlated errors
BI1 ~~ BI2
'

fit_sem <- sem(sem_model, data = data, estimator="WLSMV", ordered=colnames
(data))

# 3. Fit Indices
# =====
fit_indices <- fitMeasures(fit_sem,
                           c("chisq", "df", "pvalue", "cfi", "tli", "rmsea", "sr
mr"))
fit_indices_df <- data.frame(
  Index = names(fit_indices),
  Value = round(as.numeric(fit_indices), 3)
)

cat("\n=== Fit Indices ===\n")
kable(fit_indices_df, digits=3, caption = "Fit Indices for SEM Model")

# 4. Path Coefficients
# =====

# Extract regression coefficients with standardization
paths <- parameterEstimates(fit_sem, standardized=TRUE) %>%
  filter(op == "~") %>%

```

```

select(lhs, rhs, est, se, z, pvalue, std.all)

# Extract R2 values for dependent variables
rsq_vals <- inspect(fit_sem, "r2")

# Number of observations
n <- nobs(fit_sem)

hypotheses_summary <- do.call(rbind, lapply(unique(paths$lhs), function(de
p_var) {
  sub_paths <- paths[paths$lhs == dep_var, ]
  r2_val <- rsq_vals[[dep_var]]
  k <- nrow(sub_paths) # number of independent variables
  adj_r2 <- 1 - (1 - r2_val) * (n - 1) / (n - k - 1)

  data.frame(
    Dependent = dep_var,
    Predictor = sub_paths$rhs,
    Estimate = round(sub_paths$est, 3),
    Std_Error = round(sub_paths$se, 3),
    Z_value = round(sub_paths$z, 3),
    P_value = round(sub_paths$pvalue, 3),
    Std_All = round(sub_paths$std.all, 3),
    R2 = round(r2_val, 3),
    Adj_R2 = round(adj_r2, 3)
  )
}))

cat("\n=== Hypotheses Summary (per regression equation) ===\n")
kable(hypotheses_summary, caption = "Summary of Each Hypothesis (with R2 a
nd Adj.R2)")

5. Factor Loadings (Standardized)
# =====
loadings <- parameterEstimates(fit_sem, standardized=TRUE) %>%

```

```

dplyr::filter(op == "=~") %>%
dplyr::select(lhs, rhs, est, se, z, pvalue, std.all)

cat("\n=== Factor Loadings ===\n")
kable(loadings, digits=3, caption = "Factor Loadings (Standardized)")
# 6. Reliability (CR, AVE)
# =====

# Latent variables
factors <- c("GP", "MDA", "MSE", "BI", "WSC", "PU", "PEOU")

# CR for each factor
cr_vals <- compRelSEM(fit_sem)

# AVE for each factor
ave_vals <- AVE(fit_sem)

# Merge into one table
rel_df <- data.frame(
  Factor = factors,
  CR     = round(cr_vals[factors], 3),
  AVE    = round(ave_vals[factors], 3)
)

cat("\n=== Reliability Indices ===\n")
knitr::kable(rel_df, digits=3, caption = "Reliability (CR, AVE)")
# =====
# 7. Discriminant Validity (Fornell-Larcker & HTMT)
# =====

# --- Fornell-Larcker Criterion ---
# Get latent variable correlations
cor_matrix <- inspect(fit_sem, "cor.lv")

```

```

# Square root of AVE for each factor
sqrt_ave <- sqrt(ave_vals)

# Replace diagonal with sqrt(AVE)
fornell_larcker <- cor_matrix
diag(fornell_larcker) <- sqrt_ave

cat("\n=== Fornell-Larcker Criterion ===\n")
kable(round(fornell_larcker, 3),
      caption = "Fornell-Larcker Criterion (Diagonal =  $\sqrt{\text{AVE}}$ , Off-diagonal =
Correlations)")

```

This code performs key diagnostic checks to validate the assumptions of the SEM model. First, factor scores are computed and inspected through a scatterplot matrix to evaluate linearity among latent constructs. Multicollinearity is then assessed using Variance Inflation Factors (VIF) across different regression equations. Next, multivariate normality is tested using Mardia's test, while residual correlations are examined to check for independence of errors. Finally, the adequacy of sample size is evaluated by comparing the number of observations to the number of free parameters, ensuring that the ratio meets the recommended threshold for reliable SEM estimation.

```

# 1. Factor Scores (for assumption checking)
# =====
fscores <- tryCatch(
  lavPredict(fit_sem, method = "regression"),
  error = function(e) { NULL }
)

# =====
# 2. Linearity Check (Scatterplot Matrix among latent factors)
# =====
if (!is.null(fscores)) {
  pairs(fscores, main = "Scatterplot Matrix of Latent Factors")
} else {
  cat(

```

```

# 3. Multicollinearity (VIF for independent variables)
# =====
cat("\n=== Multicollinearity (VIF) ===\n")
if (!is.null(fscores)) {
  fs_df <- as.data.frame(fscores)

  # Example 1: PEOU ~ MSE + MDA
  lm_peou <- lm(PEOU ~ MSE + MDA, data = fs_df)
  print(car::vif(lm_peou))

  # Example 2: PU ~ PEOU + GP
  lm_pu <- lm(PU ~ PEOU + GP, data = fs_df)
  print(car::vif(lm_pu))

  # Example 3: BI ~ WSC + PU
  lm_bi <- lm(BI ~ WSC + PU, data = fs_df)
  print(car::vif(lm_bi))
} else {
  cat("\n⚠ VIF could not be computed because factor scores are not available.\n")
}
# =====
# 4. Multivariate Normality (Mardia's Test)
# =====
cat("\n=== Multivariate Normality (Mardia) ===\n")
if (!is.null(fscores)) {
  tryCatch({
    mvn_res <- MVN::mvn(fscores, multivariatePlot = "qq")
    print(mvn_res$multivariateNormality)
  }, error = function(e) {
    print(psych::mardia(fscores))
  })
} else {

```

```

cat("⚠ Multivariate normality was not tested because factor scores are
not available.\n")
}

```

```

5. Independence of errors (Residual correlations)
# =====
cat("\n=== Residual correlations ===\n")

resid_cor <- residuals(fit_sem, type = "cor") # ✓ استبدلنا lavResiduals
→ residuals
print(resid_cor)

6. Adequacy of Sample Size
# =====
cat("\n=== Sample Size Adequacy ===\n")

n <- nrow(data)
npar <- lavInspect(fit_sem, "npar")
ratio <- round(n / npar, 2)
cat("N =", n, "| Parameters =", npar, "| Ratio (N/params) =", ratio, "\n")

if (ratio < 5) {
  cat("⚠ Preferably increase sample size (rule of thumb: ≥ 5 per paramete
r).\n")
} else {
  cat("✓ Sample size is adequate.\n")
}

```

This code generates heatmaps to visualize correlation patterns at two levels. First, it computes the correlation matrix of the observed items and displays it as a heatmap, which helps identify clusters of highly related items. Second, it extracts the latent factor correlations from the fitted SEM model and plots them in a similar heatmap, with correlation coefficients shown inside the cells for clarity. These visualizations provide an intuitive way to assess the strength and direction of relationships, both among the observed indicators and among the underlying latent constructs.

```

# 1. Load libraries
# =====
library(lavaan)
library(corrplot)

```

```

# =====
# 2. Heatmap for Item Correlations
# =====
cor_items <- cor(data, use = "pairwise.complete.obs")

corrplot(cor_items,
         method = "color",
         type = "lower",
         tl.cex = 0.7,
         tl.col = "black",
         title = "Heatmap of Item Correlations", # Title inside the plot
         mar = c(0,0,2,0)) # Adjust margins for title

3. Heatmap for Latent Factor Correlations
# =====
factor_cor <- inspect(fit_sem, "cor.lv")

corrplot(factor_cor,
         method = "color",
         type = "lower",
         addCoef.col = "black", # Show correlation values inside the cells
         number.cex = 0.9, # Size of the numbers
         tl.cex = 0.9,
         tl.col = "black",
         title = "Heatmap of Latent Factor Correlations",
         mar = c(0,0,2,0))

```

This code visualizes the Structural Equation Model (SEM) using the `semPlot` package. The diagram displays latent variables (circles) and observed items (squares), with standardized estimates shown on the paths. A LISREL-style layout with a hierarchical tree structure is used to place the factors in the center, while node sizes, labels, and margins are adjusted to improve clarity and readability. Residuals and intercepts are hidden to keep the diagram clean, making the structural and measurement relationships easier to interpret.

```
library(semPlot)
```

```
semPaths(  
  fit_sem,  
  what = "std",  
  layout = "tree2",  
  style = "lisrel",  
  whatLabels = "std",  
  edge.label.cex = 0.8,  
  label.cex = 0.9,  
  residuals = FALSE,  
  intercepts = FALSE,  
  nCharNodes = 1,  
  fade = FALSE,  
  mar = c(2,2,2,2),  
  node.width = 1.2,  
  node.height = 1.0,  
  edge.color = "black",  
  curvePivot = TRUE,  
  DoNotPlot = FALSE,  
  sizeMan = 5,  
  sizeLat = 7,  
  rotation = 2  
)
```

## ANNEX VII

### PCA Results Factor Analysis

Table-A VII-1 Factor Analysis Total Variance Explained

Component	Total Variance Explained								
	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	11.230	38.724	38.724	11.230	38.724	38.724	5.229	18.030	18.030
2	3.707	12.782	51.506	3.707	12.782	51.506	4.258	14.682	32.712
3	2.460	8.482	59.988	2.460	8.482	59.988	3.941	13.591	46.302
4	1.649	5.686	65.674	1.649	5.686	65.674	3.699	12.756	59.058
5	1.497	5.161	70.835	1.497	5.161	70.835	2.449	8.444	67.502
6	1.103	3.804	74.638	1.103	3.804	74.638	2.069	7.136	74.638
7	.955	3.293	77.931						
8	.862	2.973	80.904						
9	.702	2.419	83.324						
10	.653	2.250	85.574						
11	.577	1.991	87.565						

Table-A VII-1 Factor Analysis Total Variance Explained, continued

12	.561	1.934	89.498						
13	.400	1.380	90.878						
14	.381	1.313	92.191						
15	.319	1.101	93.292						
16	.303	1.045	94.337						
17	.272	.939	95.276						
18	.249	.860	96.136						
19	.203	.700	96.836						
20	.172	.594	97.430						
21	.143	.495	97.924						
22	.133	.460	98.384						
23	.115	.397	98.781						
24	.083	.285	99.066						
25	.072	.250	99.316						
26	.070	.242	99.558						
27	.053	.182	99.739						
28	.044	.151	99.890						
29	.032	.110	100.000						
Extraction Method: Principal Component Analysis.									

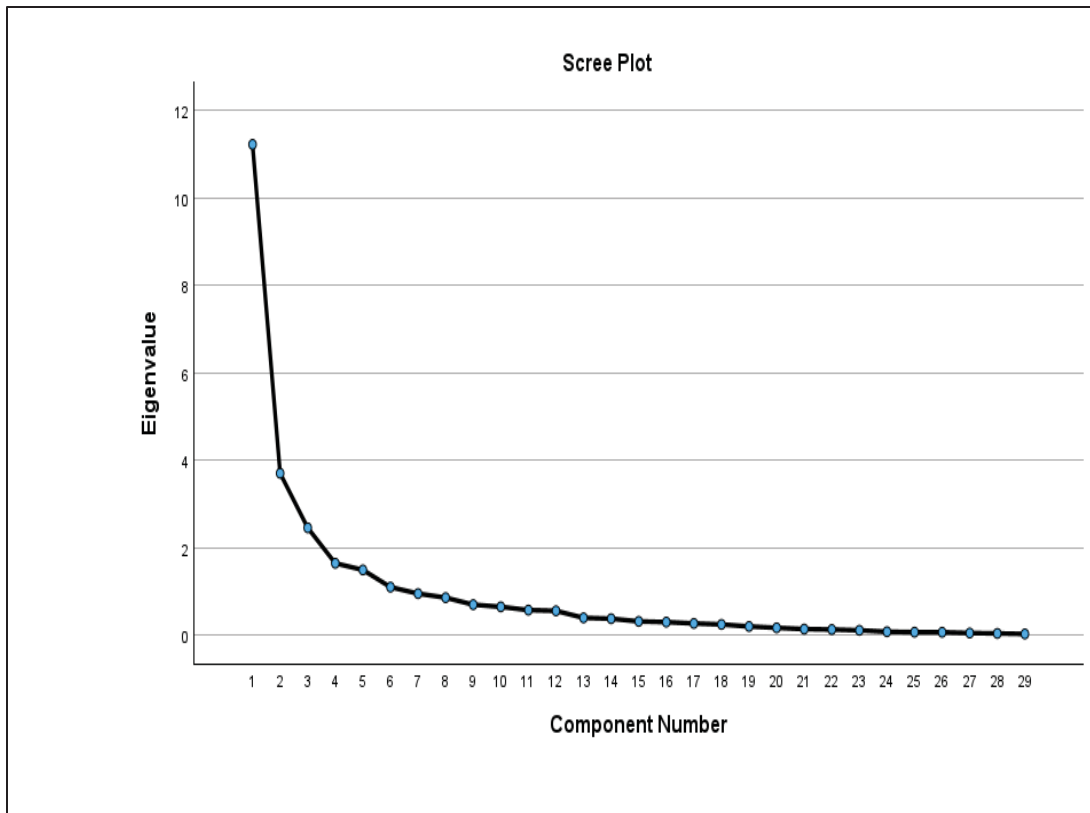


Figure-A VII-1 PCA Scree Plot

Table-B VII-2 Factor Analysis before Rotation

Component Matrix <sup>a</sup>						
	Component					
	1	2	3	4	5	6
1. Multi-objective simulation models (e.g., running what-if analysis)	.375	.583	-.230	.448	.248	-.078
2. Improved decision-making on engineering tasks and functions, and analysis	.829	-.016	-.315	.081	-.081	.027
3. Malfunction detection and localization timely	.674	.026	-.345	-.344	.116	.075
4. Improved level of customer (client) service and engagement through a participatory approach	.760	.352	-.032	.299	.118	-.139

Table-B VII-2 Factor Analysis before Rotation, continued

5. Reduced operational cost (OPEX) by cost estimation	.816	.168	-.192	-.048	.088	-.023
6. Defer capital expenditure (CAPEX) in network upgrades or expansions and reduce long-term expenses.	.623	.136	-.264	-.335	.030	-.229
7. A unified comprehensive output securely accessible to authorized users on any device.	.773	.215	-.072	.100	-.343	-.127
8. Reduced compliance issues with environmental regulations and standards	.538	.383	.202	-.362	.184	-.120
9. Enhanced transparency and collaboration across sectors and departments	.499	.623	.050	.159	.007	.305
10. Knowledge retention for new workforce generations.	.655	.218	-.071	-.023	.453	.319
11. A Proactive workforce adaptation and better allocation of resources	.568	.487	-.083	-.057	.385	.305
12. Near holistic real-time connection between the physical and the digital world for future forecast events planning	.625	.272	-.052	-.110	.015	.080
13. Improved visualization for better planning, operation, and action responses.	.767	.162	-.243	-.036	.150	-.278
14. Improved safety and reduced risk on the community, staff, and asset level.	.620	.436	.045	-.186	.290	-.007
15. Improved accuracy and reliability (simulation models or meter readings ).	.391	.617	.436	-.074	.148	-.222
1. The data cybersecurity and data ownership issues (e.g., protocols for data encryption, access privileges, addressing device vulnerabilities, and the need for routine security audits) (Technical barriers)	.690	-.484	-.171	-.087	.170	.053

Table-B VII-2 Factor Analysis before Rotation, continued

2. The data availability (e.g., the need for massive amounts of data to be collected and drawn from numerous endpoints represents a potential area of weakness) (Technical barriers).	.648	-.539	-.105	-.178	.139	-.078
3. The lack of interest from water managers due to the reasons that might affect the legacy paradigm in the water industry (Cultural barriers)	.537	-.206	.579	-.092	-.257	.128
4. Difficulties in integrating the various stakeholders across the organizations to work as a single team, and poor coordination (Organizational barriers)	.518	-.227	.595	-.270	-.293	.018
5. The lack of successful case studies application of DT that prove the cost-benefits effectiveness for the water sector (Economic barriers)	.525	-.458	-.207	.108	-.274	-.288
6. The lack of standardization and interoperability tools for technical feasibility (Technical barriers)	.611	-.414	.162	.151	.043	-.028
7. Misunderstanding the capabilities level required based on intended objectives early in the selection process (Organizational barriers)	.647	-.028	.433	-.108	.470	-.006
8. Poor engagement of proper stakeholders early in the selection process on proper technology (Organizational barriers)	.653	-.236	.518	.193	.080	-.005
9. The lack of trained workforce and skilled system users due to poor or incomplete training programs (Workforce barriers)	.571	-.324	.020	-.235	.413	.347

Table-B VII-2 Factor Analysis before Rotation, continued

10. User's acceptance to use the new technology and the reluctance of professionals (Social barriers)	.580	-.412	-.097	-.302	-	.135	-.147
11. The unexpected incremental cost of the development and implementation (Economic barriers)	.519	-.372	-.383	.237	.056		.417
12. The Limited investment in innovation, limited top management support, unwillingness to assume and support the risk associated with innovation (Organizational barriers)	.599	-.166	.289	.476	-	.146	-.291
13. The lack of a dedicated team to follow up on the improvement and evaluate the performance after the adoption decision and implementation (Organizational barriers)	.467	-.173	.423	.396	.164		.230
14. The lack of governmental promotion (e.g., digital initiatives, proper policies and strategies, and governance regulations for the new technology (Regulation barriers)	.675	-.366	-.306	.324	-	.123	-.067

Table-C VII-3 Factor Analysis after Rotation, Rotated Component Matrix<sup>a</sup>

	Component						Fact or	Component
	1	2	3	4	5	6		
1. Multi-objective simulation models (e.g., running what-if analysis)	.034	.369	.032	.270	-.051	.767	B1	C6
2. Improved decision-making on engineering tasks and functions, and analysis	.629	.268	.138	.454	.260	.202	B2	C4

Table-C VII-3 Factor Analysis after Rotation, continued

3. Malfunction detection and localization	.430	.439	-.116	.311	.472	-.022	B3	C2
4. Improved level of customer (client) service and engagement through a participatory approach	.317	.508	.330	.356	.023	.480	B4	C2
5. Reduced operational cost (OPEX) by cost estimation	.442	.508	.140	.389	.280	.199	B5	C2
6. Defer capital expenditure (CAPEX) in network upgrades or expansions and reduce long-term expenses.	.452	.585	-.122	.221	.170	-.038	B6	C2
7. A unified comprehensive output securely accessible to authorized users on any device.	.494	.371	.231	.576	-.124	.103	B7	C4
8. Reduced compliance issues with environmental regulations and standards	.071	.632	.129	.419	-.069	-.231	B8	C2
9. Enhanced transparency and collaboration across sectors and departments	-.171	.367	.186	.642	.098	.370	B9	C4
10. Knowledge retention for new workforce generations	.260	.139	.154	.817	.086	-.051	B10	C4
11. A Proactive workforce adaptation and better allocation of resources	.068	.279	.034	.852	.022	.048	B11	C4
12. Near holistic real-time connection between the physical and the digital world for future forecast events planning	.195	.439	.119	.448	.187	.082	B12	C4
13. Improved visualization for better planning, operation, and action responses.	.530	.601	.073	.204	.154	.251	B13	C2
14. Improved safety and reduced risk on the community, staff, and asset level.	.022	.705	.135	.283	.261	.178	B14	C2

Table-C VII-3 Factor Analysis after Rotation, continued

15. Improved accuracy and reliability (simulation models or meter readings ).	-.245	.744	.321	.191	-.183	.116	B15	C2
1. The data cybersecurity and data ownership issues (e.g., protocols for data encryption, access privileges, addressing device vulnerabilities, and the need for routine security audits) (Technical barriers)	.640	.121	.251	.037	.537	-.054	BR1	C1
2. The data availability (e.g., the need for massive amounts of data to be collected and drawn from numerous endpoints represents a potential area of weakness) (Technical barriers)	.665	.169	.250	-.064	.456	-.180	BR2	C1
3. The lack of interest from water managers due to the reasons that might affect the legacy paradigm in the water industry (Cultural barriers)	.140	.128	.678	.293	.063	-.413	BR3	C3
4. Difficulties in integrating the various stakeholders across the organizations of a water utility to work as a single team, and poor coordination (Organizational barriers)	.169	.225	.607	.235	.024	-.574	BR4	C3
5. The lack of successful case studies application of DT that prove the cost-benefits effectiveness for the water sector (Economic barriers)	.809	-.026	.177	.064	-.032	-.080	BR5	C1
6. The lack of standardization and interoperability tools for technical feasibility (Technical barriers)	.493	.058	.541	.032	.236	-.026	BR6	C3
7. Misunderstanding the capabilities level required based on intended objectives (Organizational barriers)	.063	.553	.598	-.055	.411	.007	BR7	C3
8. Poor engagement of proper stakeholders early in the selection (Organizational barriers)	.250	.202	.813	.079	.148	-.036	BR8	C3

Table-C VII-3 Factor Analysis after Rotation, continued

9. The lack of trained workforce and skilled system users due to poor or incomplete training programs (Workforce barriers)	.216	.187	.285	.041	.778	-.087	BR9	C5
10. User's acceptance to use the new technology and the reluctance of professionals (workforce barriers)	.639	.199	.127	.082	.232	-.348	BR10	C1
11. The unexpected incremental cost of the development and implementation (Economic barriers)	.493	-.268	.135	.294	.558	.236	BR11	C5
12. The Limited investment in innovation, limited top management support, unwillingness to assume and support the risk associated with innovation (Organizational barriers)	.482	.112	.678	.101	-.230	.187	BR12	C3
13. The lack of a dedicated team to follow up on the improvement and evaluate the performance after the adoption decision and implementation (Organizational barriers)	.063	-.030	.748	.112	.226	.188	BR13	C3
14. The lack of governmental promotion (e.g., digital initiatives, proper policies and strategies, and governance regulations for the new technology (Regulation barriers)	.787	-.063	.252	.212	.164	.223	BR14	C1
a. Rotation converged in 14 iterations.								



## ANNEX VIII

### Ethics Committee Decisions



Comité d'éthique de la recherche  
École de technologie supérieure

19 octobre 2023

**Titre de l'activité :** Digitalization evolution of urban infrastructure management with digital Twin technology  
**Responsable :** Gabriel Assaf, Professeur au département de génie de la construction – École de technologie supérieure (ÉTS)  
**Co-responsable :** Constantine Katsanis, Professeur au département de génie de la construction – École de technologie supérieure (ÉTS)  
**Étudiant.e :** Inas Abuwad, Étudiante au doctorat au département de génie de la construction – École de technologie supérieure (ÉTS)  
**Référence :** H20230903

#### DÉCISION DU COMITÉ D'ÉTHIQUE DE LA RECHERCHE

Professeur Assaf,

Vous avez soumis au Comité d'éthique de la recherche (CÉR) de l'ÉTS le formulaire de présentation de l'activité mentionnée en rubrique. Ce formulaire a été évalué le 26 septembre 2023 en comité délégué.

Selon les informations contenues dans le Formulaire de présentation, et considérant l'Article 2.5 de l'Énoncé de politique des trois Conseils – Éthique de la recherche avec des êtres humains (ÉPTC2), le comité a conclu que l'activité présentée vise l'amélioration des processus et qu'elle ne répond pas à la définition de recherche avec des participants telle que définie par l'ÉPTC2. Par conséquent, une évaluation éthique et un suivi continu de la part du CÉR ne sont pas requis.

Veillez noter que cette décision repose sur les informations présentées. Si vous devez apporter des modifications aux objectifs de l'activité, veuillez en informer le CÉR dans les meilleurs délais.

Veillez également noter qu'indépendamment de cette décision, les principes de conduite responsable en recherche s'appliquent à votre activité. Vous êtes donc tenu de vous y conformer.

Veillez agréer, Professeur Assaf, l'expression de mes sentiments les meilleurs.

Sylvie Ratté, LL. Eng., Ph.D.  
Présidente par intérim, Comité d'éthique de la recherche  
École de technologie supérieure

cc : Ghyslain Gagnon, Doyen de la recherche  
Laurence Marck / Chantal Lefebvre, Coordonnatrices du CÉR

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**Comité d'éthique de la recherche  
École de technologie supérieure**

Le 25 février 2025

Titre du projet :

Digitalization evolution of urban infrastructure management with digital Twin technologies

Chercheur responsable :

Gabriel Assaf, Professeur au département de génie de la construction – École de technologie supérieure (ÉTS)

Autres membres de l'équipe de recherche :

Constantine Katsanis, Professeure au département de génie de la construction – ÉTS

Inas Abuawad, Étudiante au doctorat au département de génie de la construction – ÉTS

Référence : 25087

Demande : Nouvelle

**DÉCISION DU COMITÉ D'ÉTHIQUE DE LA RECHERCHE**

Professeur Assaf,

Le projet mentionné en rubrique a été soumis le 20 février 2025 pour son évaluation par le Comité d'éthique de la recherche (CÉR) de l'ÉTS. La présente lettre est pour vous informer que le CÉR a procédé, le 24 février 2025, à l'évaluation du dossier en comité délégué.

Documents évalué :

- Formulaire de présentation allégé

Suite à l'évaluation du dossier, le CÉR a conclu que votre projet vise l'évaluation et l'amélioration des processus en lien avec la gestion des infrastructures. En effet, bien que vous fassiez appel à des personnes auprès desquelles vous colligerez des données, considérant l'Article 2.5 de l'Énoncé de politique des trois Conseils – Éthique de la recherche avec des êtres humains (EPTC2), votre projet ne répond pas à la définition de recherche avec des participantes et participants humains. Ce faisant, une évaluation éthique et un suivi continu de la part du CÉR ne sont pas requis. Vous pouvez donc aller de l'avant avec la réalisation de votre projet.

Veillez noter que cette décision repose sur les informations présentes au dossier. Si vous devez apporter des modifications aux objectifs du projet, aux personnes sollicitées ou aux activités réalisées, veuillez en informer le CÉR dans les meilleurs délais.

Veillez également noter qu'indépendamment de la décision du CÉR, les principes de conduite responsable en recherche s'appliquent à votre projet. Vous êtes donc tenu de vous y conformer.

Pour toute question en lien avec cette décision, veuillez contacter le bureau coordonnateur du CÉR par courriel à l'adresse [cer@etsmtl.ca](mailto:cer@etsmtl.ca), ou par téléphone au (514) 396-8800 poste 7807 ou 7129.

Veuillez agréer, Professeur Assaf, l'expression de mes sentiments les meilleurs.

A handwritten signature in blue ink, appearing to read 'Mathias Glaus'.

Mathias Glaus, Ing., Ph.D.  
Président, Comité d'éthique de la recherche  
École de technologie supérieure

cc: *Gisèle Gagnon, Doyen de la recherche*  
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