Synchronized Swimming: Framing the Digital Twin for Urban Water Systems

Josh Rodriguez
Om Sanan
Steven Conrad

26 September 2024

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Framing the Digital Twin for Urban Water Systems

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Om Sanan is a senior at Scarsdale High School in New York and is a water treatment researcher. He founded nonprofit Day Zero Water in 2018 and has interned with NREL, NASA, and MIT. His research focuses on water desalination and the energy-water nexus.

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Agenda

- Problem and Objectives
- Background of Digital Twins
- Digital Twin Dimensions and Classifications
- Methods
- Results
- Conclusions and Discussion

(Conejos Fuertes et al., 2020)

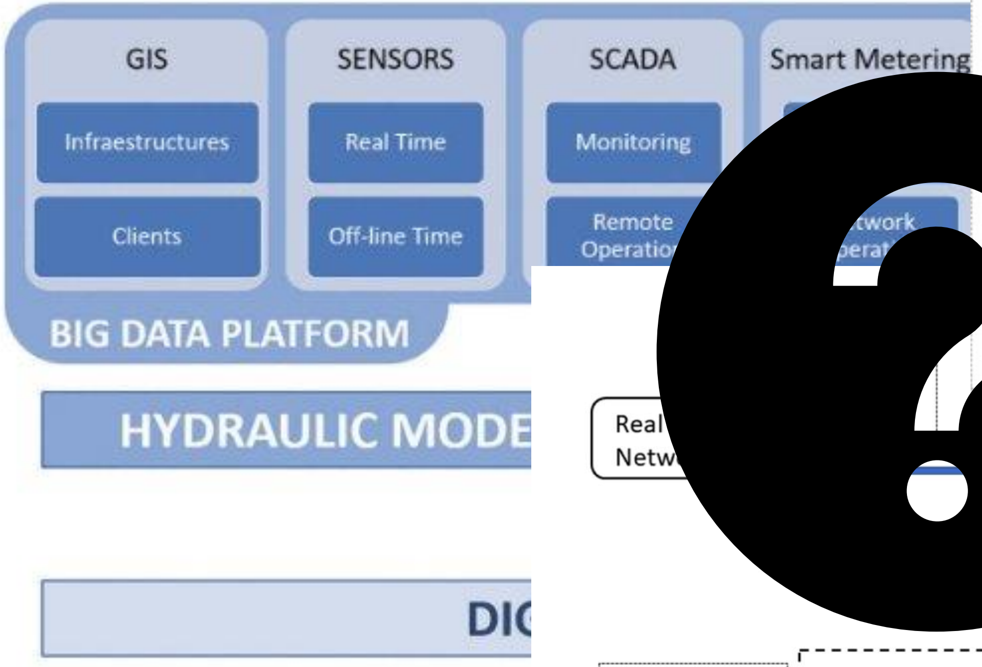
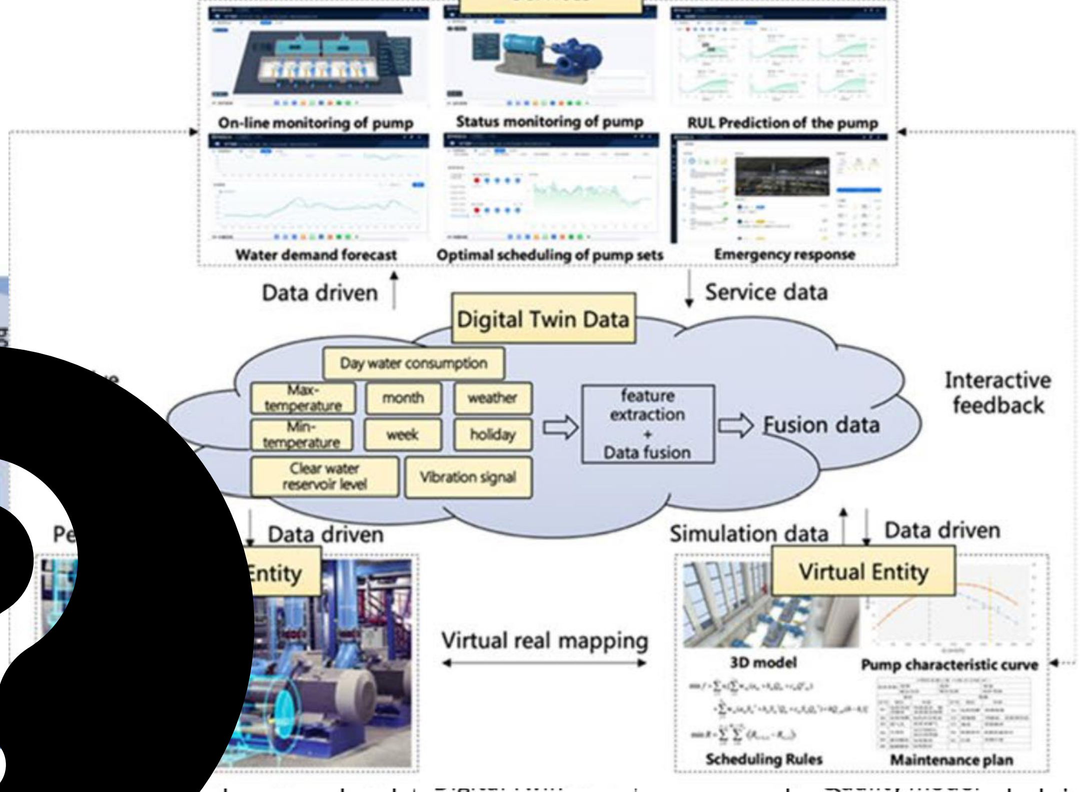
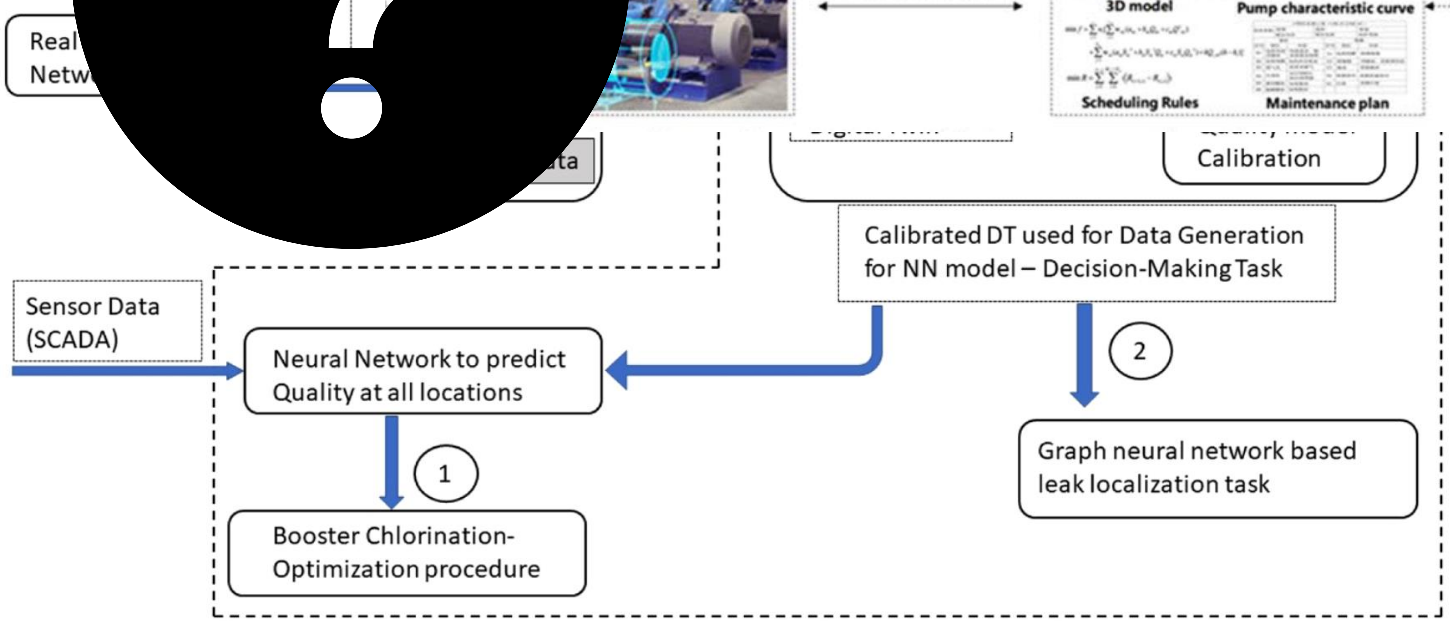


Figure 1. WDS Digital Twin structure.

(Zhou et al., 2024)





(Brahmbhatt et al., 2023)

Challenges

- The varied Digital Twin (DT) definitions and structures in literature and practice introduce confusion and make it difficult to design and implement a DT

Objectives

- Understand the dimensions of the Urban Water System (UWS) DTs
- Delineate between different classifications of digital twins
- Visualize the decision points for selecting a DT archetype

Research Overview

Case Studies of DTs in Urban Water Systems (UWSs)

What is a Digital Twin in an Urban Water System?

?

Classifications of Digital Twins

Dimensions of Digital Twins

What is a Digital Twin (DT)?

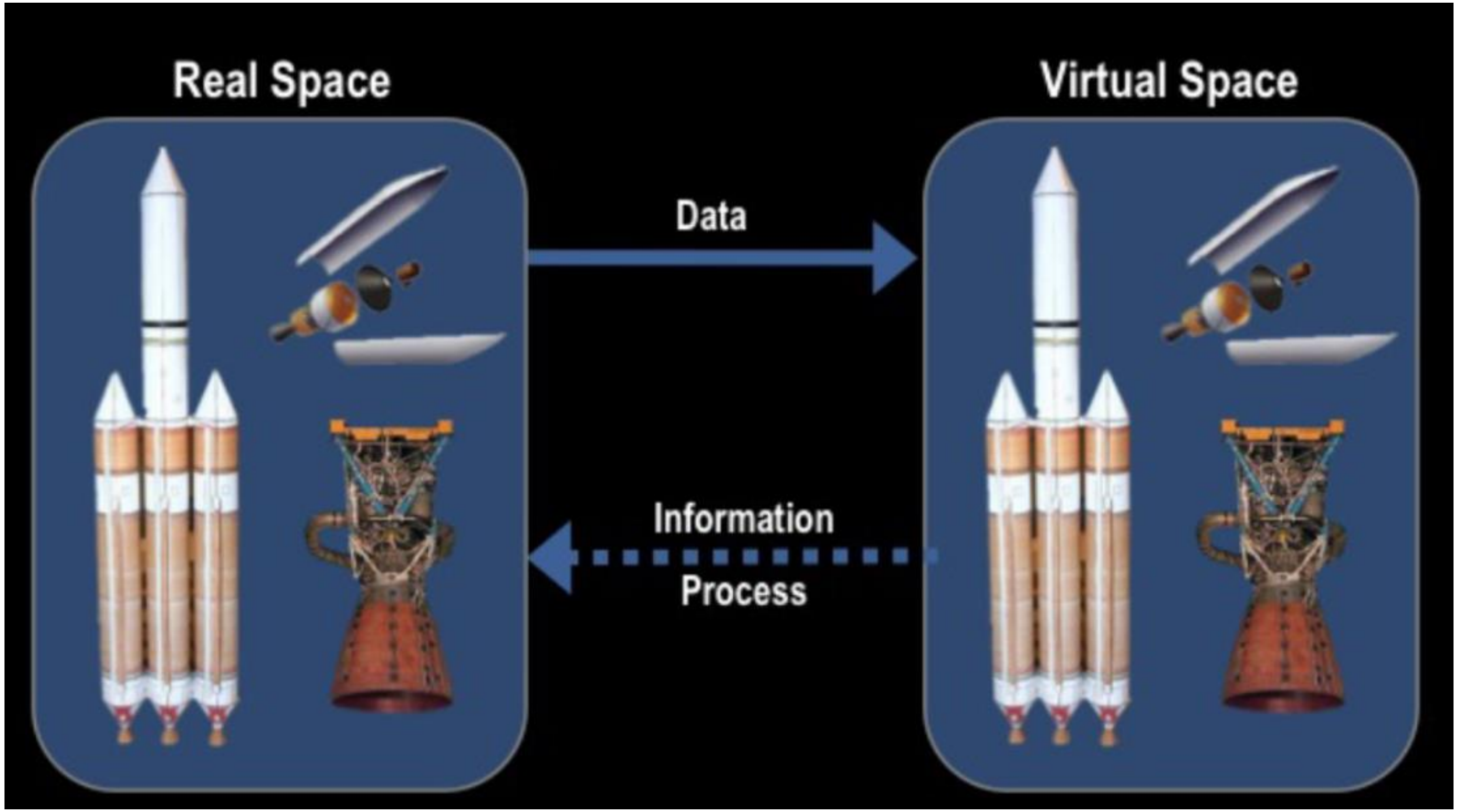


Figure 1
(Grieves, 2014)

DTs in Urban Water Systems (UWS)

*"A **digital, dynamic system** of real-world entities and their behaviors using **models with static and dynamic data** that enable insights and interactions to drive actionable and optimized outcomes."*

-Karmous-Edwards et al., 2022; pg.78

Why use a DT?

- Compared to simulations, DTs:
  - Have higher fidelity
  - Broader scope
  - Mimic system operations
- DTs in UWS can be used for:
  - Asset management
  - Model-based fault detection
  - Early warning systems
  - Sensor validation
  - Simulation of system behavior

(Ramos et al., 2023)
(Kritzinger et al., 2019)

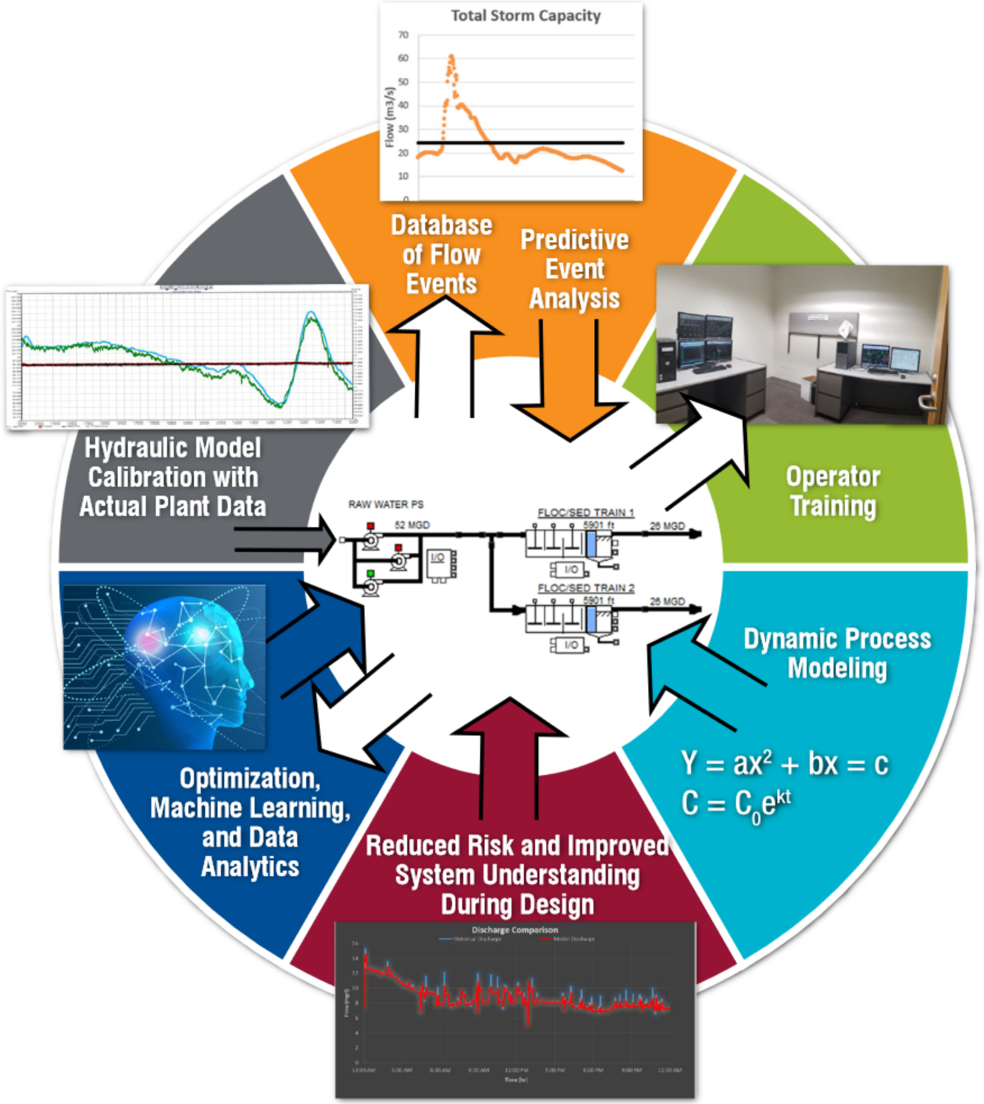


Figure 2: A Digital Twin Forms a Central Repository for Information and Provides a Basis for Analysis for Treatment Facilities (Curl et al., 2019)

What is a Digital Twin (DT)?

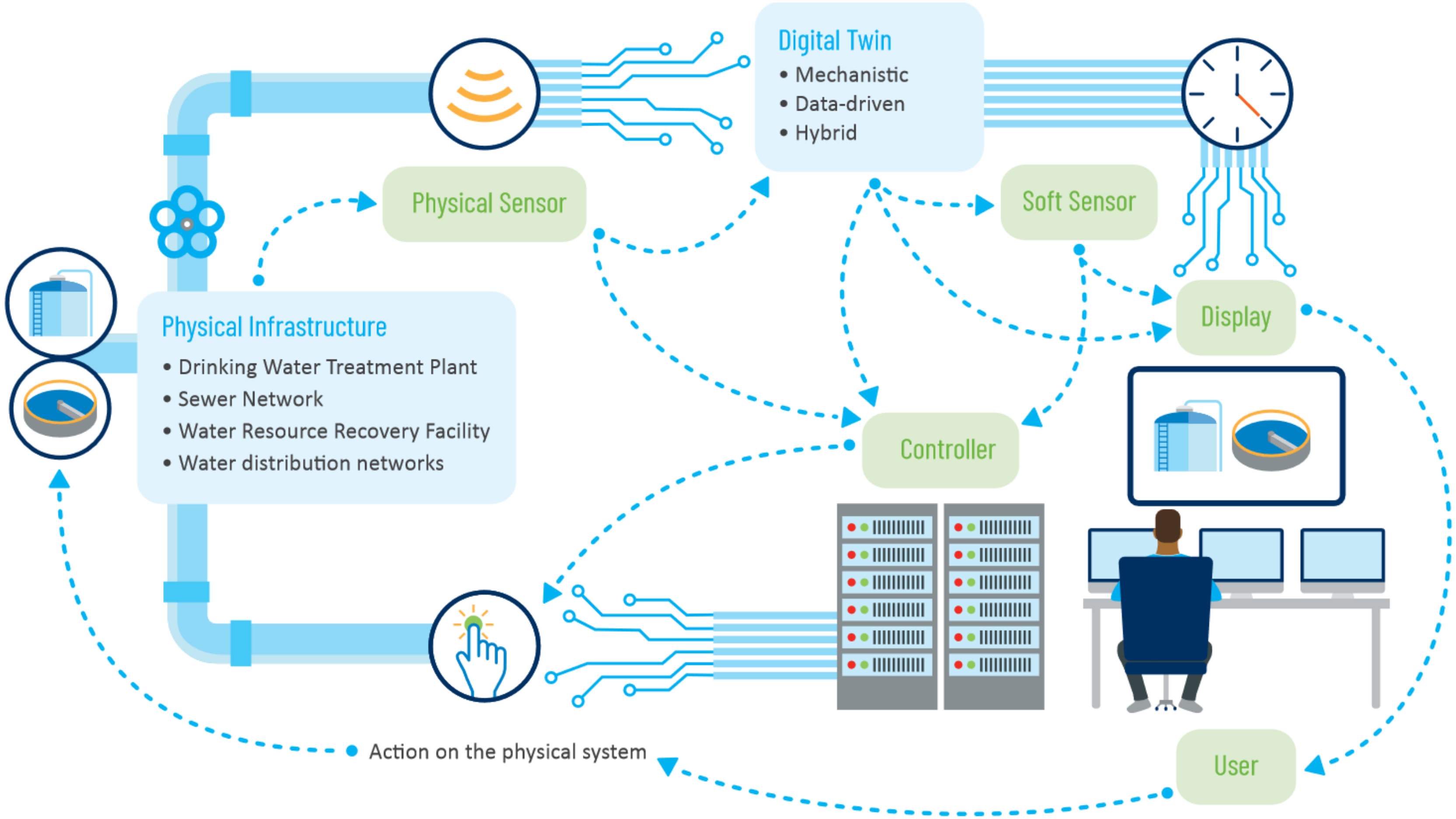


Figure 3: Basic structure of a digital twin application (Valverde-Perez et al., 2021)

Adapted from
Jones et al., 2020

DT Dimensions

Virtual System	Physical System	Interface
Fidelity	Metrology	Data Ownership
Realization	Perceived Benefits	Parameters
Twinning Rate	Physical Entity and Processes	Realization
Virtual Entity	Physical Environment	State
Virtual Environment	Use-Cases	Physical-to-Virtual (P2V) Connections
Virtual Processes		Virtual-to-Physical (V2P) Connection

Table 1: Dimensions of a digital twin, adapted from (Jones et al., 2020)

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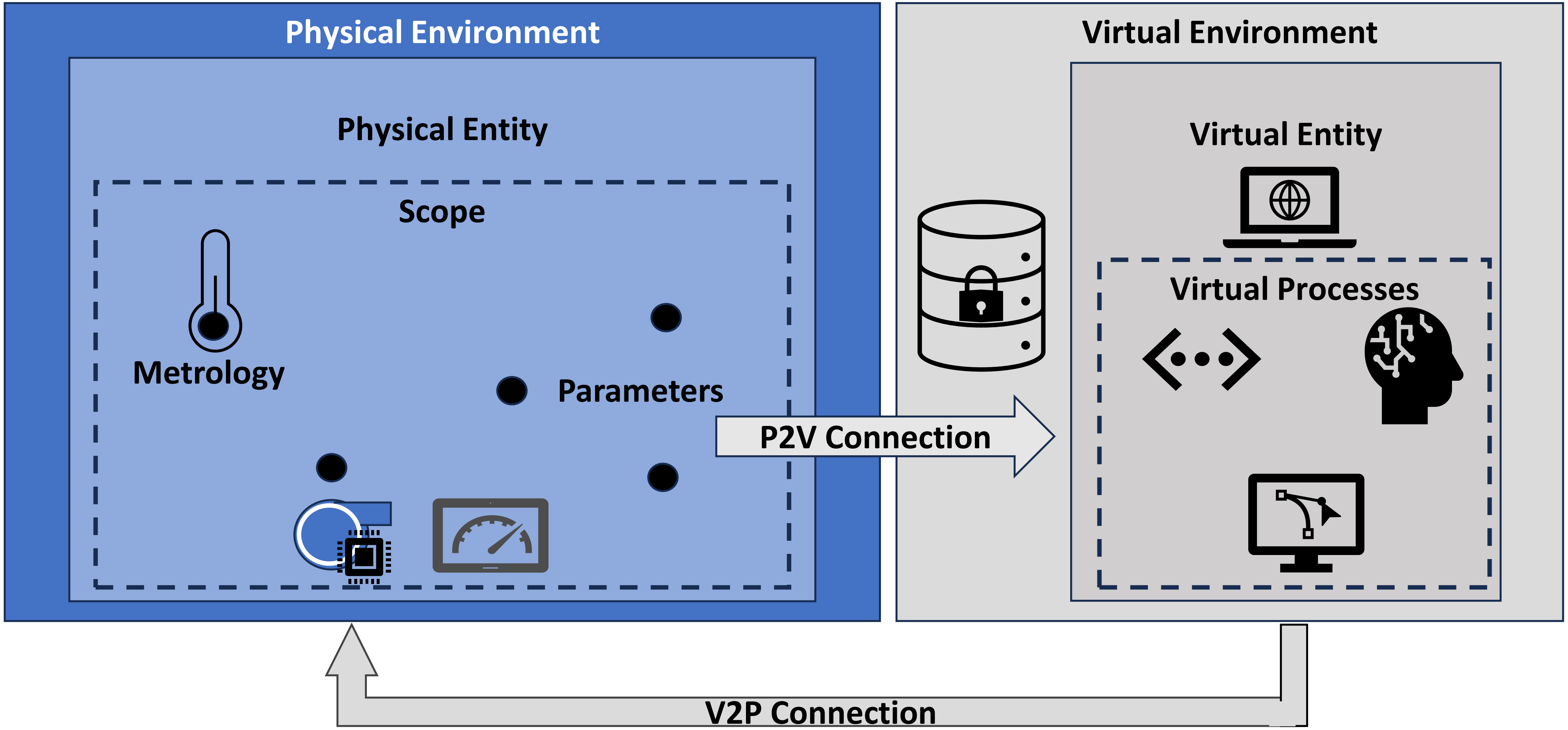
DT Dimensions

Figure 4: Subset of dimensions of a digital twin, adapted from (Jones et al., 2020)



Realization

If $X_{phys}(t) \sim= x_{virt}(t)$
$X_{phys}(t) = x_{virt}(t)$
end

Fidelity

$X_{phys}(t) - x_{virt}(t) = \Delta$

State

$X_{phys}(t)$ $X_{virt}(t)$

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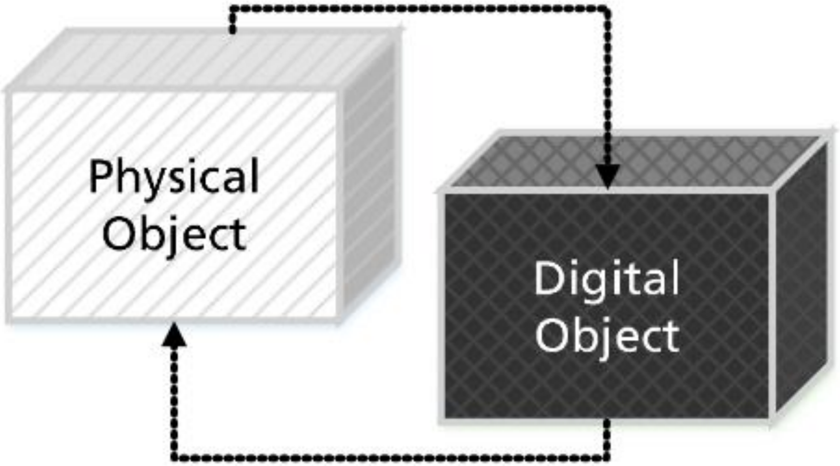
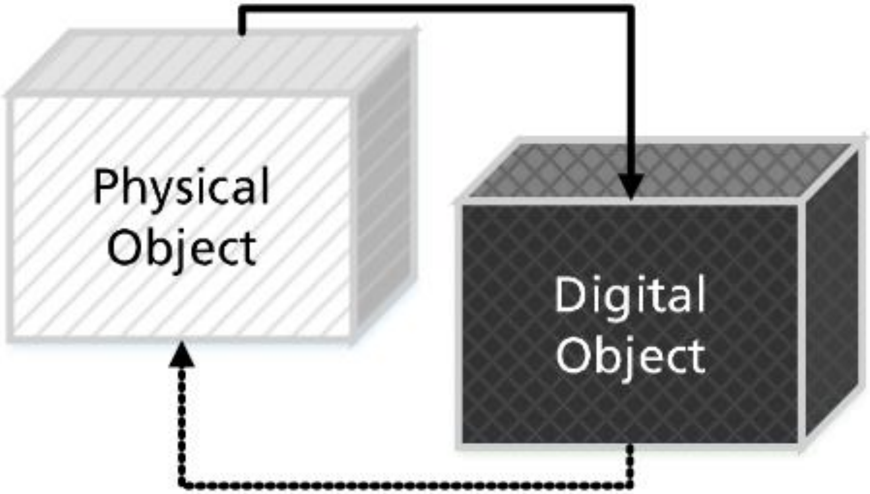
Classifying DTs

- **Real-time:** the entire data cycle is automated from sensing to model output

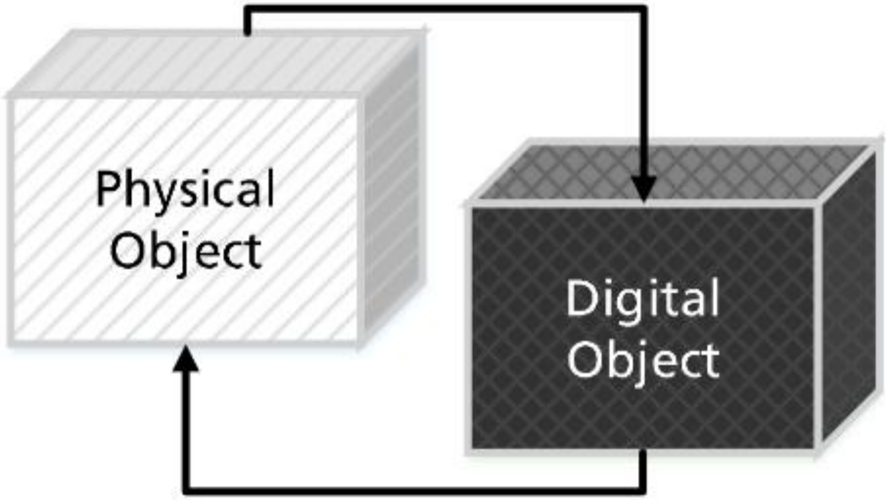
(Shafiee et al., 2018)



Digital Model



Digital Shadow



Digital Twin

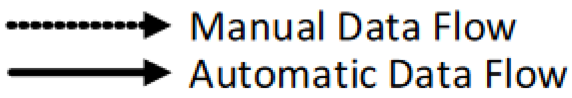


Figure 5: Digital Twin Archetypes (Kritzinger et al., 2019)

Classifying DTs

- Digital Twins have a voice in system operations
  - Directly changes (or proposes changes to) the physical system
- Digital Shadows mimic system operations and provide a test environment
- Digital Models provide a test environment

Table 2: Digital twin archetype characteristics adapted from (Kritzinger et al., 2019)

Digital Models	Digital Shadows	Digital Twins
No real-time data	Real-time data	Real-time data
Calibrated using historical data	Calibrated using real-time data	Calibrated using real-time data
User-defined operational scenarios	User-defined operational scenarios	DT-defined operational scenarios
User tests scenarios in DT environment	User tests scenarios in DT environment	DT test scenarios and presents results
No integration	Unidirectional	Bidirectional

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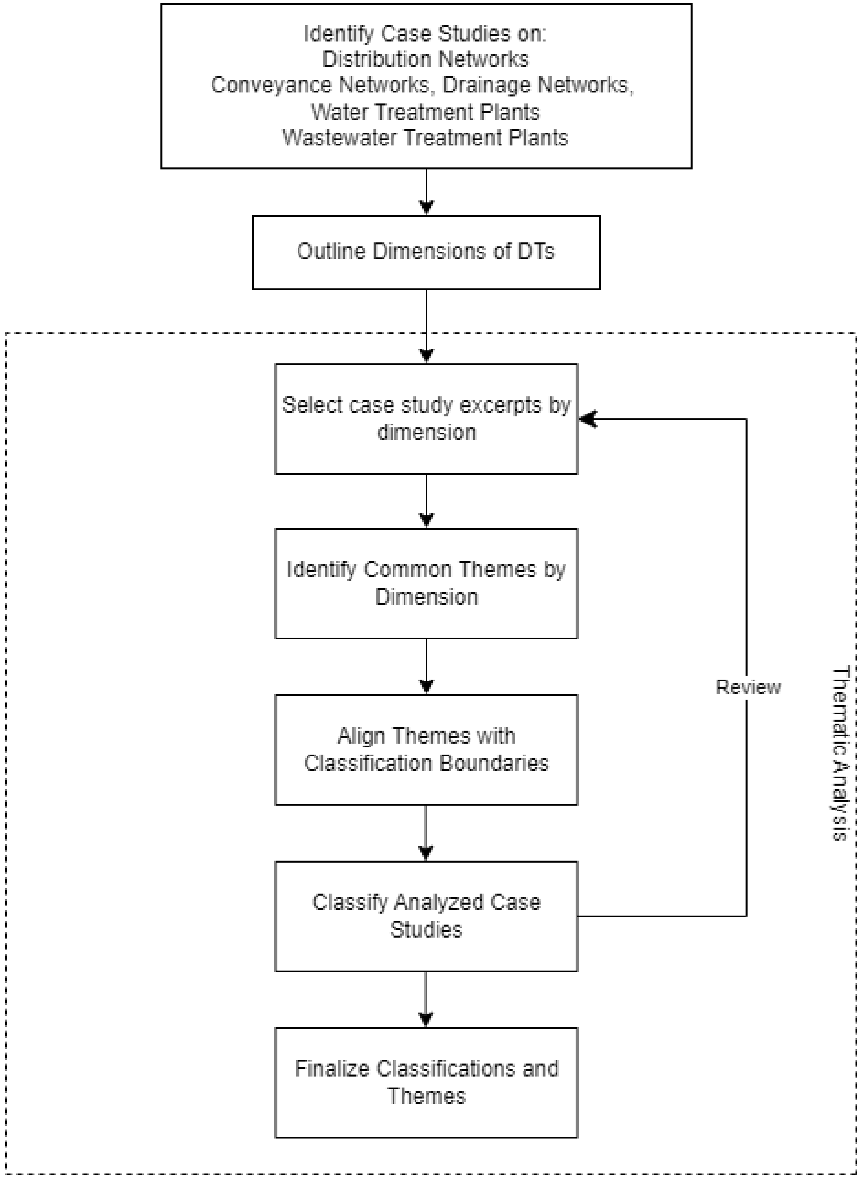
Methods Overview

- Analyzed 11 case studies of Digital Twins in Urban Water Systems
- Aim: Harmonize classification framework for UWS DTs
- Considered only current implementations, not planned improvements

Figure 6: Methods Overview



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Samples Analyzed

- Case studies were analyzed for common characteristics within the DT dimensions

- Excerpts describing DT dimensions were pulled for later thematic analysis

Table 3: List of UWS Case Studies

AUTHORS	YEAR	PUBLICATION TYPE	PHYSICAL ENTITY
Conejos Fuertes et al.	2020	Academic Journal	Distribution Network
van Rooij et al.	2022	Academic Journal	Reverse Osmosis
Tripathi et al.	2018	White Paper	Distribution Network
Pesantez et al.	2021	Academic Journal	Distribution Network
Valverde-Perez et al.	2021(a)	White Paper	Sewer Network
Valverde-Perez et al.	2021(b)	White Paper	Water Treatment Plant
Zhou et al.	2024	Academic Journal	Pump Station
Ramos et al.	2023	Academic Journal	Distribution Network
Bonilla et al.	2022	Academic Journal	Distribution Network
Bartos and Kerkez	2021	Academic Journal	Drainage System
Brahmbhatt et al.	2023	Academic Journal	Distribution Network

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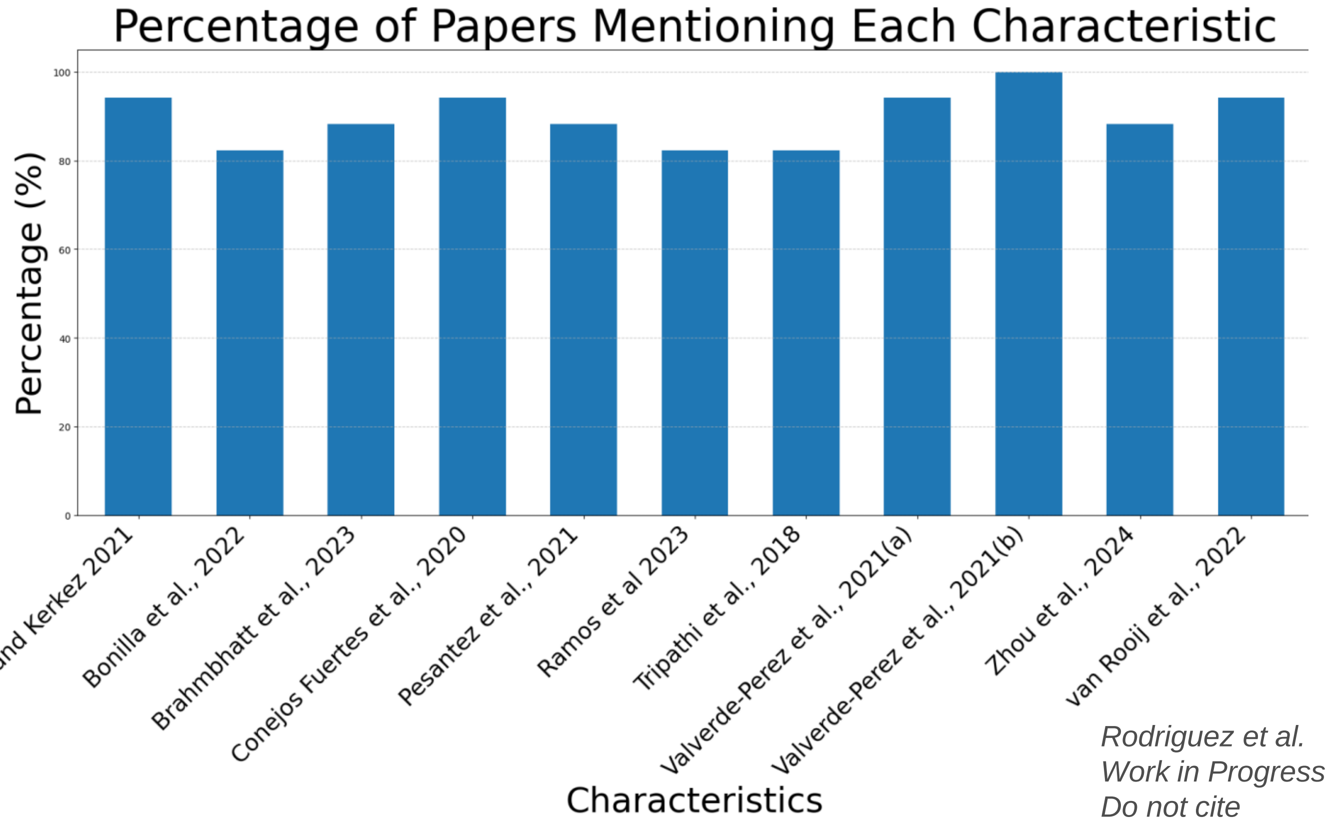
Dimensional Analysis

- Manually reviewed each case study for 17 DT dimensions
- Quantified prevalence of dimensions across case studies
- Identified fundamental dimensions present in >90% of studies
- Analyzed dimension coverage in individual case studies

Figure 7: Alignment of UWS DT Discussions with DT dimensions



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Dimensional Analysis

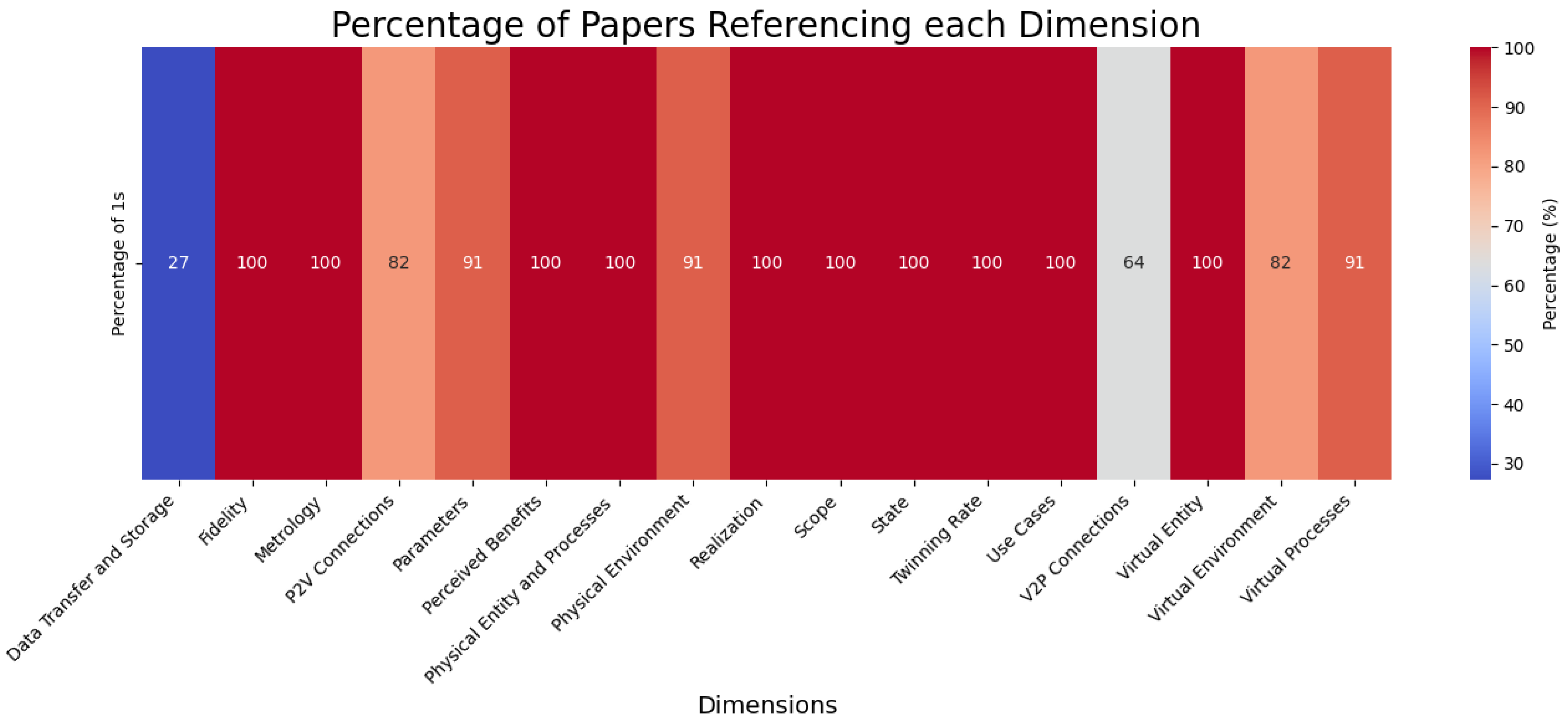

Figure 8: DT Dimensions discussed in UWS Case Studies

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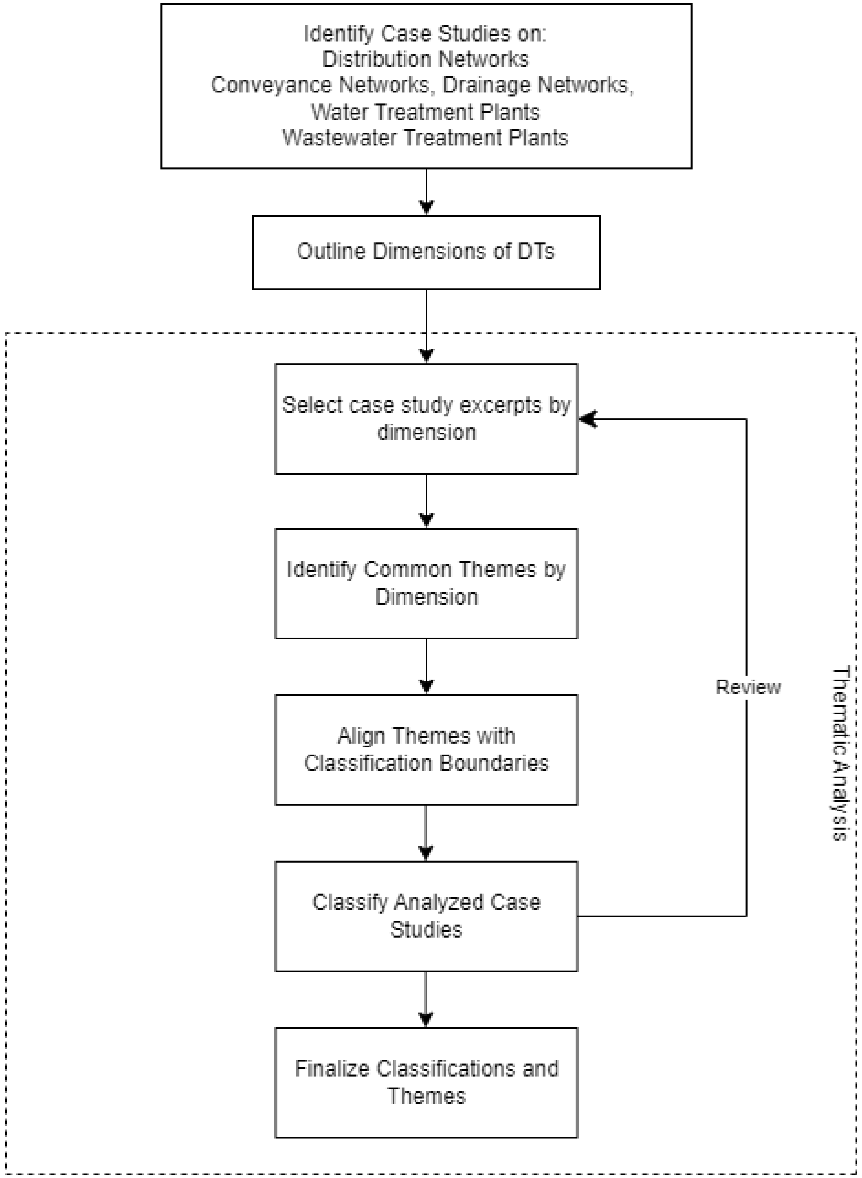
Thematic Analysis

- Conducted thematic analysis across case study excerpts
- Identified common themes within each dimension
- Resulted in 56 common themes across 17 dimensions
- Mapped themes to specific case studies

Figure 6: Methods Overview



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Thematic Analysis

Dimensions	*DT Subsystem*	Themes			
Realization	*Interface*	Manual Realization	Automatic Realization	Updating Virtual Operating Parameters	Updating Physical Operating Parameters
V2P Connections	*Physical System*	Operator Data Presentation	Actuators/Automatic Control**		
Virtual Environment	*Virtual System*	Integration with Databases	Multiple Models		
Fidelity	*Virtual System*	Continuous Calibration	Manual Calibration		
Twinning Rate	*Virtual System*	Minute-scale	Hour-scale	Historical data	Real time data
Scope	*Virtual System*	Single Parameter in Scope	Multiple Parameters in Scope	Subset of Physical System	Entire Physical System
P2V Connections	*Virtual System*	Data Preprocessing	Direct to DT		
Use Cases	*Virtual System*	Operational Monitoring and Forecasting	Real-time Optimization	What-if analysis and master planning	
Perceived Benefits	*Physical System*	Cost and Energy Efficiency	Informing Planning and Design	Improved Resilience	Training

Table 4: Subset of DT Dimensions with UWS Themes

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Thematic Analysis

Digital Shadow	Digital Twin

Dimensions	*DT Subsystem*	Themes			
Realization	*Interface*	Manual Realization	Automatic Realization	Updating Virtual Operating Parameters	Updating Physical Operating Parameters
V2P Connections	*Physical System*	Operator Data Presentation	Actuators/Automatic Control**		
Virtual Environment	*Virtual System*	Integration with Databases	Multiple Models		
Fidelity	*Virtual System*	Continuous Calibration	Manual Calibration		
Twinning Rate	*Virtual System*	Minute-scale	Hour-scale	Historical data	Real time data
Scope	*Virtual System*	Single Parameter in Scope	Multiple Parameters in Scope	Subset of Physical System	Entire Physical System
P2V Connections	*Virtual System*	Data Preprocessing	Direct to DT		
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Table 4: Subset of DT Dimensions with UWS Themes

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Classifications

AUTHORS	YEAR	PHYSICAL ENTITY	CLASSIFICATION
Conejos Fuertes et al.	2020	Distribution Network	Digital Twin
van Rooij et al.	2022	Reverse Osmosis	Digital Model
Tripathi et al.	2018	Distribution Network	Digital Model
Pesantez et al.	2021	Distribution Network	Digital Model
Valverde-Perez et al.	2021(a)	Sewer Network	Digital Twin
Valverde-Perez et al.	2021(b)	Water Treatment Plant	Digital Shadow
Zhou et al.	2024	Pump Station	Digital Model
Ramos et al.	2023	Distribution Network	Digital Model
Bonilla et al.	2022	Distribution Network	Digital Model
Bartos and Kerkez	2021	Drainage System	Digital Shadow
Brahmbhatt et al.	2023	Distribution Network	Digital Twin

Table 5: Classification of UWS DT Case Studies

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Results

	Multiple Models	Updating DT Parameters	Updating Physical Operating Parameters	Manual Realization	Automatic Realization	Continuous Calibration	Manual Calibration	Real time	Historical Data	Subset of Physical System	Entire Physical System	Remote - Direct to DT	Actuators/ Automatic Control	Operator Data Presentation
DM	50%	83%	0%	83%	17%	17%	83%	0%	100%	50%	33%	17%	0%	50%
DS	50%	100%	0%	0%	100%	100%	100%	50%	50%	0%	100%	100%	0%	100%
DT	33%	100%	100%	33%	67%	100%	67%	67%	33%	0%	67%	100%	0%	100%

Table 6: Heatmap of DT characteristics across archetypes

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Results

- Digital Twin is utilized most for real-time optimization of system and development of control schemes
- All archetypes realize common benefits, regardless of the desired use case

	USE CASES			PERCEIVED BENEFITS			
	Monitoring and Forecasting	**Real-Time Optimization**	**What-if analysis and master planning**	**Cost and Energy Efficiency**	**Informing Planning and Design**	**Improved Resilience**	**Training**
Digital Models	17%	0%	83%	50%	67%	67%	17%
Digital Shadows	100%	0%	50%	50%	50%	50%	50%
Digital Twins	100%	100%	33%	33%	67%	100%	33%

Table 7: Heatmap of DT Use Cases and Perceived Benefits across archetypes

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Takeaways

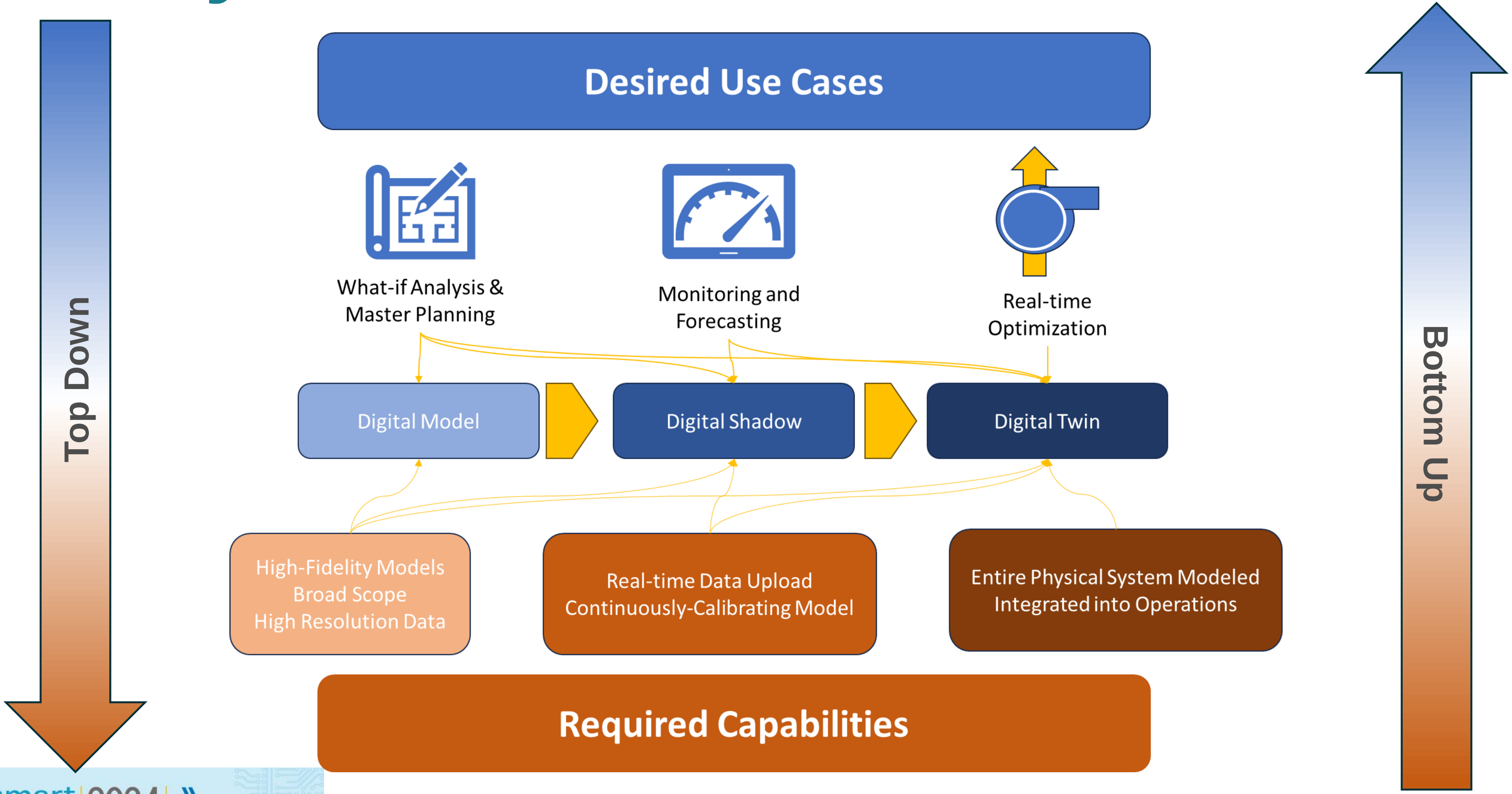

Figure 9: Decision Approaches for Selecting Desired DT Archetype

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Takeaways

- Current State of UWS DTs:
  - Many self-described "digital twins" lack the integration to be considered a digital twin
  - The perceived benefits from classified DMs are misaligned with model capabilities
    - DMs can be employed as training tools to study potential system shocks
  - DT development in UWS still in infancy, currently centered at lower integration levels
  - Standardizing the language of DTs around a classification approach will help to better determine development frameworks, costs, and potential uses and benefits
- Current Gaps:
  - Social and technological challenges with reaching autonomous DTs
- Future Directions:
  - Need for standardization and best practices in UWS DT implementation
  - Analysis of the cost-benefits of each DT archetype, including more autonomous DTs

Project Partners

NAWI National Alliance for Water Innovation

WRD WATER REPLENISHMENT DISTRICT OF SOUTHERN CALIFORNIA

NREL NATIONAL RENEWABLE ENERGY LABORATORY

SRP Delivering water and power™

EPRI ELECTRIC POWER RESEARCH INSTITUTE

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Thank you!

For further questions, please contact:
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