# Teaching Documentation

# 977-352 Cyber-Physical Systems

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College of Computing
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Prerequisites: 977-341
Sensors and Microcontroller Interface

# Preface

This teaching documentation is for the subject "977-352 Cyber-Physical Systems". The aim is to offer an elective specialized course in intelligent objects for undergraduate students in the digital engineering program under the College of Computing at Prince of Songkla University.

In engineering, knowledge of cyber-physical systems is crucial for understanding and applying engineering innovations and applications in real-world digital contexts. This course is designed for students with an engineering background and focuses on illustrating and developing the interplay between digital technology and computational foundations.

Key problem-solving skills are developed based on system engineering and integration using computational techniques. The course examines key topics in physical essentials, including system formulation and computational processes for modeling physical environments with digital transformation.

Komsan Kanjanasit

## Expected Learning Outcomes

1. PLO1.1: Be able to explore knowledge from various sources using information technology to apply it to solve problems on their own.
   CLO1.1.1: Demonstrates ethical and moral principles based on reasoning and rationale.
2. PLO2.1: Be able to explain key knowledge and theories of digital technology both orally and in writing and can select appropriate formats for presentations.
   CLO2.1.1: Has knowledge of cyber-physical systems.
3. PLO2.2: Be able to apply and integrate knowledge and solve problems in digital engineering as required by the labor market in the digital engineering field, using mathematical information or applied statistics, to apply to the needs of industry or related scientific knowledge.
   CLO2.2.1: Be able to practice operational activities.
4. PLO3.2: Be able to lead teams to solve problems, take responsibility for their actions and work in groups, and use scientific knowledge as a basis for society in appropriate areas.
   CLO3.2.1: Be able to demonstrate appropriate leadership qualities.
5. PLO4.1: Has skills in using tools and/or information technology appropriate for computer-related work.
   CLO4.1.1: Uses tools correctly.
6. PLO4.2: Be able to suggest problem-solving issues using creative digital engineering.
   CLO4.2.1: Responds using principles in presenting work.
7. PLO4.3: Be able to link learned knowledge to apply in project courses, internships, and effectively present.
   CLO4.3.1: Utilizes for benefits.
8. PLO4.4: Be able use modern technology to create innovations that meet the needs of society and the digital industry.
   CLO4.4.1: Presents perspectives for benefits.

Percentage of Weight Score (100%)

| CLO 1.1.1 | CLO 2.1.1 | CLO 2.2.1 | CLO 3.2.1 | CLO 4.1.1 | CLO 4.2.1 | CLO 4.3.1 | CLO 4.4.1 |
|---|---|---|---|---|---|---|---|
| 10% | 30% | 30% | 5% | 10% | 5% | 5% | 5% |

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# List of Abbreviations

| | |
|---|---|
| 5G | Fifth Generation |
| 6G | Sixth Generation |
| 6GFP | 6Genesis Flagship Program |
| ABM | Agent-Based Models |
| ADC | Analog-to-Digital Converter |
| AI | artificial Intelligence |
| AML | Automation Markup Language |
| AMQP | advanced Message Queuing Protocol |
| AOP | Aspect-Oriented Programming |
| AR | Augmented Reality |
| AS | Administration Shell |
| ATS | Artificial Transportation Systems |
| AV | Autonomous Vehicle |
| AWS | Amazon Web Service |
| BCI | Brain-computer Interface |
| BIM | Building Information Modeling |
| BMS | Building Management System |
| BoT | Blockchain of Things |
| CAD | Computer-Aided Design |
| CAN | Controller Area Network |
| CAS | Complex Adaptive Systems |
| CCES | Consumer-Centered Energy System |
| CE | Concurrent Engineering |
| CoAP | Constrained Application Protocol |
| CNC | Computer Numeric Control |
| CI | Collective Intelligence |
| CIM | Computer-Integrated Manufacturing |
| COVID | COronaVIrus Disease of 2019 |
| CNN | Convolutional Neural Networks |
| CNP | Contract Net Protocol |
| CPMT | Cyber-Physical Machine Tools |
| CPPS | Cyber-Physical Production Systems |
| CPS | Cyber-Physical Systems |
| CPSS | Cyber-Physical-Social Systems |
| D2D | Device-to-Device |
| DAC | Digital-to-Analog Converter |
| DAO | Decentralized Autonomous Organization |
| DDS | Data Distribution Service |
| DES | Discrete Event Simulation |
| DeSoc | Decentralised Society |
| DM | Digital Model |
| DMD | Dynamic Mode Decomposition |
| DNN | Deep Neural Networks |
| DNP | Distributed Network Protocol |
| DNS | Domain Name System |
| DoF | Degrees of Freedom |
| DS | Digital Shadow |
| DSSoT | Dynamic Social Structure of Things |
| DT | Digital Twin |
| DTA | Digital Twin Aggregate |
| DTP | Digital Twin Prototype |
| DTI | Digital Twin Instance |
| ECG | Electrocardiography |
| EDT | Experimentable Digital Twins |
| ELE | Enhanced living Environments |
| EMG | Electromyography |
| ESPN | Extrasensory Perception Network |
| FFT | Fast Fourier Transform |
| FMI | Functional Mockup Interface |

FPGA Field Programmable Gate Array
FSM Finite State Machine
GAN Generative Adversarial Network
H2OS Human-Oriented Operating System
HCI Human-Computer Interface
HDT Human Digital Twin
HEVC High Efficiency Video Coding
HIT Human Intelligence Task
HMI Human-Machine Interaction
HMS Holonic Manufacturing System
HOSVD High-Order Singular Value Decomposition
HRM Human Resource Management
HTTP Hypertext Transfer Protocol
HVAC Heating, Ventilation, and Air-Conditioning
I4.0 Industry 4.0
ICN Information-Centric Networking
ICO Initial Coin Offerings
ICL Intelligent Communities Lifecycle
ICT Information and Communications Technology
IETF Internet Engineering Task Force
IEQ Indoor Environmental Quality
IIC Industrial Internet Consortium
IIoT Industrial Internet of Thing
IIRA Industrial Internet Reference Architecture
IMS Intelligent Manufacturing Systems
IoE Internet of Energy
IoS Internet of Services
IoT Internet-of-Things
IP Internet Protocol
IPS2 Industrial Product-Service Systems
ISA International Society of Automation
ISO International Organization for Standardization
IT Information Technology
ITS Intelligent Transportation Systems
IWN Industrial Wireless Network
J2EE Java 2 Enterprise Edition
LBS Location-Based Services
LiDAR Light Detection and Ranging
LSTM Long Short-Term Memory
M2M Machine-to-Machine
MaaS Mobility as a Service
MAS Multi-Agent Systems
MB Model-Based
MCC Mobile Cloud Computing
MDS Mobility Data Specification
MEC Mobile Edge Computing
MES Manufacturing Execution System
MIMO Multiple Input Multiple Output
MMM Metropolis Meta-Model
ML Machine Learning
MLP Multilayer Perceptron
MoC Models of Computation
MQTT Message Queue Telemetry Transport
NFT Non-Fungible Token
NN Neural Network
OAP Open-Architecture Products
OPC UA Open Platform Communications United Architecture
OT Operational Technology

OWL Ontology Web Language
P2P Peer-to-Peer
PBNA Physics-Based Network Architectures
PoW Proof of Work
PHM Prognostics and Health Management
PMB Physical Model-Based
PN Process Networks
PLC Programmable Logic Controllers
PLM Product Lifecycle Management
POD Proper Orthogonal Decomposition
QoS Quality of Service
RAMI 4.0 Reference Architectural Model Industrie 4.0
RDF Resource Description Framework
RESTful Representative State Transfer
RF Random Forest
RFID Radio-Frequency Identification
RMS Reconfigurable Manufacturing Systems
RNN Recurrent Neural Networks
RoW Right of Way
RUL Remaining Useful Life
SDG Sustainable Development Goals
SDF Synchronous Dataflow
SDK Software Development Kit
SDN Software Defined Networking
SGAM Smart Grid Architecture Model
SOA Service Oriented Architecture
STFT Short-time Fourier Transform
STI Science, Technology, and Innovation
STS Socio-technical Systems
SC Supply chains
SDT Sustainable Digital Twin
SR Synchronous reactive
SINDy Sparse Identification of Nonlinear Dynamics
SME Small and medium-sized enterprises
SVM Support Vector Machines
TCP Transmission Control Protocol
TLS Transport Layer Security
TSN Time-Sensitive Networking
TTL Time-to-Live
UAV Unmanned aerial Vehicle
UDP User Datagram Protocol
UI User Interface
UML Unified Modeling Language
UGV Unmanned Ground Vehicle
V2G Vehicle-to-Grid
V2V Vehicle-to-Vehicle
V2X Vehicle-to-Everything
VANET Vehicular Ad-hoc Network
VMS Vehicle Management System
VMP Virtual Environment Platform
VR Virtual Reality
WiFi Wireless Fidelity
WNV Wireless Network Virtualization
WLAN Wireless Local Area Network
WSN Wireless Sensor Networks
XaaS Everything as a Service

# Chapter 1

# Cyber-Physical System Perspectives

**Chapter Objectives**

- Learners familiarize the cyber-physical systems.
- Learners understand cyber-physical systems using computational techniques.
- Learners can describe the applications of cyber-physical systems.

The advent of the Internet-of-Things (IoT), artificial intelligence (AI), and communication technologies has led to the transformation of the engineering paradigm through cyber-physical systems (CPS), which find extensive applications across various societal domains such as homes, energy, agriculture, healthcare, transportation, business, and manufacturing. CPS employs computational techniques to facilitate interactions among diverse entities, enabling them to undertake requisite actions to achieve specific objectives. CPS has heavily utilized computational techniques to tackle a range of technical hurdles. However, there is a need for studies that can elucidate these contributions by providing CPS types and their characteristics, highlighting the relevance of computational techniques in modeling different CPS aspects, and examining the application of computational techniques in existing works. This chapter aims to address perspectives by 1) offering a general dialogue on various CPS types and their attributes; 2) presenting different computational approaches; 3) elucidating the suitability of computational theory for modeling diverse CPS aspects; and 4) exploring how computational techniques has been employed in different CPS types to tackle their challenges. Additionally, key challenges outline for exploration where computational techniques could serve as a potential solution.

## 1.1 Introduction

Cyber-physical systems (CPS) represent a new breed of engineered systems that rely on seamlessly integrated computing, communication, and control technologies. The concept of CPS traces back to 1941 when the first fully functional program-controlled computation machine, the Z3, was used for aircraft wing surveys. However, it wasn't until the 1990s, with advancements in sensors, instrumentation, networking, and embedded computing, that interest in facilitating interactions between computational and physical systems gained momentum. The term "cyber-physical systems" was formally coined around 2006 by the National Science Foundation in the United States.

The broad exploration of CPS is driving the development of customer-centric and intelligent solutions across various industries, including home automation, smart cities, energy management, healthcare, transportation, agriculture, and entertainment. CPS facilitates disruptive innovations by enabling interactions among different system components through digital platforms like blockchain, allowing for informed real-time decisions in the physical realm. For instance, in the energy sector, users with distributed energy resources can utilize a smart grid's digital layer to trade electricity with each other based on negotiated parameters. Similarly, in transportation systems, vehicles can interact

with each other and roadside nodes through digital platforms to access real-time traffic information and optimize their travel routes.

The utility of CPS stems from their interoperability, connectivity, networking capability, communication, decentralization, autonomy, and modularity. Interoperability enables CPS components to exchange understandable data, while connectivity via various communication protocols facilitates this exchange. CPS modularity allows them to adapt and reconfigure their responses to meet users' needs. For this, CPS as interconnected networks of components or subsystems require networking capabilities to ensure seamless interaction without sacrificing autonomy or decentralized control.

The distinctive feature of cyber-physical systems (CPS) lies in the direct interaction among their components to make real-time decisions, setting them apart from traditional critical infrastructure systems. However, this characteristic also introduces challenges in modeling the decision-making processes of individual agents within CPS to maximize collective benefits while adhering to system constraints. Particularly in scenarios involving rational agents with conflicting interests, modeling their intricate interactions to determine whether to cooperate or compete for specific objectives becomes highly challenging. These objectives encompass various goals such as cost reduction, revenue maximization, supply-demand balancing, reliability and security confirmation, visibility and care promotion, and environmental sustainability. Therefore, a robust decision-making process grounded in solid mathematical principles is essential to ensure efficient and secure CPS operation.

In this context, computational technique emerges as a natural approach for modeling interactive decision-making in CPS. Computational technique is a formal analytical framework equipped with mathematical tools to model complex interactions among self-interested players. It has found applications across diverse domains including economics, finance, operational research, energy, social science, political science, psychology, military, and retail markets for many decades.

There has been a surge in focusing on computational approaches for CPS. Given the diverse types of CPS arising from differences in applications and agent interaction patterns within each system, a question arises: is it feasible to comprehend the full scope of how computational techniques can model CPS operation? To address this question, this detail aims to provide a comprehensive point of the state-of-the-art works in computational techniques applied to CPS. This part serves multiple purposes: assisting users in conducting new perspectives requiring agent interactions within CPS, preparing to tackle emerging CPS challenges, designing, and implementing efficient and cost-effective operational algorithms for CPS, and developing new services offered by CPS. By offering clear insights into advancements in computational techniques and studies of CPS, this part aims to be beneficial in fields such as energy, engineering, economics, signal processing, medicine, agriculture, and transportation.

## 1.2 CPS Emerging

As a burgeoning area, the exploration of Cyber-Physical Systems (CPS) encompasses various intersecting fields of science and engineering. Consequently, the formal definition of CPS has evolved over time, shaped by the perspectives of different scholars. CPS is delineated as a technical platform wherein physical processes interact with computations through a feedback loop, and vice versa. Meanwhile, CPS is characterized as a networked physical engineering system that oversees and regulates the functioning of physical systems through computational means. In essence, CPS embodies a fusion and synchronization of physical systems and digitally networked systems, facilitated by a feedback loop. Here is the following formal definition of CPS:

Definition: A CPS is a system that integrates both a physical system and a digital (or cyber) networked system within a unified framework. In this setup, the actions within the physical system can be observed, analyzed, and managed by the computational capacity, flexibility, and adaptability of the digitally networked system, facilitated by communication through a feedback loop between the two systems. A fully autonomous CPS possesses the capability to learn from its environment, make decisions, and operate autonomously in real-time, whereas a semi-autonomous system operates independently only under predefined conditions.

### 1.2.1 Characterization

The structure of a CPS varies based on its type and functionalities. However, as per the definition, each CPS typically necessitates the following components: 1) the creation of a digital replica or twin of its physical configuration for real-time monitoring and analysis, 2) an intelligent control unit responsible for estimation and decision-making processes, and 3) a unit dedicated to executing algorithms that implement the decisions within the physical setup through a feedback control loop. To facilitate these essential functions, the architecture of a CPS generally comprises five levels, regardless of its specific classification and intended use. These levels include a smart connection level, a data-to-information conversion level, a cyber level, a cognition level, and a configuration level, as illustrated in **Figure 1.1**.

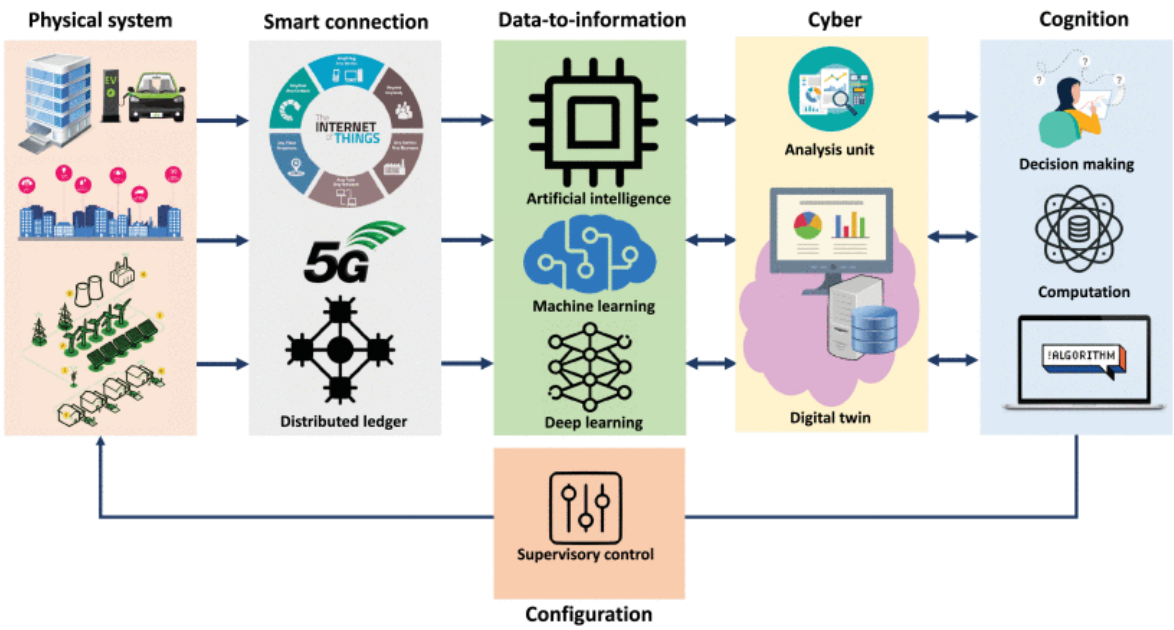


**Figure 1.1** An illustration of the cyber and physical spaces of an operational CPS.

[Source: Tushar, W., et al. (2023)]

- **Intelligent Connectivity Level**

The initial phase in establishing a digital representation of a physical system for monitoring, analysis, and decision-making entails acquiring precise and dependable data from various components of the physical setup. In order to ensure accurate data collection and measurement, the Internet of Things (IoT) has emerged as a favored tool for data acquisition. IoT rooted in networked smart devices, facilitates the real-time monitoring and sensing of diverse environmental and mechanical parameters within a CPS, effectively gathering information and transmitting it to the server through appropriate

communication protocols like 5G. In the intelligent connectivity level of CPS, two critical considerations come into play. Firstly, a seamless and wireless method for data acquisition needs to be established, accounting for the varied types of data originating from different CPS components. Secondly, ensuring secure communication protocols for data transfer from IoT devices to the server is imperative. Additionally, the selection of suitable sensors with specific specifications to gather data from various machinery and components also holds significance.

- **Data-to-Information Transformation Level**

Accessing data and information promptly is pivotal for the successful operation of any business, and the same holds true for the effective implementation of CPS. Data transformation endeavors to uncover correlations and underlying patterns to extract valuable information. Data collected from diverse CPS components can be categorized into three types: structured data, semi-structured data, and unstructured data. Structured data typically utilizes a distributed database system for management and storage, while unstructured data are stored using the Hadoop distributed file system, alongside other structured query language options. Semi-structured data are standardized into a unified format via extensible markup language and are stored in either a relational database management system or distributed database system. An efficient data-to-information transformation level is essential for extracting meaningful insights from acquired data, with data mining serving as a prominent technique. Generally, data mining techniques analyze extensive datasets to unearth valuable structures. Popular data mining techniques applied in CPS include clustering, classification and regression, artificial intelligence, deep learning, Bayesian learning, and machine learning.

- **Digital Level**

The digital level serves as the central information repository, aggregating data from all interconnected components within the network to construct the digital replica of the physical structure. As per IBM, a digital twin is a virtual rendition of a system constructed and continually updated with real-time data, employing simulation, machine learning, and reasoning to aid decision-making. Consequently, this level of the CPS manages, analyzes, and benchmarks all information, facilitating optimized decision-making at the cognitive level. However, this level is also highly susceptible to cyberattacks and security breaches, underscoring the criticality of ensuring cyber-level security for the secure and efficient operation of the CPS. Notably, extensive work has delved into the security of cyber-physical systems across various domains, including green buildings, smart grids, transportation systems, medical CPS, autonomous robot systems, smart cities, and smart agricultural systems.

- **Cognitive Level**

This facet of a CPS facilitates informed decision-making regarding actions within the physical structure of the system. Decisions are predicated on a comprehensive understanding of the monitored system and the analyzed data from the digital level. CPS addresses cognitive challenges pertinent to both human and artificial cognition. For instance, CPS can undertake specific cognitive tasks from users and, through information exchange, generate the requisite outputs. The cognitive level relies on diverse computational models, formulates algorithms, and generates control signals to execute various actions within the CPS's physical structure.

- **Management Level**

The management level functions as the supervisory control of the overall CPS, implementing corrective and preventive decisions formulated at the cognitive level within the physical space of the CPS. Consequently, any changes in circumstances within physical space are monitored, recorded,

and analyzed at the digital level, with subsequent actions planned at the cognitive level. To adapt the quality and efficiency required for the newly adopted circumstances, the management level executes necessary control actions within the physical space.

### 1.2.2 Attributes

The five-level framework equips CPS with a range of characteristics essential for effective operation across diverse application domains. These features include adaptive control, reliance on data, predictive maintenance, system interconnectivity, integration with the Internet of Things (IoT), real-time monitoring and control, interaction between humans and machines, as well as security and privacy provisions.

**1) Adaptive Control**

Adaptive control refers to the capability of a CPS to adjust its operational strategy in response to changing environmental conditions to achieve optimal outcomes. For instance, in medical CPS, respiratory modules assist patients in breathing by adjusting pressure levels based on real-time data. Similarly, adaptive control is employed in smart agricultural systems to manage irrigation and moisture distribution, and in autonomous robotic systems for military surveillance and intervention. This approach is also utilized in green buildings for HVAC and lighting control, in smart grids for demand response, in transportation for coordinating electric vehicles, and in manufacturing for laser welding and additive manufacturing processes.

**2) Data-Driven**

Data forms a foundational component of CPS, enabling interactions between physical and cyber systems. Consequently, CPS can be described as data-driven systems. Data obtained from various sources profoundly influences the management, control, and performance of CPS subsystems, driving the development of numerous data-driven techniques and algorithms. For example, data-driven approaches address security concerns in smart grids and optimize energy usage in green buildings. Moreover, IoT data is instrumental in medical imaging, smart city initiatives, transportation systems, robotics, agriculture, and Industry 4.0 applications. Ensuring the reliability of this data is crucial, given its pivotal role in informing CPS decision-making processes.

**3) Predictive Maintenance**

CPS leverage extensive data usage to implement predictive maintenance strategies, which entail analyzing data to identify anomalies and predict potential equipment or process failures. This proactive approach enables preemptive maintenance actions to be taken, minimizing downtime and enhancing overall system reliability. Predictive maintenance applications span various domains, including green buildings, smart grids, transportation systems, manufacturing plants, medical facilities, agriculture, and robotics.

**4) Interconnection Between Systems**

A fundamental characteristic of CPS is the connectivity among its various components. For instance, in a smart city, green buildings equipped with smart building management and automation systems are interconnected and capable of sharing resources such as energy and water. An illustration of such a community is depicted in **Figure 1.2**. Through communication, different agents within a CPS interact to achieve individual and collective objectives by making informed decisions. In this process, each agent may act independently, striving to achieve its own goals such as cost reduction, resource supply-demand balance, increased access to community resources, and enhanced communication for critical operations. Conversely, agents can also collaborate and work together to achieve goals that

yield collective benefits for the entire CPS. Instances of such collaboration are observed in green buildings, robotics, smart grids, transportation systems, and manufacturing plants.

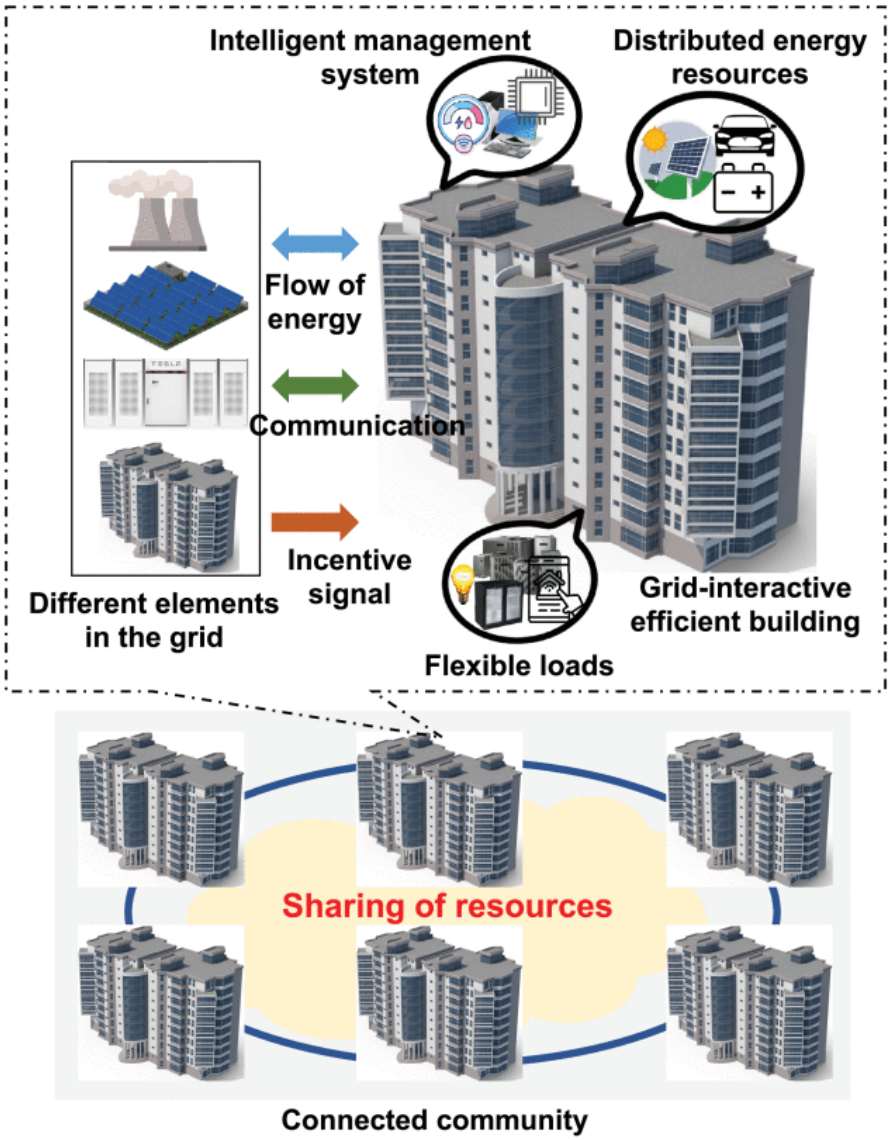


**Figure 1.2** An illustration of different green buildings.

[Source: Tushar, W., et al. (2023)]

**5) Internet of Things**

The integration and data exchange among various subsystems of CPS have been facilitated by the emergence of the Internet of Things (IoT). IoT can be described as a wireless network that enables the widespread presence of diverse objects or "things" using Radio-Frequency Identification (RFID) tags, sensors, actuators, mobile phones, and other devices, allowing these objects to interact and collaborate to achieve common objectives. The application of IoT is crucial and extensive in CPS. For instance, IoT's highly integrated and open nature is particularly suitable for smart agriculture,

enabling the integration of autonomous equipment from various organizations for tasks such as irrigation, weather forecasting, and rapid detection of events like threats, floods, and earthquakes. By facilitating communication among different appliances within green buildings, IoT can assist building owners not only in reducing resource usage and costs but also in sharing unused resources with other community members to enhance sustainability. Examples of such roles of green buildings are evident in smart city initiatives and smart grid applications. In robotics, IoT plays a vital role in designing multi-robot systems in both industrial and academic settings. Specifically, robot localization becomes more reliable when robots can interact with an IoT-based smart environment.

**6) Real-Time Monitoring and Control**

The utilization of IoT has enabled CPS to monitor the functioning of its various subsystems in real-time, promptly detect changes in the environmental context, and make informed and intelligent decisions accordingly. With the aid of digital twins, large manufacturing plants can now oversee and supervise every stage of the production process to ensure the mass production of high-quality goods within shorter time frames. Continuous monitoring of critical patients and the provision of real-time telemedicine services, whether onsite or remotely, are also feasible in medical CPS. For instance, telemedicine is proposed as an effective means to improve cardiovascular disease management while reducing healthcare costs and demonstrates how real-time monitoring of patient conditions can save lives through automated oxygen saturation management. Continuous monitoring of subsystem activities and control of their operations for increased productivity are also prevalent in various domains such as green buildings (for HVAC, lighting, and flexible appliances control), smart grids (for phase measurement units auditing and security), transportation (for coordinated electric vehicle charging and discharging), agriculture (for adaptive irrigation), and robotics (for localization and routing control).

**7) Human-Machine Interaction**

Human-machine interaction (HMI) involves the communication and collaboration between humans and machines, typically facilitated through a graphical user interface. The agent-based structure of CPS allows its various agents to directly engage with humans to receive instructions for completing specific tasks. HMI is extensively utilized in medical CPS, smart grid systems, robotics, transportation, and manufacturing. In the medical field, for instance, the interaction introduces a touchless and gesture-based HMI framework for operating rooms, enabling surgeons to define personalized gestures to control medical computerized systems. In smart grids, customers can set their energy preferences online to participate in demand response programs. HMI also plays a role in designing rehabilitation robots and socially assistive robots in robotics, supporting caregivers, parents, and educators. It is utilized in developing automated vehicles and digital twin-based smart manufacturing processes in transportation and manufacturing, respectively. Additionally, HMI is employed in precision agriculture for real-time visualization of sensor data on temperature, humidity, and solar irradiation, allowing users to manage agricultural CPS.

**8) Security and Privacy**

Given the interactive decision-making process and extensive data usage in CPS, ensuring system security, and protecting user privacy have become paramount concerns. It is projected that cybercrime costs the global economy. Sectors such as smart grids, smart cities, green buildings, medical facilities, agricultural farms, and manufacturing plants are particularly vulnerable to cyberattacks due to their heavy reliance on IoT and Internet-based protocols for monitoring and control. To maintain the security of CPS operations, novel preventive methodologies and security architectures are being developed. For example, the protection demonstrates how artificial intelligence can safeguard green buildings from cyberattacks. Artificial intelligence is also effective

in protecting smart grids, intelligent vehicles, and smart cities by creating adaptive baseline behavior models and detecting new attacks using predictive analytics and machine intelligence. Other technical approaches utilized to enhance CPS security include big data analysis, cryptography, machine learning, deep learning, and distributed ledger technology. Additionally, to ensure data privacy and enable data sharing from CPS, provably private transformations are required, with offering various differentially private techniques relevant to CPS.

### 1.2.3 Types

Various characteristics empower CPS to function across diverse application domains. Based on these applications, various types of CPS operate either autonomously or collaboratively to provide environmentally sustainable, reliable, secure, efficient, adaptable, and cost-effective services. The objective of this section is to acquaint readers with specific CPS that have notably seen numerous applications of computational theory.

**1) Sustainable Buildings**

Sustainable buildings, also referred to as intelligent or smart buildings, possess the ability to collect and respond to data. Prioritizing sustainability, these structures incorporate advanced technologies such as 5G, artificial intelligence, Internet of Things (IoT), and cloud and edge computing, enhancing energy efficiency and user comfort. Like other CPS, the building management system (BMS) in sustainable buildings continuously monitors the building's condition and environment in real-time using data collection systems such as IoT devices and sensors. These systems measure various environmental parameters such as temperature, noise, humidity, electricity and water usage, as well as human activity, and transmit the data to a central control center for analysis and operational adjustments. Potential features that differentiate sustainable buildings from conventional ones include:

- IoT integration for seamless processing of building environmental data, including temperature, noise, humidity, electricity, and water usage, human activity monitoring, and energy consumption estimation.
- BMS functionality for adapting building operations based on human needs and activities.
- Flexible load management for scheduling and overseeing household activities.
- Utilization of big data management techniques for analysis and predictive modeling.
- Integration of artificial intelligence for automated, informed, and real-time decision-making processes.
- Incorporation of distributed energy resources to enhance the utilization and management of renewable energy sources.

A visual representation of sustainable buildings is depicted in **Figure 1.3**.

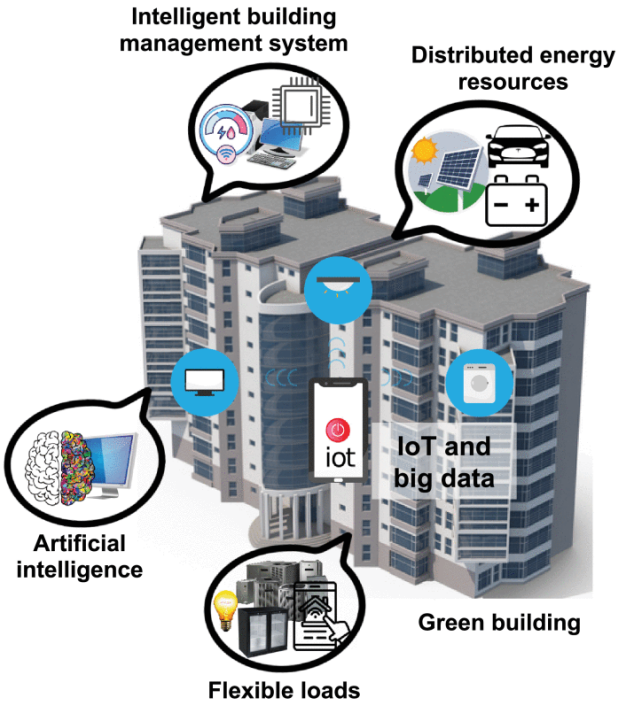


**Figure 1.3** A graphical illustration of a green building.

[Source: Tushar, W., et al. (2023)]

**Application in Green Buildings**

Within green buildings, the physical system encompasses the building structure itself, along with appliances such as HVAC systems, lighting fixtures, washing machines, hot water systems, refrigerators, and more. These smart appliances are interconnected through various communication protocols, enabling real-time communication among them and with the home automation system within the building. Utilizing artificial intelligence and machine learning techniques, the home automation system can extract valuable insights from the building's subsystems, analyzing them within its digital twin. This analysis enables the application of computational techniques to make informed decisions regarding energy usage, cost optimization, thermal comfort, home security, privacy protection, and resource management and sharing. As a CPS, green buildings embody the attributes, making computational techniques a valuable approach for addressing numerous challenges related to building design and construction, energy and comfort management, and resource sharing while upholding security and privacy.

- **Construction and Incentives**

Government incentives play a crucial role in promoting the construction of green buildings worldwide. Computational techniques have been utilized to design effective reward and penalty schemes aimed at encouraging green building development projects. For instance, the structure is developed as a prospect theory-based evolutionary computational model to explore strategies for promoting green building construction, determining dynamic rewards and static penalties as effective strategies. Additionally, while government incentives are essential, compliance with government regulations is necessary for real estate developers to undertake green building projects. Through evolutionary computational frameworks, studies such as overly stringent government

regulations may be inefficient in motivating developers to achieve green construction targets, highlighting the need for a balanced approach between regulation and builders' incentives. Addressing conflicts in construction contracts, conforming to architectural designs, and gauging occupants' perspectives on dwelling in green buildings are also critical aspects that can be managed using computational theoretic models for better social acceptance.

- **Energy Usage and Comfort**

Computational theory plays a vital role in modeling the interaction between different appliances to manage energy usage and ensure comfort within buildings. HVAC systems, lighting, and hot water systems are major energy consumers in buildings, presenting opportunities for energy conservation. Studies leverage computational theory combined with reinforcement learning to develop techniques for optimizing HVAC system settings based on historical weather data, grid operations, and human activities. Similarly, demand-side management approaches aim to reduce peak energy consumption in communities. Furthermore, non-cooperative game models, such as the one proposed, enable efficient control of residential air-conditioning systems to minimize electricity costs while maintaining occupants' thermal comfort.

- **Energy Sharing**

Modern buildings possess the capability to communicate and share resources with one another, enhancing overall sustainability and cost-effectiveness. Efforts focus on designing computational algorithms for multiple green buildings to share resources like renewable energy and battery capacity. These algorithms aim to find solutions that benefit all participating buildings by improving sustainability and reducing costs.

- **Cybersecurity**

Cybersecurity is a significant concern for green buildings due to their susceptibility to cyberattacks, given their wireless networks and IoT infrastructure. Computational theory has emerged as a valuable tool for addressing cybersecurity challenges in green buildings. Models enable effective control of attacks and defense mechanisms to ensure secure information transmission. Similarly, a computational technique is proposed for implementing security measures while considering system failure conditions and control principles. Moreover, defense mechanism policies against various attacks strike a balance between security overhead and control costs. Through computational theory, green buildings contribute to enhancing the energy efficiency of modern smart grids by offering energy management services as active prosumers.

**2) Intelligent Power Grid**

An intelligent power grid, also referred to as a smart power grid, harnesses modern information technologies to deliver electricity more efficiently by dynamically responding to various conditions and events. As outlined by the National Institute of Standards and Technology (NIST), the intelligent power grid comprises seven domains: customers, markets, service providers, operations, bulk generation, transmission, and distribution as referred to **Figure 1.4**. At the core of the intelligent power grid, embodying its characteristics as a CPS, lies the intelligent infrastructure system, consisting of three main subsystems: the intelligent energy subsystem, intelligent information subsystem, and intelligent communication subsystem.

The intelligent energy subsystem facilitates advanced power generation, distribution, and consumption. Unlike traditional power grids, the intelligent power grid offers greater flexibility in power generation and flow patterns. However, this flexibility also introduces complexities in power

flow control. The intelligent information subsystem is responsible for advanced information management, encompassing data modeling, information analysis, integration, and optimization. Additionally, it supports business settlement and transactions, and enables real-time monitoring and management of devices within the intelligent power grid.

Facilitating connectivity and data transmission among systems, devices, and applications, the intelligent communication subsystem serves as the backbone of the intelligent power grid. This subsystem encompasses various network types, including enterprise bus, wide area networks, field area networks, and premises networks. Ensuring efficient operation of the intelligent power grid, the communication subsystem must support Quality of Service for data, exhibit high reliability and extensive coverage, and guarantee security and privacy measures.

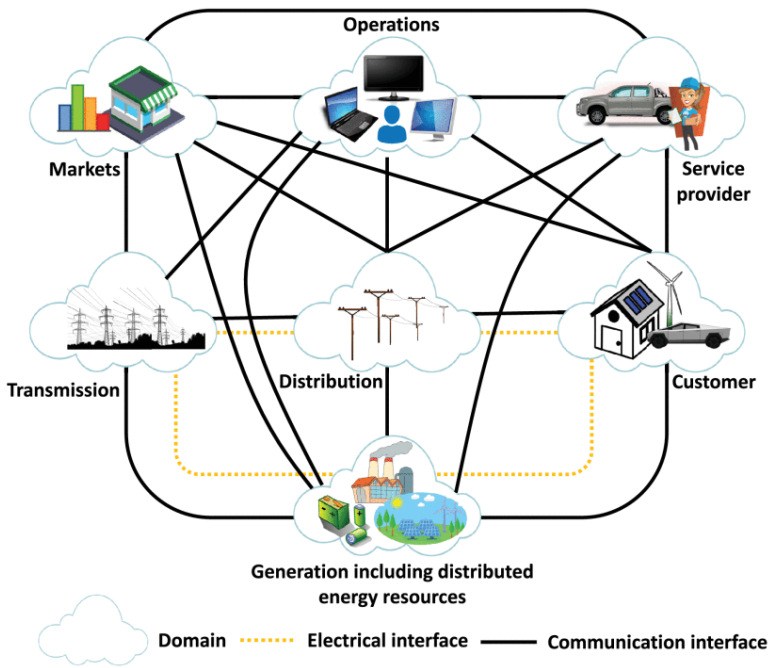


**Figure 1.4** A graphical illustration of the conceptual model of smart grid.

[Source: Tushar, W., et al. (2023)]

**Application in Smart Grid**

In the smart grid, resources used for the generation, transmission, and distribution of electricity, buildings, electric vehicles, and battery storage can be thought of as the physical systems of the CPS. These resources are mostly interconnected and can communicate with one another to make intelligent decisions in order to attain individual objectives. The decisions are taken in cyberspace via computational theory and distributed leader technology using data-driven techniques based on big data from different subsystems. Different computational intelligence techniques are utilized for the decision-making process and cloud-based information processing makes the decision-making faster and scalable. Smart grid attributes such as IoT enable the controller to sense any changes in the environmental settings and access the internet of information to make predictive decisions about various parameters for adaptive control of the activities of various components within the system. Security and privacy are of paramount importance in a smart grid where real-time monitoring and

control are strictly used for energy and thermal comfort management without compromising the privacy and security of the people. Users can actively participate in energy management through human-machine interaction and can influence the overall energy system behavior through social platforms. The practice of computational theory is extensive in the smart grid. Beginning from designing demand response management schemes, computational theory finds its applications in developing transactive energy frameworks, implementing peer-to-peer energy sharing schemes, designing real-time pricing and incentive mechanisms, managing energy in microgrids, and providing solutions to maintain power system security and stability.

- **Demand Response**

Demand response can be defined as the voluntary reduction or schedule of electricity use by customers with the purpose of keeping the electricity grid stable by maintaining the balance between demand and supply of electricity. The direct involvement of customers in demand response makes computational theory a perfect candidate to model the voluntary change in energy usage behavior by the people. Now, demand response can be done either via direct control of customers' load by the electricity operator or through providing incentives to the customers through a real-time pricing scheme. In the direct control demand response scheme proposed, the purpose of using a cooperative strategy is to minimize the cost of forming unions of multiple users and single retailers that enable residents to indirectly access the balancing market to reduce the risks and costs for the retailer. In indirect control, on the contrary, the use of computational theory helps to optimize the scheduling of flexible loads, develop suitable incentives through dynamic pricing schemes, and engage extensive customers participation in demand response. Another alternative demand response technique has emerged, and cooperative management is proposed to demonstrate how trading can bring financial benefits to the participating customers without any negative impact on the physical distribution network.

- **Transactive Energy**

Transactive energy and peer-to-peer energy sharing are the other two branches of the smart grid that have broad applications of computational theory. Transactive energy uses economic and control techniques to manage the flow of energy within a power system. On the other hand, peer-to-peer energy sharing is a part of a transactive energy mechanism that helps prosumers in a community to share their surplus with other peers at a price negotiated by themselves. In both cases, prosumers' flexibility in changing their energy usage behavior plays an important role where computational theory has been used extensively. For example, a nucleolus-based cooperative solution is proposed that utilizes the flexible loads of prosumers and considers the uncertainties of renewable energy resources to manage energy in local communities. A computational model is used to develop a joint energy and reserve dispatch model to ensure the reliability of system operation under renewable energy uncertainty. To maximize the benefit of distributed energy resources for flexible prosumers in terms of procuring revenues by trading electricity in the market, it explores algorithmic and non-cooperative management respectively to realize suitable transactive energy frameworks. Other aspects of transactive energy and peer-to-peer sharing, in which computational theory has been used extensively include regulation services, balancing supply and demand, reducing electricity cost, peak load reduction, encouraging customer participation, security of energy transactions, and privacy-preserved energy trading for neighborhood area networks.

- **Pricing**

Both demand response and transactive energy services necessitate the active participation of prosumers. A key incentive to motivate prosumers actively participate in energy management is an attractive pricing scheme. Consequently, designing new and fair pricing schemes has been a core

focus of smart grid research for a long-time using computational theory due to its inherent ability to capture people's rational behavior. For example, a dynamic pricing profile using non-cooperative management is introduced to engage prosumers to address the duck curve problem. With a similar purpose of helping the grid, a dynamic pricing strategy is studied that not only achieves significant peak load reduction but also enables participating prosumers to achieve noticeable profits for participating in the demand response program.

- **Microgrid Management**

Another aspect of smart grids that finds considerable use is microgrid management including energy trading between microgrids and designing energy management services within a microgrid. In terms of energy trading, non-cooperative management, multi-level interactive models, and cooperative theory. For managing energy within microgrids, on the other hand, hierarchical decision-making processes are modeled using computational theory for maximizing profits for different stakeholders within a microgrid including users, microgrid controller, and microgrid aggregators. For optimal dispatch of power within a microgrid, an evolutionary theory is used, whereas some use a technique for distributed control of microgrid with the same purpose of dispatching active and reactive powers. Finally, non-cooperative schemes are used for managing energy within microgrids considering the intermittent nature of renewable energy generation.

**3) Advanced Transportation Systems**

The concept of advanced transportation systems emerged, incorporating cognitive information into both road infrastructure and vehicles. Since then, the transportation sector has undergone significant evolution. Particularly, with accidents and fatalities on the rise, adversely impacting both the economy and environment, there is a growing need for next-generation transportation systems in air traffic, car control, and railways, leveraging advanced computing and sensing capabilities to enhance safety and throughput.

The advanced transportation systems have the capacity to help vehicles navigate traffic congestion, reduce energy and land consumption, enhance driving control, safety, and security, act as distributed energy resources to balance electricity demand and supply, reduce costs for vehicle owners, and improve environmental sustainability. Transformative technologies and innovative tools contributing to revolutionizing the transport system for a safer and greener future include in-vehicle sensor technology, in-roadway sensors, over-highway sensor technologies, IoT and cloud services, big data analysis tools, artificial intelligence, traffic sensing technologies, distributed ledger technology for transportation, and vehicle-to-vehicle communication and networks.

**Application in Intelligent Transportation Systems**

As the Internet of Things (IoT) and emerging computational techniques continue to transform the technological landscape, transportation networks and vehicles are evolving into smarter entities. Innovations in personalized electric cars, heavy automotive vehicles, roadside real-time communication and monitoring devices, and intelligent transportation systems are revolutionizing mobility options, offering safe, hassle-free, cost-effective, and efficient transportation solutions worldwide. Leveraging real-time information on traffic conditions, weather, and driver behavior patterns, the cyber unit of each vehicle utilizes game theory to calculate the safest and fastest route to its destination and adaptively adjust routes as circumstances change. This necessitates interconnectedness among all components of the intelligent transportation system through a smart communication system like 5G, direct interaction between humans and vehicles, and individual control units for executing real-time action plans devised by the cyber unit. Computational theory finds extensive use in vehicle-to-vehicle (V2V) and vehicle-to-grid (V2G) technologies for

coordinating energy operations among various stakeholders. For instance, computational models facilitate electricity trading between electric vehicles, autonomous decision-making in V2V interactions, modeling lane-changing behavior, enabling longitudinal autonomous driving, and distributing computation tasks among neighboring vehicles.

- **Intelligent Driving**

Intelligent transportation systems offer autonomous driving capabilities, real-time information processing for safe driving, and cost savings through efficient fuel usage. Theoretic traffic models enable testing and comparison of autonomous vehicle decisions and control systems, while model-based approaches optimize communication efficiency among autonomous vehicles and ensure safe and economical longitudinal driving for hybrid electric vehicles.

- **Monitoring and Control**

Real-time monitoring and precise control of traffic conditions, including vehicles and pedestrians, are vital for autonomous driving. Cooperative mechanisms manage traffic control in intersections, stochastic approaches accurately control lane changes by autonomous vehicles, and empirical game theory facilitates safe interaction between vehicles and pedestrians for navigation.

- **Energy Services**

V2G technology serves various purposes such as providing regulation services to the grid, coordinating charging and discharging of electric cars, enabling peer-to-peer energy sharing, and supporting demand response management. Computational models motivate electric vehicles to provide grid services, coordinate charging and discharging schedules, facilitate energy sharing, and contribute to infrastructure planning projects for smart cities and demand response management.

**4) Telemedical Systems**

Telemedical systems represent networked systems of medical devices that deliver life-critical and context-aware services in hospitals, ensuring high-quality continuous care for patients. Advancements in medical sensors, wireless sensor networks, and cloud computing have transformed standalone monitoring systems into remote monitoring systems, overcoming geographical barriers and enabling both in-home and in-hospital care for patients. These systems also provide a platform for leveraging computational resources to make intelligent decisions about patient conditions, based on analysis of historical data from digital records and real-time data from smart devices and biosensor-based monitoring systems.

A telemedical system is depicted in **Figure 1.5**. To deliver life-critical services effectively, a typical telemedical system architecture consists of four layers: the data acquisition layer, data concentration/aggregation layer, cloud processing and storage layer, and action layer. The data acquisition layer collects patient medical information and forwards it to nearby computationally capable devices. The data concentration/aggregation layer aggregates data from each device, sends it to the cloud for processing, and securely stores patient information. The cloud processing and storage layer securely stores patient information, processes data following privacy-preserving procedures, and utilizes advanced analytics to support health professionals in making informed decisions about patients. Finally, the action layer provides passive (ECG monitoring) or active actions (robot-assisted surgery) for medical treatment.

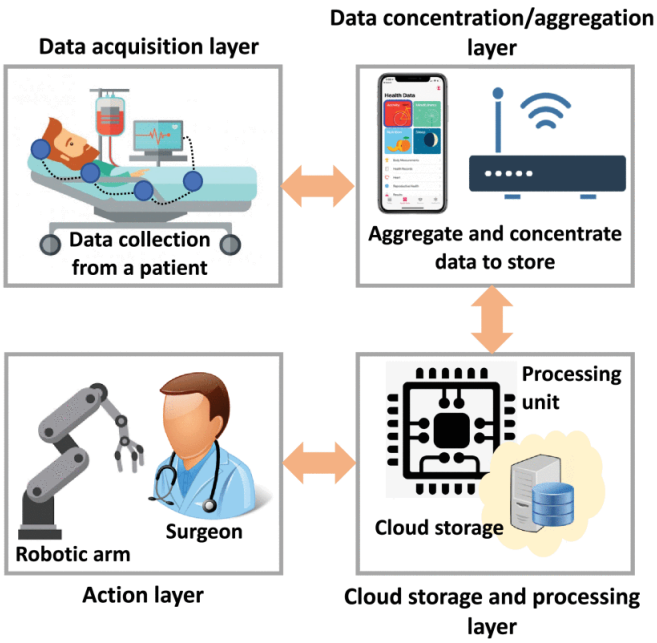


**Figure 1.5** A graphical illustration of four layers of a Tele-medical system.

[Source: Tushar, W., et al. (2023)]

**Application in Telemedical Systems**

Within a telemedical system, the physical setup encompasses hospitals equipped with patient monitoring units, tele-consultation interfaces, and sensory units featuring various sensors like ECG sensors, medical super sensors, motion sensors, and EMG sensors. Data is collected by these sensors transmitted via a wireless local area network (WLAN) to a collector, where it undergoes conversion into actionable information. This information is then processed in a cloud-based medical server, allowing doctors to remotely access and assist patients in real time. The architecture of telemedical systems is detailed with key attributes of these systems include real-time monitoring and control, IoT-driven data-driven decision-making, human-machine interaction, system security, and patient information privacy. Computational theory finds utility in telemedical CPS through applications in diagnosis, treatment optimization, and building trust between doctors and patients.

- **Emergency Service**

In critical medical emergencies, such as health monitoring in wireless body area networks, data packets containing vital health information need to be transmitted with minimal processing time. The evolutionary model is used to expedite the transfer of critical data in a priority-based time-slotted manner. Low-latency data transmission is also considered focusing on fog-based Internet-of-Health Things, proposing a weighted majority theoretic approach for selecting fog devices in delay-sensitive healthcare systems.

- **Diagnosis and Treatment**

Computational theory proves effective in optimizing the diagnosis and treatment of various diseases. A computational model is used to consult on liver transplantation for patients with Alcoholic Liver Disease. For privacy-aware medical imaging, a novel encryption method is proposed using bargaining, while a theory-based meta-heuristic FIR filter is employed for medical image

compression. Cooperative approaches and computational models for analyzing clinical decision support systems are explored. Cancer treatment is modeled, employing an evolutionary model-based approach to determine optimal chemotherapy drug dosages.

- **Trust Management**

Computational theory contributes to establishing trust between patients and healthcare systems, especially with AI advancements. It analyzes continuity and trust in primary healthcare using evolutionary theory. The evolutionary models examine behavioral strategies of doctors, governments, and netizens to impact public opinion on doctor-patient relationships. The key role highlights the importance of security, privacy, and low-latency interoperability in medical CPS.

**5) Autonomous Robotic Systems (UAV/UGV)**

Autonomous robotic systems, including unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs), are gaining prominence as the next generation of Cyber-Physical Systems (CPS). UAVs, commonly referred to as drones, can fly without a human pilot or crew onboard. Conversely, UGVs are robotic systems designed to operate on land without human intervention. Hence, both UAVs and UGVs operate without onboard human operators but can be controlled remotely from a fixed control station. Some unmanned systems operate autonomously, requiring no human intervention during their missions. Autonomous robots may navigate between pre-defined points or adapt to their environment based on real-time information. Consequently, autonomous robotic CPS are built upon technologies such as simultaneous localization and mapping, accurate data acquisition and processing, machine learning, artificial intelligence, and secure communication and control protocols.

The cyber and physical domains of autonomous robotic CPS are intricately linked with a coupling effect. This coupling effect involves macroscopic data flowing from the physical domain to the cyber domain for analysis and processing before affecting the physical domain again. Additionally, there is mutual reliance between different components in the cyber and physical domains at a micro level. Understanding these coupling effects is crucial for the smooth operation of UAVs and UGVs with constrained communication, computation, and control resources.

**Application in Autonomous Robotic Systems (UAV/UGV)**

Autonomous robotic systems, such as UAVs and UGVs, require efficient communication protocols to interact with each other and with the environment for precise routing, localization, and task completion. The physical architecture of UAVs and UGVs typically includes a central processing unit for flight or routing control, along with a ground control station for human operators to access vehicle control. Smart communication links enable data transfer from the station to the vehicles, while the central processing unit analyzes real-time environmental data to generate secure control commands. Adaptive control, real-time monitoring, data-driven adaptation, and security are crucial for successful UAV and UGV operation. Computational theory is extensively utilized in this domain of CPS to model decision-making and agent interaction, including optimal UAV placement, UAV and UGV coordination, energy conservation, and security.

- **Communication Services**

The positioning of UAVs impacts communication service quality and coverage for UGVs on the ground. Optimal UAV placement can significantly reduce the number of deployments needed to provide desired network services. A non-cooperative model determines optimal UAV locations for communication services to ground based UGV groups. The multi-agent UAV routing is used where

UAVs collect information via surveillance without relying on a reliable communication medium for coordination. Similarly, an AI-based approach for UAVs is employed to adjust flight algorithms, ensuring suitable positioning for strong connectivity. Joint coverage and connectivity for distributed UAV networks are facilitated through computational theory. Notably, UAV communication platforms enable coordination and control of both UAVs and UGVs, as depicted in **Figure 1.6**.

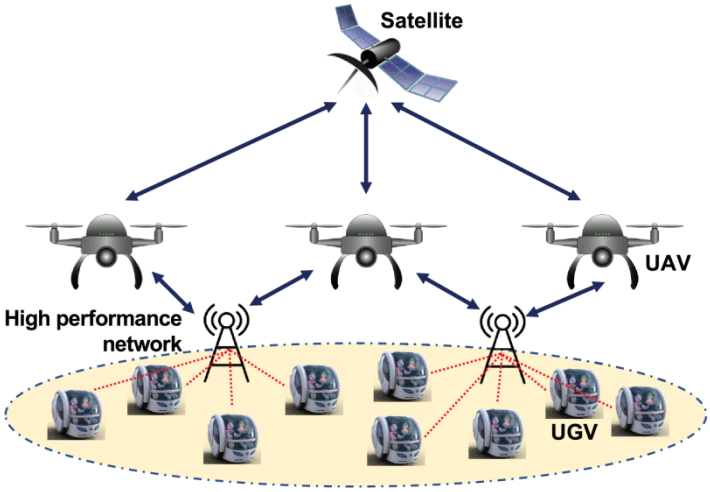


**Figure 1.6** Multiple UAVs for communications between UGVs to operate on the ground.

[Source: Tushar, W., et al. (2023)]

- **Surveillance**

Effective coordination between UAVs and UGVs, leveraging real-time spatial, temporal, and electromagnetic data, is crucial for efficient path planning and achieving objectives. For instance, a theory-based optimization technique for path planning of multiple UAVs is used to enhance mission efficiency and range. Similarly, the operation analyzes coordination among robots with shared objectives using a potential model for recurring scenarios. The alliance between UAVs and UGVs for cooperative surveillance is explored using a co-evolutionary algorithm to prioritize early detection and enhance success rates. A dynamic multi-team model is introduced for tactical decision-making by multiple UAVs with incomplete information.

- **Energy Efficiency**

Unmanned vehicles often operate in inaccessible or hazardous areas, making frequent battery replacements impractical. Thus, optimizing UAV and UGV operation and maintenance is essential for efficient energy utilization. UAV cooperative control in communication networks employs potential models for power control to prolong battery life. The delay-aware and energy-efficient task management techniques are investigated for IoT platforms, utilizing joint-auction coalition, non-cooperative approaches, coalition formation, and non-cooperative matching models with no-regret learning to develop mechanisms.

- **Security**

Computational theory plays a significant role in modeling and analyzing cyber-physical security for time and location-critical UAV and UGV applications. A common approach involves modeling interactions between UAV or UGV operators and potential interdictors, analyzing their strategies and rationality to identify equilibrium points under various security regimes. A dynamic approach is used for securing networked UAV systems and securing transmission in a two-tier UAV network.

The threats are from autonomous adversaries disrupting resource transfer. Another is employed as an interdependence-aware framework for compensating power losses due to attacks by malicious agents within the network.

**6) Smart Cities**

A smart city is an urban area that leverages technology to become connected and adaptable, addressing 21st-century environmental, social, and economic challenges while enhancing the quality of life for its residents. Smart cities integrate various CPS to reduce infrastructure risks, enhance information and operational security, and strike a balance between financial impact and public safety Smart city initiatives encompass a broad spectrum of applications essential for urban functionality. For instance, access to a smart digital health system, powered by advanced sensors and communication networks, is vital for ensuring public health. Intelligent transportation systems play a crucial role in improving road safety and efficiency by providing real-time traffic updates and assisting drivers in finding parking spaces.

The implementation of a smart grid within a smart city optimizes power generation, distribution, and consumption, leading to cost reduction, pollution mitigation, and environmental benefits. Buildings in smart cities are equipped with green technologies, including smart appliances, adaptive control systems, and renewable energy sources, fostering energy efficiency and sustainability. Interconnected buildings can share resources such as energy, enhancing community resilience and self-sufficiency. Public safety is another key focus of smart cities, ensuring prompt emergency response and service delivery during crises. Emergency departments rely on state-of-the-art technologies to coordinate responses effectively, although alternative solutions are necessary in the event of technology failures. **Figure 1.7** provides an overview of how diverse CPS can coexist and collaborate to make a smart city operational.

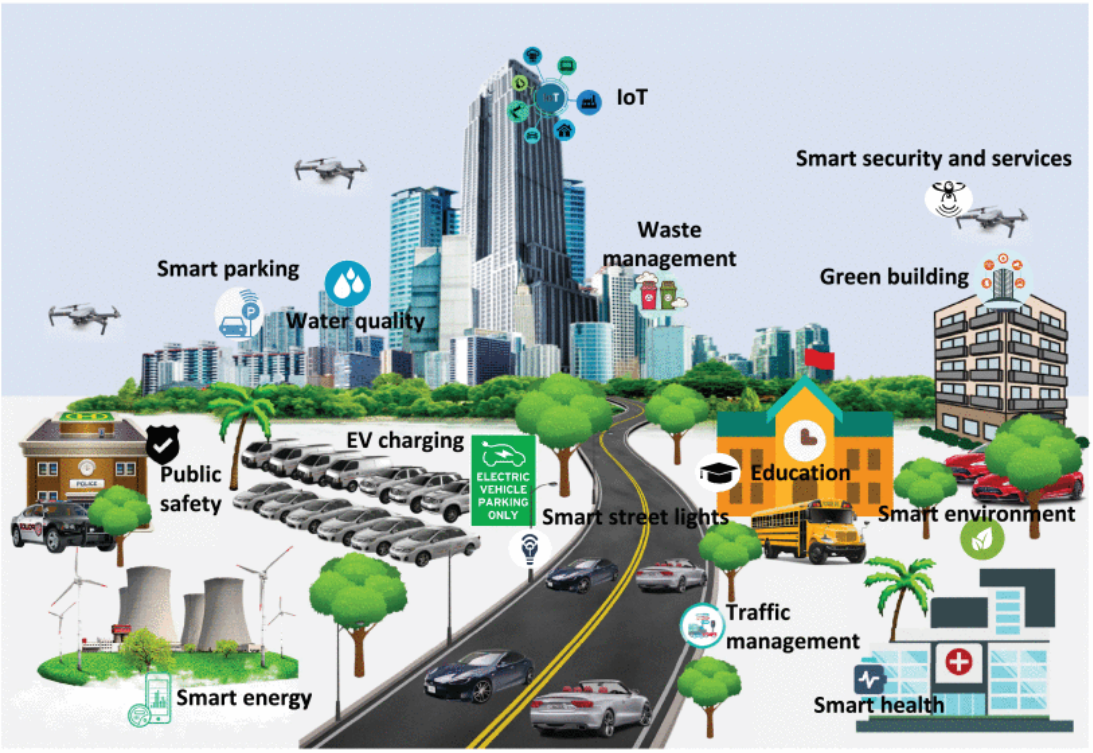


**Figure 1.7** An illustration of smart city.

[Source: Tushar, W., et al. (2023)]

**Application in Smart Cities**

A smart city serves as a platform integrating various Cyber-Physical Systems (CPS) to efficiently manage assets, resources, and services within urban areas, thereby enhancing overall city operations. The architecture of a smart city closely resembles, encompassing all attributes. This architectural framework and its attributes facilitate data collection and flow across different CPS, followed by processing and analysis of information for monitoring and managing power plants, traffic and transportation systems, water supply systems, waste management systems, health systems, community service systems, and ensuring citizen security. Given the scale of operation in a smart city, data management poses significant challenges, with advanced technologies emerging as a highly effective tool. The employment to design an intelligent edge computing algorithm can alleviate the substantial computing pressure experienced by smart cities as data volumes increase. Additionally, an edge computing technique is proposed, employing an evolutionary model to qualitatively assess the validity and stability of trust management mechanisms for smart cities. While many smart city activities are discussed as part of different CPS, waste management and security surveillance hold relevance.

- **Waste Management**

The seamless data flow across different agents within the smart city enables game theory to contribute significantly to waste management systems. For example, the contractors' decision behaviors use an evolutionary game to enhance construction and demolition waste management. The study delves into how contractors' decisions may be influenced under varying circumstances, pinpointing key factors affecting their decision-making process, such as supervisory intensity, supervision costs, penalties, waste disposal costs, and revenues from illegal dumping. A technique is proposed to analyze diverse express packaging waste recycling models for smart cities. Employing a differential game, this work seeks to understand the behavioral characteristics of individuals and different recycling models to aid in designing effective incentive measures and recycling schemes. It's noted that a cooperation-driven recycling model may yield the highest revenue, with subsidies deemed necessary for enhancing recycling efforts in the smart city.

- **Security**

Security stands as another critical aspect of the smart city, given its reliance on data-driven infrastructures. In terms of ensuring privacy and security, computational techniques have been instrumental in safeguarding critical infrastructures like smart grids, gas and water systems, traffic systems, and IoT. For instance, a dynamic multi-stage model is developed using reinforcement learning to identify optimal attack sequences to enhance system security. A utilization is revealing the interdependence of power systems on natural gas and water systems, potentially incentivizing attackers to target water and gas systems for cyberattacks, necessitating appropriate security measures for these critical infrastructures. A computational model optimally allocates backup power sources for base stations to ensure uninterrupted services to power and transportation sectors of the smart city in case of power interruptions due to cyberattacks on the smart grid. The use of repeated enhanced clustered Wireless Sensor Networks (WSNs)-based IoT security solution is to combat selective forwarding attacks and maintain network stability.

**7) Smart Agricultural Systems**

As the global population is projected to surpass 9.0 billion by 2050, feeding such a large number of people presents significant challenges, including limited resources, a scarcity of skilled labor, shrinking arable land, and the impacts of climate change. Precision agriculture, which leverages smart CPS, has emerged as a promising approach to address these challenges. Precision agriculture

integrates autonomous, data-intensive, and disruptive technologies to identify and quantify spatial soil variability, develop tools for precise crop nutrition management, and utilize vast amounts of data to make site-specific management decisions. With the advancement of the Internet of Everything (IoE), agricultural land becomes a substrate for smart agriculture, where various sensors collect heterogeneous data connected to the internet through rural networks. Real-time data collected is stored in cloud databases, processed, and analyzed to identify land characteristics and requirements. Intelligent decision-making units then use weather, site information, and market conditions to make appropriate decisions, which are communicated to either the domotic system or the responsible farmer for action.

**Applications in Smart Agricultural System**

The smart agricultural system comprises a sensor layer, which serves as the physical component of the CPS. This layer encompasses various crop sensors and smart objects tasked with real-time data collection and monitoring. Thermal drones may also be intermittently utilized for detecting heat from agricultural materials and objects. The network layer facilitates seamless connectivity between different components through communication technologies interfacing sensors with the Internet. Leveraging an Internet of Things (IoT) platform, wireless sensor networks enable large-area surveillance, aiding farmers in maintaining optimal conditions for maximum productivity. The service layer, acting as the cyber and cognition levels of the CPS, is responsible for processing and analyzing collected data to make optimal decisions regarding agricultural plans. Equipped with a data processing unit and decision support system, this layer manages field data and orchestrates decisions for optimizing crop yield, conserving resources, and ensuring quality. Finally, the application layer, akin to the configuration level, empowers farmers to take necessary actions by providing visualizations of information and recommending various field optimization strategies, including irrigation, pesticide control, cultivation processes, and crop disease protection. Given the applications across different layers, the primary attributes of a smart agricultural system encompass adaptive control, IoT integration, real-time monitoring and control, interconnectivity, predictive maintenance, and human-machine interaction, rendering game theory a suitable tool for modeling smart agricultural activities. The exploration for innovative agricultural practices spans a broad spectrum, ranging from crop selection to contemporary challenges such as water allocation for agricultural purposes. Within the agricultural CPS, computational techniques find principal applications in two domains: smart farming and water management.

- **Smart Farming**

Smart farming empowers farmers with enhanced control over cultivation processes, including animal husbandry, crop disease management, pest control, moisture regulation, and weather prediction, facilitated by real-time crop monitoring, inspection of irrigation equipment, and predictive maintenance. For instance, a cooperative smart farming technique incentivizes farms to collaborate for improved performance and problem-solving. A perfect-information non-cooperative model with a hierarchical structure is used to illustrate how the production efficiency of multiple farms may be affected if certain farms deviate from strategies equilibrium. Blockchain-based trust management for agricultural green supply is devised utilizing a computational model to ensure data reliability from various sensors. Addressing agricultural land fragmentation proposes a non-cooperative scheme to demonstrate that governmental strategies should vary across agricultural lands for effective management. Finally, the examine of how grain production management can mitigate global warming under financial constraints and the time value of money, employing an evolutionary model to evaluate financially constrained producers adopting sustainability strategies while considering long-term government regulations.

- **Water Management**

Water management stands as another pivotal aspect of agriculture, with agriculture being the largest consumer of water. A water management system administers water distribution across lands or schedules water flow for irrigation. Historical conflicts among farmers over shared water bodies have been modeled to develop water management solutions. Various water management is issued among farms. For instance, an oligopoly model is used to define water volume equilibrium, offering a solution to irrigation dilemmas. The model of the pumping of water is from a common aquifer using differential open-loop and feedback, demonstrating increased dynamic inefficiency with broader landowner access to the aquifer. Combining computational theory with policy analysis investigates how irrigation institutes influence equilibrium outcomes among irrigators. Water management for irrigation remains a challenge within the smart agricultural CPS. The model of decision-making in farming irrigation systems is considering uncertainties. An intelligent IoT irrigation system is developed to conduct cruise irrigation based on humidity data and a path-planning algorithm.

**8) Industry 4.0**

Industry 4.0, enabled by the integration of innovative functionalities such as IoT, IoE, big data analytics, cloud manufacturing, and fog computing within CPS, represents a significant opportunity for advanced industrial systems and applications. Building on the foundation of the Third Industrial Revolution, Industry 4.0 leverages technologies like the Industrial Internet of Things (IIoT), artificial intelligence (AI), autonomous robots, and smart digital technologies to create a more interconnected, automated, and holistic manufacturing ecosystem. This interconnectedness allows for higher efficiency, productivity, scalability, security, privacy, and autonomous operation of production processes. CPS plays a crucial role in realizing the vision of Industry 4.0 by coupling physical production and operations with cyber systems through technologies like big data, augmented reality, cloud computing, and IoT, facilitating the seamless exchange of real-time information and commands.

**Application in Industry 4.0**

Industry 4.0's architecture encompasses all levels illustrated and consequently embodies all desired attributes expounded. Consequently, akin to other CPS elucidated in this dialogue also finds expanded applications in the realm of manufacturing, particularly for quality assurance, sustainable manufacturing, and production certainty in Industry 4.0.

- **Quality Assurance**

Regardless of the product category, this domain pertains to healthcare services or food quality assessment that has found application across all manufacturing sectors. In healthcare services, an equilibrial service composition model is introduced in cloud manufacturing. This model employs both cooperative and non-cooperative model to delineate interactions between manufacturing cloud service providers and consumers, ensuring enhanced service quality tailored to consumer needs. In the sports industry, computational models are used to optimize services in sports arenas. Specifically, a two-player game-based model aids monitoring officials inefficient decision-making by leveraging IoT-based data on athletes' performance. For smart food quality assessment, a model-based framework is established. This framework employs a computational technique to construct a computing platform for quantifying food quality probability using IoT-based data sourced from restaurants and food hubs.

- **Sustainable Manufacturing**

In the fashion industry, there's a notable shift towards sustainable manufacturing with the culture of product disposal in favor of responsible consumerism. However, widespread adoption of this practice by major manufacturing entities remains elusive. The strategy delves into how various models effectively capture stakeholder engagement to promote sustainable product usage and its potential impact on the apparel industry. Evolutionary theory is utilized to comprehend how governmental regulations and enterprise decisions influence the manufacturing sector's adoption of green and low-carbon innovations.

- **Production Certainty and Others**

To mitigate supply chain risks and uncertainties associated with producing customized products, a three-level model in the domain of crowd-sourced manufacturing is considered. This model navigates interactive decisions to ascertain optimal solutions for single manufacturers, multiple distributors, and multiple subcontractors, ensuring maximized profits for all stakeholders. Among other manufacturing sectors, applications are discernible in cellular manufacturing systems, cloud manufacturing, vaccine manufacturing, the warehousing industry, and prefabricated building projects.

### 1.3 CPS Challenges

The literature effectively showcases how the attributes of CPS and their diverse applications are reshaping our daily lives. CPS such as telemedicine systems, smart grids, smart agricultural systems, and autonomous robots play pivotal roles in providing essential services like emergency medical care, electricity, sustainable food production, and defense mechanisms. Conversely, the convenience and advancements facilitated by green buildings, intelligent transportation systems, Industry 4.0, and smart cities significantly enhance our quality of life.

The detail illustrates the alignment between CPS characteristics and those of multi-agent systems. Consequently, the efficacy of various CPS outcomes heavily relies on the interactions among different agents and their decision-making processes. In this context, computational theory emerges as a crucial tool in CPS applications. The attribute addresses a myriad of decision-making and control challenges prevalent in CPS. However, despite the considerable contributions to CPS applications thus far, several potential challenges remain unresolved, particularly regarding innovative approaches to harmonize the roles of various CPS for collective societal benefit.

#### 1.3.1 Collaborative Building Communities

While green buildings excel at efficiently managing their resources individually and are capable of resource sharing with neighboring buildings, exploring how such individual and collective resource management can benefit other CPS requires further investigation. For instance, given that buildings account for a significant portion of total electricity consumption, collectively they could play a crucial role in offering demand flexibility to the grid. However, fostering cooperation among multiple buildings to act as a connected community presents challenges, especially considering that building owners typically prioritize their own interests. Employing game theory could offer a viable approach to modeling such a scenario. For example, coalition formation or potential game frameworks could incentivize alliances among different green buildings, leveraging their capacity to manage distributed energy resources to provide demand flexibility to the grid.

### 1.3.2 Intelligent Transport for Medical Emergencies

Efficient emergency response is integral to medical CPS, where optimizing ambulance management is paramount. In emergencies, dispatching ambulances with priority and selecting the most efficient route to reach patients swiftly are critical. Integrating ambulances into intelligent transportation systems offers a potential solution to enhance the efficiency of medical services. In such a setup, ambulances could interact with other intelligent vehicles, information hubs, and satellite navigators to determine the optimal route for reaching their destination promptly, potentially saving countless lives. For instance, employing a computational technique could model scenarios where ambulances, as components of the intelligent transportation system, respond to medical emergency requests issued by the medical CPS, optimizing their reaction time and travel route.

### 1.3.3 Interference Management in Autonomous Robotics Systems

UAV-based networks are susceptible to wireless interference, especially as the deployment of numerous UAVs and UGVs for various tasks increases. Addressing interference management in such scenarios necessitates the development of novel techniques. One potential approach is employing computational theory to analyze the dynamics of large numbers of interacting rational agents, such as UAVs or UGVs. Computational theory can capture the stochastic nature of systems, such as channel dynamics in UAV-based networks, without requiring extensive information exchange during algorithm execution. Thus, it presents a promising tool for modeling interference in UAV-based networks with limited backhaul and fronthaul connectivity.

### 1.3.4 Reinforcement Learning for Smart Agriculture

In the models based on reinforcement learning, an agent learns autonomously from past experiences and its environment utilizes feedback to strategically determine actions that optimize its objectives. This approach is particularly well-suited for smart agriculture, where it can mitigate the impact of uncertainties such as weather conditions, patterns of weed attacks on crops, market volatility, and local food demand. Moreover, such models could prove valuable for optimizing water distribution among different farms, continuously improving performance across sessions to enhance water usage efficiency.

### 1.3.5 Resource Recycling in Smart Cities

Smart cities encompass various CPS coexisting within a single platform, presenting challenges in managing resources for different systems simultaneously. However, this also presents opportunities for resource recycling within the smart city ecosystem. For instance, if UAVs are primarily deployed for goods delivery, they could opportunistically provide security services to the city, thereby reducing costs and long-term waste accumulation, benefiting the environment. Nevertheless, effectively modeling the opportunistic use of resources for diverse purposes remains a significant challenge.

### 1.3.6 Knowledge-Based User Engagement for Smart Grid

The prosumers assume a significant role in smart grid energy management. Therefore, energy users must gain insight into future energy transitions and equip themselves with the requisite knowledge and skills to participate effectively. People's perceptions of technology and their capabilities significantly influence the adoption of new technologies. Consequently, considerable development efforts should be directed toward developing courses and training modules tailored to different demographics, educating them about the importance of future energy transitions and their environmental and societal impacts.

### 1.4 Chapter Summary

This chapter details the advancement of CPS. Initially, various types of CPS are introduced and discussed their framework. The relevance of applications to CPS is highlighted by examining the properties of CPS comprehensively. Following this, theoretic approaches are aimed at addressing challenges across different CPS, accompanied by a brief of these approaches. Additionally, several crucial topics and their significance are identified and given. It anticipates that the information proves valuable, fostering a deeper understanding of the role of CPS studies. It is a useful resource for those looking to delve into the CPS field.

**Note:** The LAB section depicts a basic Node-RED architecture for CPS-based implementation as a prototype. These approaches promote end-user development to create and configure the CPS systems using low-code visual programming environments like Node-RED. Initially introduced as a visual wiring tool tailored for CPS applications, Node-RED has evolved into a more general-purpose tool. It facilitates interfacing with sensor data, communication, cloud connectivity, database connectivity, social media alerts, data analysis, system monitoring, and implementing services using Node.js functionality. Node-RED enables developers to create reusable code and quickly prototype applications using an intuitive graphical interface displayed in a web browser with drag-and-drop JavaScript-based software blocks called nodes.

**Problems**

1. Detail the characterization of cyber and physical spaces.
2. Describe the application type of cyber-physical systems in green buildings.
3. Describe the application type of cyber-physical systems in the smart grid.
4. Describe the application type of cyber-physical systems in transportation systems.
5. Describe the application type of cyber-physical systems in telemedical systems.
6. Describe the application type of cyber-physical systems in autonomous robotic systems.
7. Describe the application type of cyber-physical systems in a smart city.
8. Describe the application type of cyber-physical systems in agriculture systems.
9. Describe the application type of cyber-physical systems in smart farming.
10. Explain the application type of cyber-physical systems in Industry 4.0.
11. Diagnose the challenges of cyber-physical systems.

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# Chapter 2

# Society 5.0

**Chapter Objectives**

- Learners understand the impact of cyber-physical systems on a society.
- Learners familiarize the platform of society 5.0 in connection with cyber-physical systems.
- Learners can describe the human evolution of technologies with cyber-physical systems.

The connectivity technology was initially designed to meet the growing demand for capacity and facilitate the increasing significance of IoT in various industries, the development of 5G and 6G demands a significantly more comprehensive approach, embracing a broader community. While 5G has predominantly centered around industry verticals, forthcoming 6G mobile networks are expected to prioritize human-centric approaches. The emergence of cyber-physical-social systems (CPSSs) aims to seamlessly integrate human beings into existing cyber-physical systems across social, cognitive, and physical dimensions. CPSSs play a pivotal role in realizing the human-centered vision of Society 5.0, where human interactions with social robots and embodied artificial intelligence are increasingly commonplace. This chapter builds upon research on robonomics in the context of the 6G era. Robonomics as an emerging field explores the dynamics of social human-robot interaction and its socio-technical implications, alongside blockchain technologies and cryptocurrencies, including tokens beyond mere coins. It delves into the tokenization process, which involves creating tokenized digital replicas of assets and access rights in both the physical and digital realms, emphasizing its crucial role in shaping the future Web3 and its underlying token economy with a successor to information and platform economies. Introducing a CPSS-based bottom-up multilayer token engineering framework tailored for Society 5.0, it empirically illustrates how purpose-driven tokens can augment the collective human intelligence of a blockchain-enabled decentralized autonomous organization.

## 2.1 Introduction

With the rapid advancements and widespread adoption of technologies like cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), and autonomous mobility, the boundaries between cyberspace and physical space are increasingly blurring. These technological strides have not only propelled industrial automation and economic prosperity but also heralded a new digital revolution centered around addressing human, social, and environmental needs. Originating from Japan, Society 5.0 endeavors to integrate social and environmental considerations into the fabric of a digital society. Conceptually, Society 5.0 is described as a human-centered smart society that harmonizes economic progress with resolving social issues through the seamless integration of cyberspace and physical space. Such a human-centric approach holds promise across various domains, including mobility, healthcare, manufacturing, infrastructure, food and agriculture, energy and climate, and disaster prevention, aligning closely with mission to advance technological innovation for the betterment of humanity.

The ongoing fourth industrial revolution has been propelled by the Internet of Things (IoT) in conjunction with various emerging technologies, notably cyber-physical systems (CPSs). CPSs play a pivotal role in bridging the gap between manufacturing and information technologies, paving the way for the emergence of smart factories. This technological advancement underpins the concept of Industry 4.0, which is a key focus area in strategic plans such as Germany's High-Tech Strategy 2020 Action Plan, General Electric's Industrial Internet initiative in the United States, and China's Internet+ initiative. Notably, in January 2021, the European Commission introduced the inaugural edition of its policy brief on Industry 5.0. A significant aspect of Industry 5.0 is its paradigmatic shift from technology-centric progress to a profoundly human-centered approach.

An essential principle of Industry 5.0 is the idea that technology should serve people rather than vice versa, enhancing the capabilities of workers through innovative technological tools such as virtual and augmented reality (VR & AR), mobile robots, and exoskeletons, thereby enabling up-skilling and re-skilling. It's worth highlighting that while Industry 4.0 emphasizes minimal human intervention due to automation, Industry 5.0 prioritizes enhancing human abilities over automating human tasks. The policy also explores the relationship between the concepts of Industry 5.0 and Society 5.0. While both concepts signify a fundamental shift towards a new societal and economic paradigm, Society 5.0 extends beyond the manufacturing sector to address broader social challenges by integrating physical and virtual domains.

Society 5.0 aims to establish a sustainable society focused on human security and well-being, in alignment with the United Nations' Sustainable Development Goals (SDGs). It aims to generate new values by fostering connections between individuals and technology, as well as between physical and digital realms, through the process of digitalization. The digitalization underscored serves as a tool and stresses the importance of maintaining humans as central actors in building a society conducive to happiness. The definition of Society 5.0 is provided as a human-centric society that harmonizes economic progress with addressing social issues through a highly integrated system that merges cyberspace and physical space, incorporating controllable technologies like AI, robots, and IoT into cyberspace.

Society 5.0 emerges as an initiative within Japan's 5th Science and Technology Basic Plan, aiming to adopt a human-centric approach that integrates individuals into contemporary cyber-physical systems. By integrating humans at social, cognitive, and physical levels, CPSs evolve into cyber-physical-social systems, enabling diverse cyber-physical social interactions. It delved into the human-centric nature of Society 5.0, describing its objective as creating equal opportunities for all and fostering an environment conducive to maximizing individual potential. To achieve this, Society 5.0 leverages emerging information and communications technology (ICT) to eliminate social barriers hindering self-realization for everyone.

To elucidate the distinctions between Industry 4.0/5.0 and Society 5.0 is conducted a comparative analysis across various aspects including technology involvement, research domains, power source, motto, and underlying motivation. It argues that while Industry 4.0 is driven by the goal of mass production and Industry 5.0 aims for a smart and sustainable society, Society 5.0 is primarily motivated by the aspiration for humanity to coexist harmoniously with nature.

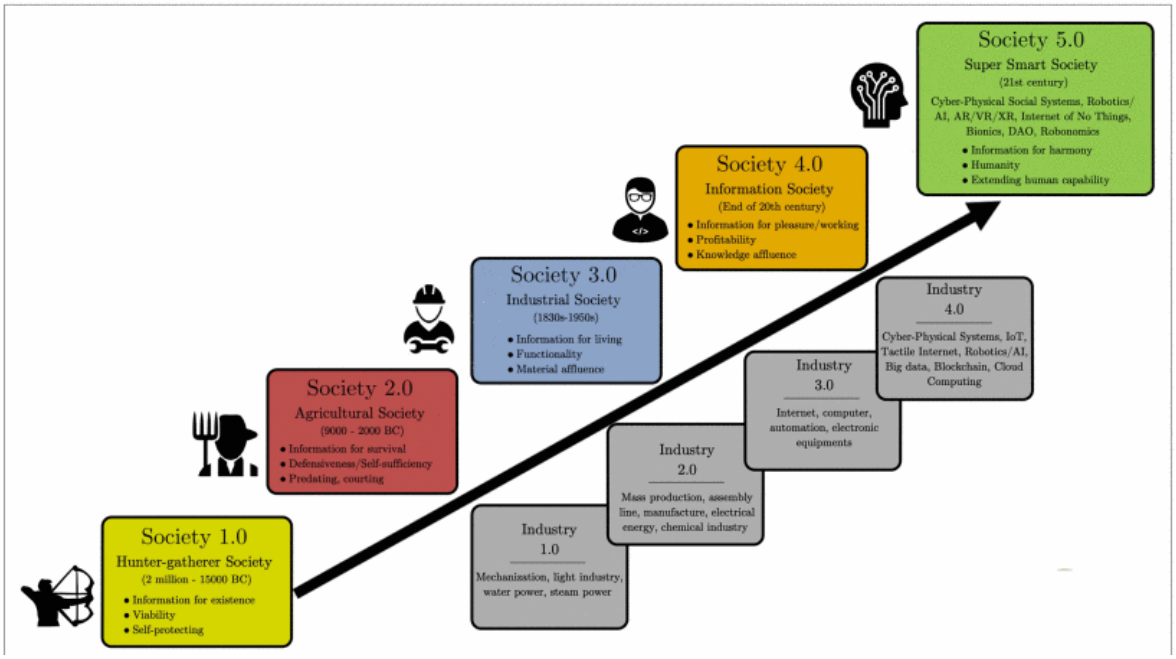


**Figure 2.1** Co-evolution of society and industry toward society 5.0.

[Source: Beniiche, A., Rostami, S., & Maier, M. (2022)]

For clarification, **Figure 2.1** illustrates the progression from past to future societies and their co-evolution with industry. The interconnections between Society 5.0 and preceding societies on one side, and with Industry 4.0 on the other, were detailed While Society 4.0 is primarily aimed at constructing an information-driven society using ICT to enhance profitability, Society 5.0's principal objective is the integration of cyberspace and physical space to advance humanity. Society 5.0 seeks to revolutionize not only industry through ICT but also the living environments and behaviors of the populace. It places significant emphasis on the societal impact of technology and strives to establish a super-smart society, necessitating more complex metrics compared to Industry 4.0, which primarily focuses on cost reduction in manufacturing without addressing social concerns.

Similar to Industry 4.0, Society 5.0 endeavors to seamlessly blend the digital and physical realms by leveraging social robots, ambient intelligence, advanced human-computer interfaces (HCIs), embodied artificial intelligence, and various forms of extended reality including VR & AR, alongside the aforementioned CPSS. Society 5.0 delineates two specific visions. The first entails human-robot collaboration, where robotics including social robots and humans cooperate wherever possible. Humans concentrate on tasks requiring creativity, while robots handle other functions, giving rise to the concept of decentralized autonomous organizations (DAOs). A DAO, unique to Ethereum blockchain, relies heavily on crowdsourcing human expertise to tackle challenges that robots and autonomous AI agents alone may not proficiently solve. The second vision of Society 5.0 involves bionics, which explores the intelligent utilization of biological resources for industrial purposes to achieve a balance between society, economy, and ecology. This scheme particularly highlights the Internet of No Things as a chosen CPSS, alongside DAO and robonomics, as elaborated further below.

It is noteworthy that Society 5.0 seeks to counterbalance the commercial emphasis of Industry 4.0. Its overarching goal is the establishment of the world's first super-smart society. In contrast, Industry 4.0 has focused on creating a smart factory, characterized by full automation and minimal human presence on-site. Notably, Society 5.0 also anticipates a shift from conventional monetary economies

to future non-monetary economies based on technologies capable of measuring non-monetizable activities contributing to human co-becoming within the context of tokenomics.

It is noteworthy that Society 5.0 resonates remarkably well with the ambitious outlook of future 6G networks. 6G is projected to prioritize human-centricity to a greater extent than 5G, which primarily targets industry verticals such as smart grids or smart cities, as delineated in the inaugural 6G white paper of the 6Genesis Flagship Program (6GFP). 6GFP envisions a "transition from 5G engineering to 6G humanity" by addressing not only productivity in vertical industries, technology facilitators, and sustainability objectives, but also societal challenges such as automation. It exemplifies the potential of CPSSs by presenting two notable 5/6G instances of human-in-the-loop-centric systems. The first is the Tactile Internet, widely recognized as one of the most compelling 5G low-latency applications. The second is the prospective Internet of No Things, serving as a pivotal stepping stone toward ushering in the post-smartphone era of 6G. Arguably more significant, it also delved into robonomics, an emerging domain in the 6G era, and the role of advanced blockchain technologies in realizing the Society 5.0 vision.

Robonomics investigates the socio-technical ramifications of social human-robot interaction (sHRI), alongside blockchain technologies and cryptocurrencies encompassing not only coins but also tokens for the societal integration of robots into human society. It explored advanced blockchain technologies like oracles, facilitating the on-chaining of blockchain-external off-chain information originating from human users. In doing, oracles harness human intelligence alongside machine learning. The empirical findings showcased the significant role of third parties such as human observers and particularly social robots in the blockchain-enabled trust game, a cornerstone of behavioral economics. The influence exerted by on-chaining oracles and especially the embodied communications enabled by persuasive robots were demonstrated to potentially wield a greater social impact than monetary incentives like the considered cryptocurrency Ether.

The objective is to propel the bionic convergence of robonomics, DAO, and the Internet of No Things as preferred CPSS to enhance the collective intelligence (CI) of Society 5.0 within the next-generation Internet, known as Web3. Three principal contributions are concerned. Firstly, it elucidates the transition from 6G robonomics to non-monetary tokenomics and expounds on key enabling concepts such as tokenization, tokenized digital twin, token economy, and purpose-driven tokens in greater depth. Secondly, given that token design is still in its nascent research phase, it addresses the pivotal problem of token engineering and presents the CPSS-based bottom-up token engineering DAO framework for Society 5.0, encompassing its multilayer architecture and mechanism design. Thirdly, it experimentally demonstrates the potential of the biological stigmergy mechanism for advancing CI in a CPSS-based DAO via tokenized digital twins. The inaugural concept is still investigating the advancement of CI in a stigmergy-enhanced Society 5.0 based on CPSS and token engineering.

### 2.2 Society 5.0 with SDG

The scientific and technological innovations including significant advancements in computing power are driving positive changes in both business and society. However, alongside these advancements, the world is grappling with various global challenges such as natural resource depletion, climate change, economic inequality, and terrorism. This point has led to an age of uncertainty marked by increasing complexity at all levels.

Considering these challenges, it is crucial to fully leverage the Internet of Things to acquire new knowledge and create value by bridging the gap between humans and technology and between the physical and digital worlds. This approach is essential for effectively addressing societal issues,

improving quality of life, and fostering sustainable economic growth. Encouraging collaboration among stakeholders at different levels to embrace a shared vision for the future is vital in realizing such a society through digitalization.

In 2016, the Japanese Cabinet introduced the concept of "Society 5.0" as part of its 5th Science and Technology Basic Plan, aiming to establish a "Super Smart Society." Positioned as the fifth stage of human societal development, Society 5.0 envisions a sustainable society interconnected by digital technologies, catering to the diverse needs of its citizens by delivering necessary goods and services precisely when and where they are needed. This vision emphasizes that while digitalization serves to enhance societal well-being, humans must remain central to the process to ensure a society that prioritizes happiness and a sense of fulfillment.

The Japanese government showcased its vision of Society 5.0 at CeBIT 2017, a prominent European business festival focusing on innovation and digitalization. This initiative underscores Japan's commitment to advancing digitalization across various sectors, including business, government, and society, to address pressing societal challenges and drive positive change.

Global discussions are underway regarding the implementation of the United Nations' Sustainable Development Goals (SDGs), which were adopted in September 2015 as a universal framework. The primary objective of these goals is to achieve peace and prosperity for all individuals and the planet by addressing challenges with an inclusive approach that ensures no one is left behind. Recognizing the importance of the SDGs, the Japanese government has prioritized their implementation, particularly through the lens of science, technology, and innovation (STI).

The Japanese government has identified the SDGs Implementation Guiding Principles as a key policy area, emphasizing the role of STI in driving progress towards these goals. To mobilize STI for the SDGs, the Advisory Board for the Promotion of Science and Technology Diplomacy has deliberated on these principles and formulated recommendations. These recommendations focus on four key action areas:

- Creating a global future through the advancement of Society 5.0.
- Leveraging global data to facilitate innovative solutions.
- Promoting cooperation at an international level to address SDGs collectively.
- Developing human resources capable of spearheading STI efforts to achieve the SDGs.

The 12 service platforms depicted in **Figure 2.2** are developed by fully harnessing the capabilities of the Internet of Things, as well as big data, computation, artificial intelligence, display, and robotics technologies. Japan is currently advancing a series of government initiatives, including the “Robot Industry” and “Connected Industries” programs introduced by the Ministry of Economy, Trade, and Industry (METI), as well as the “Conference toward AI Network Society” initiative introduced by the Ministry of Internal Affairs and Communications (MIC). These initiatives aim to foster the development of advanced common platform technologies, services, and systems, including system of systems, to create new markets and transform society into a prosperous one by generating new values through cyber-physical systems.

As illustrated in **Figure 2.3**, CPS involves the collection of various big data elements from intelligent sensing devices equipped with low-power networks, which are then stored in information storage devices. Analytical tools such as AI, leveraging high computing power in cyberspace, can analyze and visualize this valuable data. This data, often imperceptible to humans alone, informs decision-makers about actions to address societal issues and foster economic growth in the physical world.

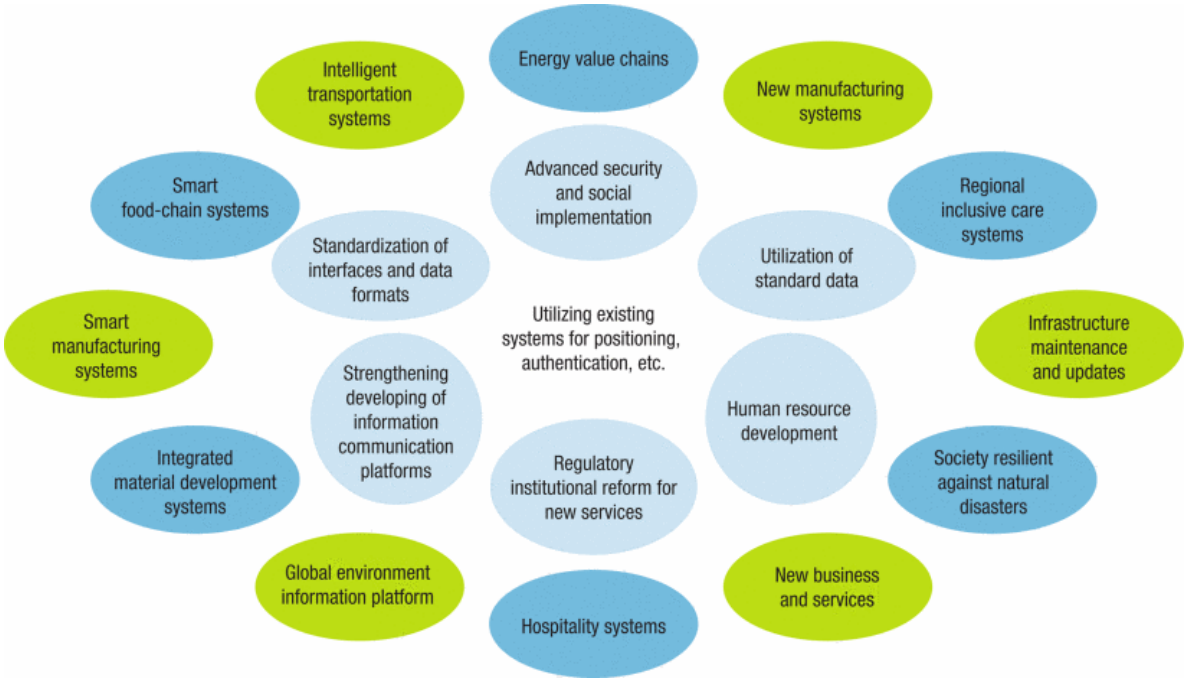


**Figure 2.2** The 12 service platforms for creating a super smart society.

[Source: Shiroishi, Y., Uchiyama, K., & Suzuki, N. (2018)]

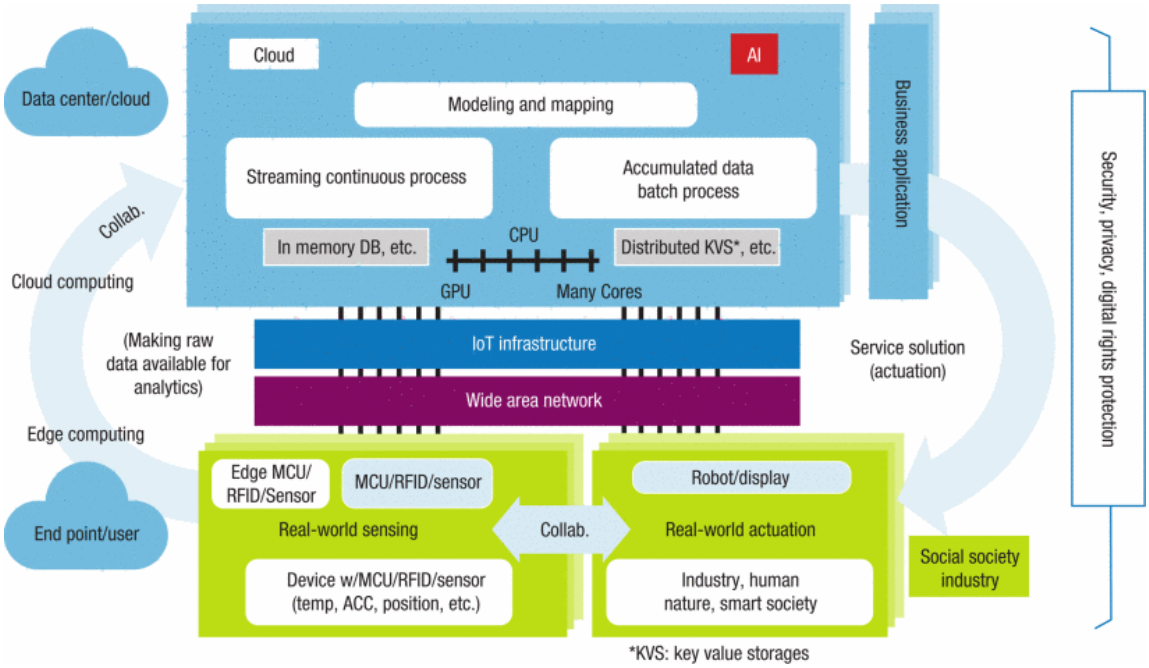


**Figure 2.3** A cyber-physical system.

[Source: Shiroishi, Y., Uchiyama, K., & Suzuki, N. (2018)]

In Japan, a series of government initiatives, including ImPACT (Impulsing Paradigm Change through Disruptive Technologies Program) and SIP (cross-ministerial Strategic Innovation Promotion program), are aimed at realizing such advanced technologies and service platforms. ImPACT focuses on developing disruptive science and technology innovations that can bring about significant changes in industry and society through high-risk, high-impact research and development efforts. On the other hand, SIP encompasses the entire spectrum of activities from fundamental research to practical application and commercialization, including initiatives to reform regulations and systems.

Under SIP, projects such as automated driving systems, energy carriers, cybersecurity for critical infrastructure, and technologies for advancing agriculture, forestry, and fisheries are currently underway, with allocated budgets from the Council for Science, Technology, and Innovation (CSTI), which oversees the planning and coordination of science, technology, and innovation policies within the Japanese Cabinet. Moreover, The Engineering Academy of Japan (EAJ), a distinctive non-governmental engineering academy in Japan, is conducting several academic studies focused on authentic proposals and policy recommendations for advancing Society 5.0. These include initiatives such as the "SDGs Project," "Next-Generation Computing Project," and "Telexistence Project."

It is witnessing an era where advancements in science, technology, and innovation (STI) are extending human lifespans to 100 years, underscoring the increasing importance of empowering individuals through broader stakeholder engagement and digitalization technologies. It is embarking on the journey towards achieving genuine human security and well-being. It is imperative to cultivate a pioneering mindset and the capacity for disruption, if necessary, by expanding the number of individuals who take initiative and act as catalysts for change. To expedite the establishment of a sustainable global society, collaborative ecosystems that integrate perspectives from industry, academia, and citizens must be pursued.

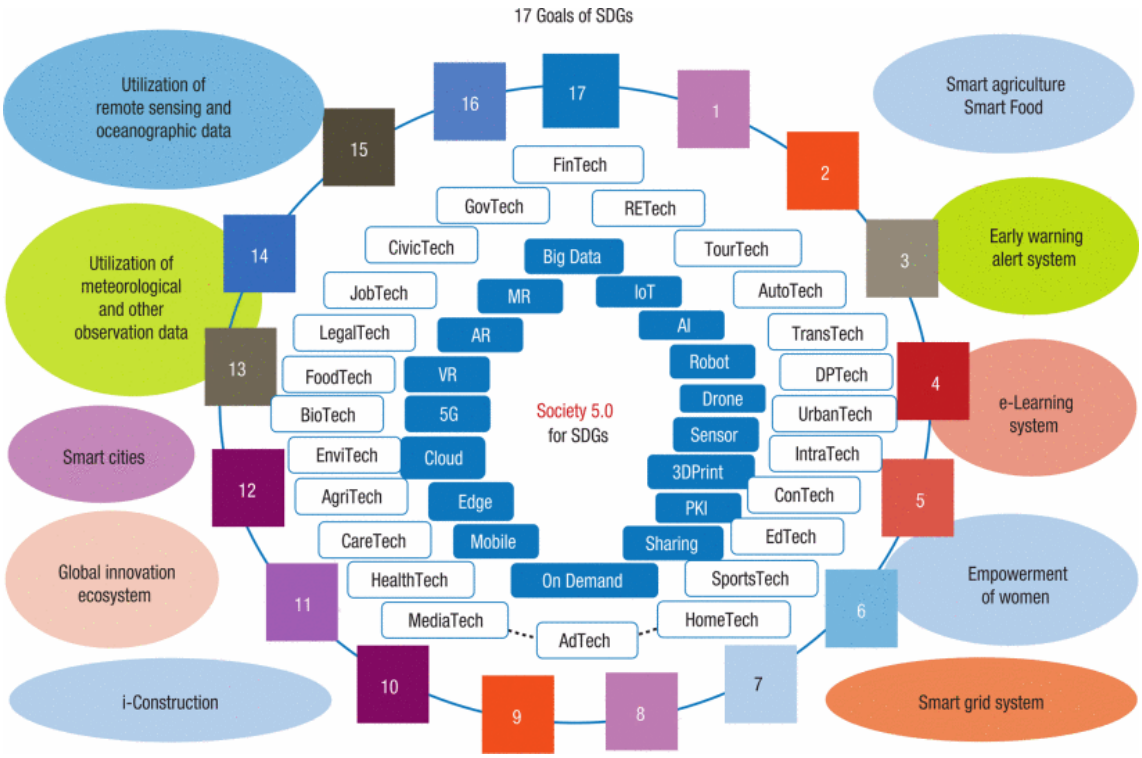


**Figure 2.4** Society 5.0 for SDGs.

[Source: Shiroishi, Y., Uchiyama, K., & Suzuki, N. (2018)]

Japan's foremost business federation (Keidanren) is actively promoting this transformative endeavor. Through the fifth revision of its Charter of Corporate Behavior, Keidanren is committed to proactively advancing the Sustainable Development Goals (SDGs) by embracing the vision of Society 5.0. **Figure 2.4** provides an overview of Society 5.0 for SDGs, highlighting its concept, challenges, key technologies, and systems, alongside the 17 SDGs. While STI has significantly enhanced lifestyle convenience, it has also amplified social complexity, exposing certain drawbacks of a digital society. Society 5.0 offers pathways to mitigate or eliminate these drawbacks, but doing so necessitates dismantling what the position paper terms the "five walls": government ministries and agencies, legal frameworks, technologies, human resources, and societal acceptance. Addressing these challenges represents a global endeavor, and professional bodies such as the IEEE Computer Society are poised to play a central role in fostering robust collaboration between industry and society on STI, trans-disciplinary, and multi-dimensional issues.

It is found in an era marked by intricate societal challenges and uncertainties. The Society 5.0 initiative introduced by the Japanese Cabinet envisions the development of a Super Smart Society—a sustainable community where diverse values are interconnected through Cyber-Physical Systems (CPS), fostering safety, security, and comfort for its inhabitants. CPS has the potential to bridge gaps between different sectors, countries, regions, and societies that would otherwise remain disconnected. The successful realization of Society 5.0 and the Sustainable Development Goals (SDGs) hinges on stakeholders collaboratively addressing challenges and leveraging the full capabilities of CPS.

To advance towards enhanced human security and well-being, it is imperative to embark on a path of transformation facilitated by a collaborative ecosystem characterized by a shared vision for the future, crafted with the active involvement of all stakeholders. Specifically, the following steps should be taken:

- Present a forward-looking vision illustrating societal transformations driven by Science, Technology, and Innovation (STI).
- Identify and surmount challenges by generating novel value propositions through CPS.
- Foster partnerships across industry, multidisciplinary academia, and both public and private sectors to facilitate collaborative efforts.

### 2.3 Robonomics to Tokenomics

The impact of blockchain and other decentralized technologies on the interaction between humans and robot agents is provided for insights, as well as their integration into human society. In this context, blockchain technologies can function as a ledger where robots and humans can access and record various valuable items, such as ownership titles or financial transactions. Additionally, smart contracts enable the encoding of self-enforceable and self-verifiable agreement logic between robots and humans. Cryptocurrencies can be utilized to enable robots to hold financial obligations and engage in value exchanges with humans, and vice versa.

The transition from traditional monetary economics to non-monetary tokenomics and the pivotal role of tokens in blockchain-based ecosystems were explored. Decentralized blockchain technologies have been employed in non-monetary contexts through a process known as tokenization across various value-based scenarios. Tokenization of an existing asset involves creating a tokenized digital twin for any physical object or financial asset, resulting in tradable units that digitally encapsulate value. These tokens can serve as incentives to coordinate actions among actors within a regulated ecosystem to achieve desired outcomes. Tokens have the potential to disrupt by extending the concept of value

beyond the economic domain, leveraging them for reputation purposes or voting rights. Through tokenization, various types of digitized value can be utilized within an incentive ecosystem, with rewards and benefits shared among stakeholders.

Tokens can represent a wide range of existing digital or physical assets, as well as access rights to assets and permissions in both digital and physical realms. Stored as entries in the ledger, tokens are associated with a blockchain address, representing the identity of the token holder. Initially, tokens were created using underlying blockchain protocols. However, with the emergence of Ethereum, tokens have ascended the blockchain protocol stack and can now be generated at the application layer, leading to the development of application tokens. Leveraging Ethereum, application tokens can be issued easily and inexpensively through specific smart contracts known as token contracts, following Ethereum token standards like ERC-20.

Tokens are regarded as a key application of blockchain networks and are seen as a major catalyst behind the evolution of the next-generation Internet, commonly referred to as Web3. As depicted in **Figure 2.5**, whereas Web1 (the read-only web) and Web2 (the read-and-write web) facilitated the knowledge economy and the current platform economy, respectively, Web3 ushered in the token economy where individuals' contributions are rewarded with tokens. Token economy introduces entirely new use cases, business models, and categories of assets and access rights in a digital format that were previously economically unfeasible, thereby enabling novel use cases and models for creating value. It is worth noting that the term "token economy" is not new; it has been extensively studied in cognitive psychology as a means of exchange and, more importantly, as a method of positive reinforcement to establish desirable human behavior, which itself can be seen as a form of value creation. Unlike coins, which have traditionally been used solely as a medium of payment, tokens can fulfill a wide range of non-monetary functions. These purpose-driven tokens play a crucial role in incentivizing autonomous groups of individuals to collaborate and contribute toward a shared objective. The exploration of tokens, particularly their different types and roles, is still in its nascent stages.

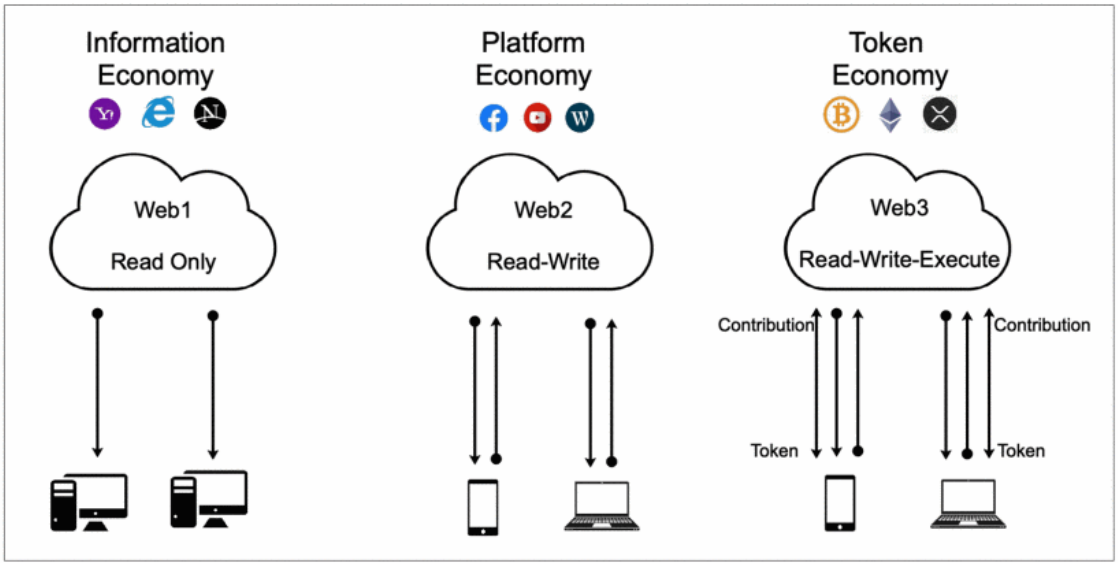


**Figure 2.5** Evolution of internet economy.

[Source: Beniiche, A., Rostami, S., & Maier, M. (2022)]

The token economy plays a pivotal role in bringing about the emerging DAO, which has gained significant attention due to the rapid advancement of blockchain technology. The DAO can be conceptualized as a social system comprising intelligent agents that evolve together through human-machine integration, drawing from both real-world and artificial blockchain systems. Within the DAO, all operational rules are recorded on the blockchain in the form of smart contracts. Token economy incentives, in conjunction with distributed consensus protocols, are leveraged to enable the self-operation, self-governance, and self-evolution of the DAO. The use of tokens as incentives serves as the primary driver for the DAO, with the incentive mechanism layer of their multi-layer DAO reference model playing a pivotal role in token design.

### 2.4 Human-Centered Society

Numerous tokens have been introduced; however, many of these tokens suffer from inadequate functionality and mechanism design. This is sought to rectify these deficiencies by exploring purpose-driven tokens and presenting the crucial concept of token engineering.

#### 2.4.1 Driven Tokens and Token Engineering

The various roles and types of tokens are still in the early stages of exploring. Purpose-driven tokens, for example, incentivize individual actions towards a specific collective goal or purpose, such as promoting public goods or reducing negative externalities like CO2 emissions. This approach enables the creation of public goods without relying on traditional intermediaries like governments. Platforms like Ethereum have advanced the concept of collective value creation by providing a public infrastructure for easily creating application tokens through smart contracts, allowing for incentivization of virtually any purpose. However, as operational use cases remain limited, further development is needed to fully realize the potential of this tech-driven public goods creation.

Tokens can represent a wide range of digital or physical assets, along with access rights and permissions in both digital and physical realms. Each token is recorded in a ledger and associated with a blockchain address, serving as the identifier of the token holder.

Proof of work (PoW) is a crucial mechanism for sustaining public goods. While collective production of public goods can generate positive externalities, it may also introduce negative externalities, such as the energy-intensive mining process in blockchain networks. When designing purpose-driven tokens to support public goods provision, behavioral economics methodologies like nudging and behavioral game theory offer valuable tools for guiding individuals towards desired actions. Interested readers can find more details about our recent work on playing a blockchain-enabled version of the trust game in behavioral economics with on-chaining oracles and persuasive social robots.

Moving forward, it delves into the significant issue of token engineering, a term emerging to encompass the theory, practice, and tools for analyzing, designing, and verifying tokenized ecosystems. This involves developing a bottom-up token engineering framework alongside designing suitable mechanisms to address the challenges posed by purpose-driven tokens. Mechanism design, a subfield of economics, deals with incentivizing individuals to contribute to collective goals and is often referred to as “reverse game theory” as it starts with the desired outcome and works backward to design the incentive mechanisms.

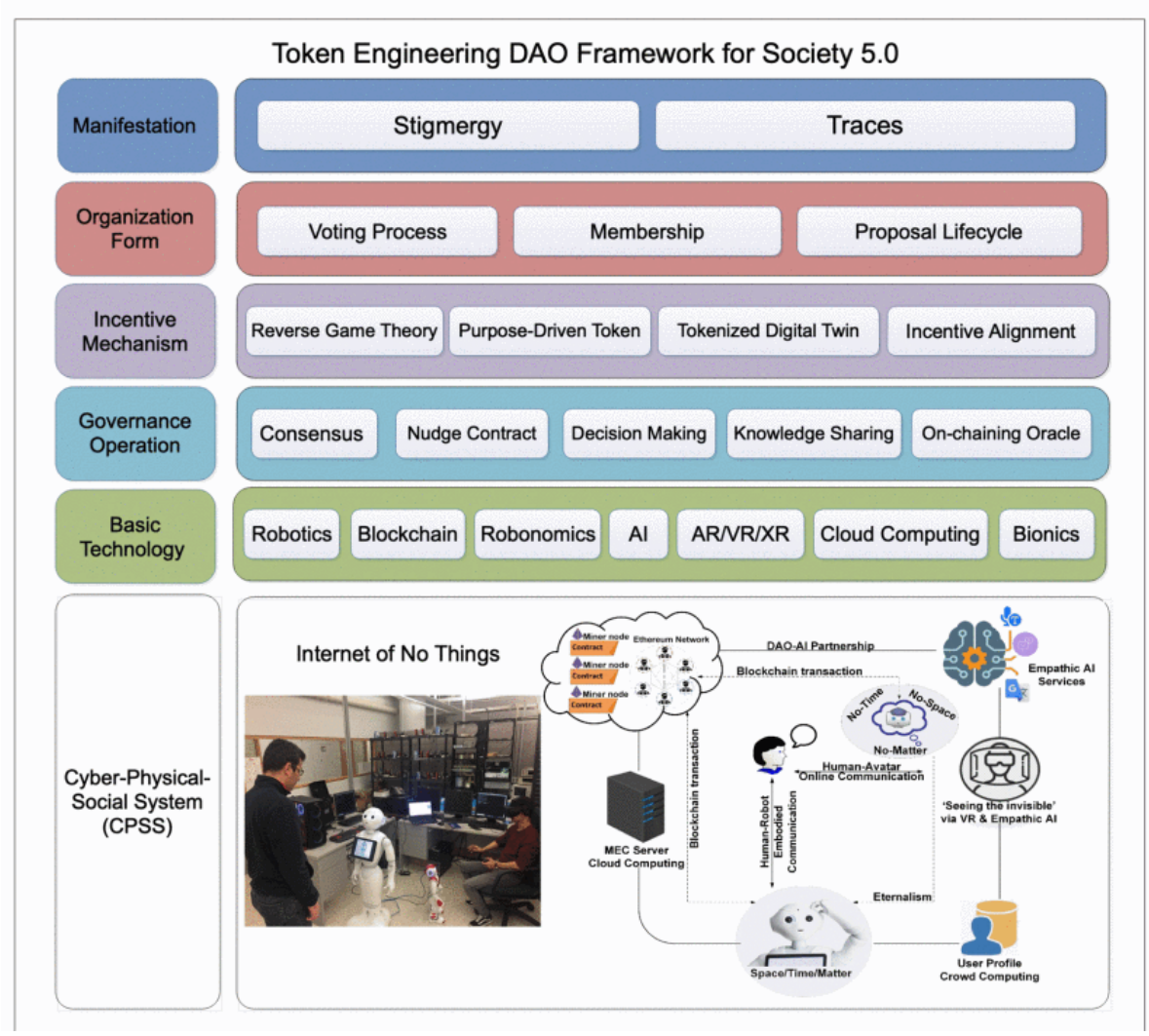


**Figure 2.6** CPSS-based bottom-up token engineering DAO framework for society 5.0.

[Source: Beniiche, A., Rostami, S., & Maier, M. (2022)]

### 2.4.2 Token Engineering DAO Framework for Society 5.0

A multilayer DAO reference model was proposed for token design, intentionally kept generic without specific ties to Society 5.0. As illustrated in **Figure 2.6**, the DAO reference model consists of the following layers:

- Basic technology
- Governance operation
- Incentive mechanism
- Organization form
- Manifestation

For details on this generic DAO reference model and a comprehensive description of each layer, interested readers are detailed explanations for each layer as follows.

### 1) Basic Technology Layer

This layer encompasses all the foundational technologies that support DAOs and their derivative applications, including Internet Protocol, Blockchain, Big Data, and Artificial Intelligence.

- **Internet Protocol**: DAOs typically operate on peer-to-peer (P2P) networks to encourage participation from nodes distributed globally.
- **Blockchain Technology**: Decentralization and open autonomy are central features of DAOs. Blockchain technology is pivotal for enabling DAOs to fulfill their functions. The consensus mechanism of blockchain empowers nodes in a decentralized system with the ability to effectively reach consensus. Smart contracts encode operational rules of DAOs into the blockchain as computer code, thereby realizing a "code is law" form of governance. Additionally, asymmetric encryption and timestamping ensure the security and ownership authentication requirements of DAOs.
- **Artificial Intelligence**: With advancements in AI technologies such as deep learning, reinforcement learning, and generative adversarial networks (GANs), individual nodes within a DAO are evolving into autonomous agents, capable of perception, reasoning, decision-making, and other functions. These agents exhibit autonomy as they possess capabilities akin to Belief-Desire-Intention (BDI) systems. In the future, they may replace humans in various tasks. Furthermore, smart contracts are expanding beyond mere automatic enforcement based on predefined If-Then statements to include What-If deduction, computation, and intelligent decision-making in unknown scenarios, enhancing the intelligence of DAOs.
- **Big Data**: Big data technology facilitates the collection of real-time state data, intra-chain transaction data, and system operation data from DAO nodes, aiding in understanding the evolution and development trends of DAOs. It's noteworthy that blockchain itself ensures data security and anonymization.
- **Internet of Things**: Blockchain can be integrated with the Internet of Things (IoT) to form the Blockchain of Things (BoT), which digitally transforms and integrates smart devices and physical assets into DAOs. As a reliable IoT service platform, DAOs can monitor the entire lifecycle of smart devices securely, facilitate automated trading among equipment, and ensure interoperability between smart devices using smart contracts.

### 2) Governance Operation Layer

This layer encompasses the encoding of consensus through smart contracts, facilitating self-governance and continuous iterative upgrades of organizations through both on-chain and off-chain collaboration. Specifically, this layer includes consensus mechanisms, smart contracts, digitalization, intelligent matching, and on/off-chain collaboration.

- **Contractualization of Consensus**: Organizations typically operate based on consensus-based contracts, which serve to safeguard the rights and interests of individuals, organizations, and society through legal restraints. However, implementing contracts often presents challenges such as assessing validity, effecting alterations, and determining liability for breaches. DAOs are built on smart contracts deployed on and secured by blockchain. Smart contracts encode agreements between parties in the form of business logic, automatically executing and enforcing them. Essentially, smart contracts program the complex relationships among network nodes, facilitating all procedures from negotiation to fulfillment. DAO enables nodes representing different interests to negotiate, clarify rights

and obligations, validate contract terms, and program contracts on blockchain for distribution, verification, and auto execution.

- **Digitalization as a Foundation**: Smart contracts provide trust guarantees for DAO governance, with digitalization serving as its foundation. Digitalization involves collecting and analyzing data, which is then utilized for business model innovation, ecosystem reconstruction, and enhancing user experience. Digitalization serves as a tool for intelligent management and decision-making within DAOs.

- **Intelligent Matching**: DAOs, operating on decentralized processing-storage carriers, often leverage AI technology to automatically match and connect people, organizations, knowledge, events, products, and services. This reduces communication costs and improves efficiency. For instance, DAOs can automate role/task matching by digitizing individual/organizational information and behavior data, matching individuals to roles based on contributions and abilities, and completing task identification, recommendation, and matching automatically. This facilitates the quick mobilization of human and knowledge capital and enables multi-dimensional evaluation of individual work processes and results within DAOs.

- **On-Chain and Off-Chain Collaboration**: Unlike traditional centralized management where controlling shareholders' interests dominate, DAOs adopt a collaborative governance mode that combines on-chain and off-chain approaches. On-chain governance determines, updates, and maintains consensus through smart contracts, creating a credible system in an environment of mutual distrust and ensuring the benefits of all stakeholders. Off-chain governance consists of measures aimed at establishing, recognizing, diffusing, and renewing consensus. DAOs currently exhibit a blend of on-chain and off-chain governance, but as technology matures, emphasis shift more towards on-chain governance. Additionally, forks, including soft and hard forks, serve as effective means to resolve governance disputes within DAOs. Compared to how public companies handle disputes, forks have a relatively low market impact, underscoring the advantages of DAO governance based on a consensus mechanism.

### 3) Incentive Mechanism Layer

Token incentives serve as the primary motivator for DAOs. Tokens represent negotiable digital assets and serve as proof of rights and interests. Real-world financial instruments like stocks, bonds, and options can be digitized into tokens. Typically, tokens integrate attributes of equity (value appreciation, long-term income), property (right to use goods or services), and currency (circulation within a defined scope).

Sponsors, developers, and other stakeholders of DAOs share property rights of the system, while tokens serve as the primary economic incentives for other participants. Token Economy, a novel economic model, utilizes the financial attributes of crypto-digital assets to map commodities and services to tokens, enabling low-cost or even zero-cost transactions. Common types of tokens include payment tokens, functional tokens, and asset tokens.

Each DAO can issue its tokens and define various elements of the token model such as circulation, lock-in period, and distribution mode based on project attributes. The key to token model design lies in mechanism design, aiming to promote incentive compatibility among participants and achieve a win-win situation. A well-designed token model integrates monetary capital, human capital, and other forms of capital, transforming the relationship between people and organizations, reducing

operational costs, and meeting funding needs. Moreover, as tokens are anchored to the project itself, high-quality projects can lead to a continuous increase in token market value, further incentivizing participants economically.

**4) Organization Form Layer**

The organizational structure of DAO embodies a multicenter stereoscopic network structure and a small number of basic teams along with large-scale community autonomy. In contrast to traditional organizational forms, DAO transitions from orderliness to a mixture, from the pursuit of stability and solidification to a focus on dynamic balance, and from relative simplicity to diversification. Its characteristics can be outlined as follows:

- **Flat:** Hierarchical order within the organization is dismantled, allowing for individuals to exhibit maximum flexibility while ensuring transparent and efficient management.
- **Open**: Internal and external organizational boundaries are eliminated, enabling DAO to adjust dynamically based on specific projects, requirements, and tasks, and subsequently disband or dissolve upon mission completion.
- **Parallel:** Every individual or organization has a corresponding virtual counterpart within DAO. Through interaction between the virtual and real worlds, closed-loop feedback, and collaboration both on-chain and off-chain, optimization of decision-making and parallel tuning of organizational governance can be achieved.
- **Human–Machine Integration**: As technology advances, DAO evolves into human–machine integration. Intelligent agents within DAO are empowered by humans to undertake various business activities, engaging in competition, coordination, and cooperation akin to human counterparts.

**5) Manifestation Layer**

DAO exhibits a diverse array of manifestations, which can vary based on the services offered. It may encompass digital currencies like Bitcoin, public development platforms/systems such as Ethereum, or interconnected IoT devices like self-driving cars. Furthermore, depending on the level of decentralization, DAOs can range from fully decentralized entities like public blockchains to partially decentralized ones like consortium blockchains (Hyperledger and EOS). DAO commonly adopts a model comprising Nonprofit Foundations, Commissioned Companies, and various manifestations. In this model, nonprofit foundations primarily handle fundraising, including Initial Coin Offerings or ICOs, token distribution, management, and oversight. Commissioned companies are tasked with technology development, marketing, and legal services. DAO is often represented in the form of an open-source community to facilitate both on-chain and off-chain collaboration.

This scheme tailors the generic DAO reference model to meet the specific needs of Society 5.0 and highlights the adjustments made in the CPSS-based bottom-up token engineering DAO framework. The multilayer token engineering DAO framework for Society 5.0 is built upon cutting-edge CPSSs. While the Internet of Things, a prominent example of CPS, has facilitated the rise of Industry 4.0, advanced CPSSs like the future Internet of No Things, mentioned briefly earlier, play a pivotal role in ushering in Society 5.0. The Internet of No Things establishes a unified service platform for seamlessly blending digital and physical worlds, providing various human-centric services without the need for users to possess or carry computing or storage devices. It envisions Internet services to seamlessly emerge from the surrounding environment when required and vanish when no longer needed. The transition from the current device-centric Internet to the Internet of No Things is delineated into three phases:

- Bearables (smartphones)
- Wearables (smart jackets)
- Nearables

Nearables refers to nearby computing and storage technologies as well as service provisioning mechanisms that possess the intelligence to learn and adapt based on user context and history, enabling the delivery of user-specific services. The bottom layer labeled as the basic technology layer, illustrates the fundamental enabling technologies such as blockchain that underpin the Internet of No Things. Additionally, this layer encompasses future technologies like bionics, which are expected to assume a significant role in the development of a future super-smart Society 5.0.

Above the basic technology layer lies the governance operation layer. Broadly speaking, this layer establishes consensus through smart contracts, such as voting mechanisms, and achieves self-governance of the DAO through collaboration both on-chain and off-chain (via on-chaining oracle). Moreover, this layer incorporates nudging mechanisms through smart contracts (nudge contract), collective decision-making processes, and knowledge sharing among its participants. The incentive mechanism layer encompasses various token-related techniques and their proper alignment to facilitate token engineering. Subsequently, the organization form layer entails the voting process and membership throughout the lifecycle of a proposed DAO project. It is worth noting that in economics, public goods with regulated access rights, such as membership, are referred to as club goods.

The manifestation layer empowers members to undertake simple, locally independent actions that collectively give rise to the emergence of complex adaptive system behavior within the DAO and Society 5.0. Given its remarkable resemblance to decentralized blockchain technology, the investigation shows the potential of the biological stigmergy mechanism, commonly observed in social insect societies like ants and bees. Particularly, their inherent capacity for self-organization and indirect coordination are explored through olfactory traces created by members in the environment. Upon detecting these traces, other members of society are prompted to perform subsequent actions, thus reinforcing the traces in a self-sustaining autocatalytic manner without the need for any central controlling entity.

### 2.4.3 The Human Use of Human Beings: Cybernetics and Society

An illustrative case of transitioning from a Web2-based social network to Web3 occurred when Facebook announced in June 2019 its plans to introduce a new infrastructure for managing their proprietary token called Libra (later renamed Diem), alongside implementing suitable mechanisms to maintain its price stability when exchanged with fiat currencies. However, merely designing tokenized currencies does not suffice to actualize the vision of Society 5.0. To illustrate this point, consider the growing public scrutiny surrounding the impact of social media on our lives, as evidenced by the reflections of former and founding executives who have expressed regret over their roles in shaping today's social media landscape.

Insights for more human-centered solutions can be gleaned from the principles of cybernetics. The founding figure of cybernetics explores the idea in the seminal work “The Human Use of Human Beings: Cybernetics and Society,” where the potential dangers posed by machines operating on cybernetic principles. It argues that while machines themselves may be innocuous, they can be wielded by individuals or groups to exert greater control over the rest of humanity. To mitigate the manifold risks associated with this scenario, it underscores the importance of interdisciplinary collaboration involving anthropologists and philosophers. It contends that scientists must have a deep understanding of human nature and inherent purposes, emphasizing the crucial role of internal communication facilitated by feedback loops in safeguarding societal well-being.

**2.5 Collective Intelligence**

It delves into how Society 5.0 can achieve the integrity of internal communication by drawing inspiration from the sophisticated cognitive abilities observed in colonies of social insects, akin to biological superorganisms with brain-like capabilities. The concept of stigmergy elucidates a class of self-organization mechanisms that offer an elegant explanation for the apparent coordination of collective activities within social insect colonies despite individuals seemingly working in isolation. Stigmergy involves individuals leaving traces in their environment, which can influence subsequent actions through feedback loops. The colony utilizes these traces to organize and regulate collective behavior, thereby facilitating indirect communication and maintaining social cohesion by integrating environmental and social organization. Notably, in the field of swarm intelligence, particularly in swarm robotics within AI, stigmergy is widely acknowledged as a fundamental concept. It illustrates how the CPSS-based token engineering DAO framework can be applied to Society 5.0, outlining the iterative bottom-up design process of purpose-driven tokens and associated mechanisms.

**Step 1: Clarify Purpose:** The initial step in designing any tokenized ecosystem entails defining its intended outcome or purpose. In the context of Society 5.0, the objective is to establish a techno-social environment within CPSS frameworks that enhances human capabilities and fosters collective intelligence (CI) among interconnected individuals and entities, as envisioned in the forthcoming 6G era.

**Step 2**: **Choose Preferred CPSS**: The chosen framework is the Internet of No Things, recently introduced as a cutting-edge CPSS. This selection is based on its evolution towards nearables, which facilitate the creation of intelligent environments catering to user-centric services. The concept of an extrasensory perception network (ESPN) is introduced, integrating pervasive computing within nearables, such as social robots and virtual avatars, to influence human behavior through social cues. In this dialogue, the emphasis is on leveraging blockchain and robonomics to extend the online environment of ESPN and enhance offline agents.

**Step 3: Establish Proof of Work (PoW):** PoW is fundamental for sustaining technology-driven public goods, particularly in creating club goods with regulated access rights to mitigate the "tragedy of the commons." To achieve this, advanced blockchain mechanisms is utilized, specifically on-chaining oracles, which reliably integrate off-chain information onto the blockchain. These oracles, sourcing information from human users, effectively tap into human intelligence. In the context of PoW, the oracles' roles is defined in governing CPSS operations through decision-making and knowledge sharing, pivotal in advancing CI.

**Step 4: Design Tokens with Aligned Incentives**: The majority of tokens lack well-designed incentive mechanisms. Given that tokens serve as the cornerstone of DAOs, their incentive structures are critical yet nascent. Notably, tokenization involves creating tokenized digital twins to coordinate actors and regulate ecosystems towards desired outcomes, incorporating voting rights. This process entails:

- Generating a digital twin representing a physical or digital asset.
- Establishing one or more tokens that assign access rights and permissions of the asset to token holders' blockchain addresses.

**Step 5: Foster Indirect Communication through Stigmergy**: Encourage DAO members to document their purpose-driven token activities within ESPN's blockchain-enabled online environment. These

blockchain transactions serve as traces, guiding collective behavior towards enhanced CI in a stigmergy-influenced Society 5.0.

**Figure 2.7** provides a detailed explanation of the functionality of each of these five steps, along with their operational interactions.

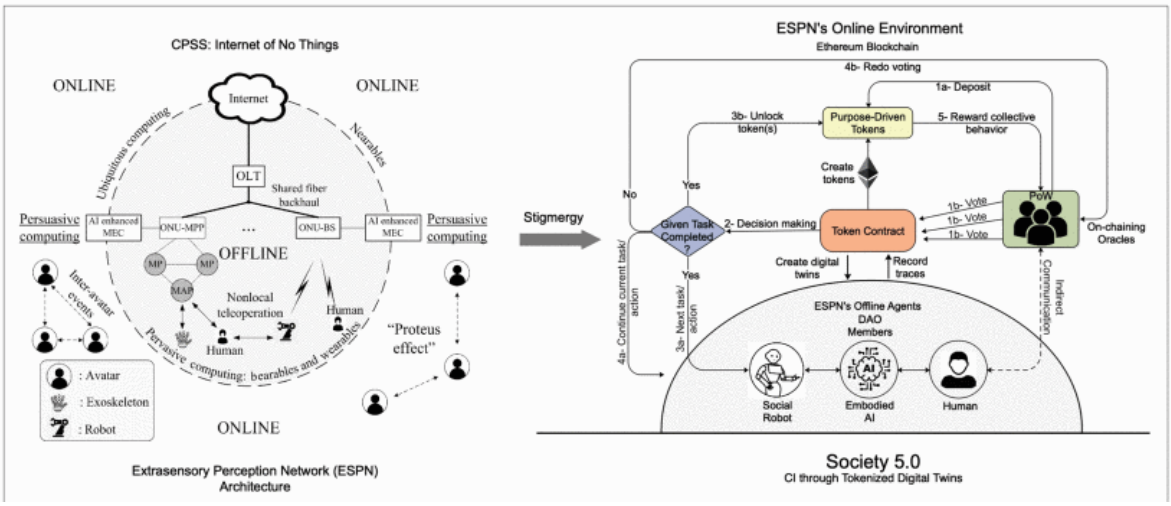


**Figure 2.7** Stigmergy-enhanced society 5.0 using tokenized digital twins in CPSSs.

[Source: Beniiche, A., Rostami, S., & Maier, M. (2022)]

## 2.6 Implementation

A broad characterization of human intelligence is its efficacy in accomplishing tasks. The human intelligence tasks (HITs) are operationalized by utilizing the ImageNet image database, a widely employed resource in deep learning studies, and tokenizing it. Essentially, individuals are tasked with uncovering a concealed reward map, comprised of purpose-driven tokens, through image tagging. This process leverages the collective intelligence of workers on Amazon Mechanical Turk (MTurk) and validates their responses using a blockchain oracle-based decision-making system reliant on voting. It gauges collective intelligence (CI) as the ratio of the number of discovered or rewarded tokens to the total count of purpose-driven tokens.

The configuration and procedural details are illustrated in **Figure 2.8**. It devised an HIT platform using JavaScript, enabling humans to select from a pool of 20 ImageNet images and furnish relevant image tagging data. This information along with the selected images is then transmitted to appropriately configured MTurk and Amazon Web Services (AWS) accounts via an intermediary OOCSI server. Responses from MTurk workers for each submitted HIT are assessed by an on-chain oracle. This oracle employs ERC-20-compliant access tokens to regulate the voting process and distribute purpose-driven tokens associated with each accurately tagged image. Subsequently, individuals imprint the discovered/rewarded tokens as stigmergic traces on the blockchain, aiding other participants in updating their understanding of the reward map and continuing its exploration.

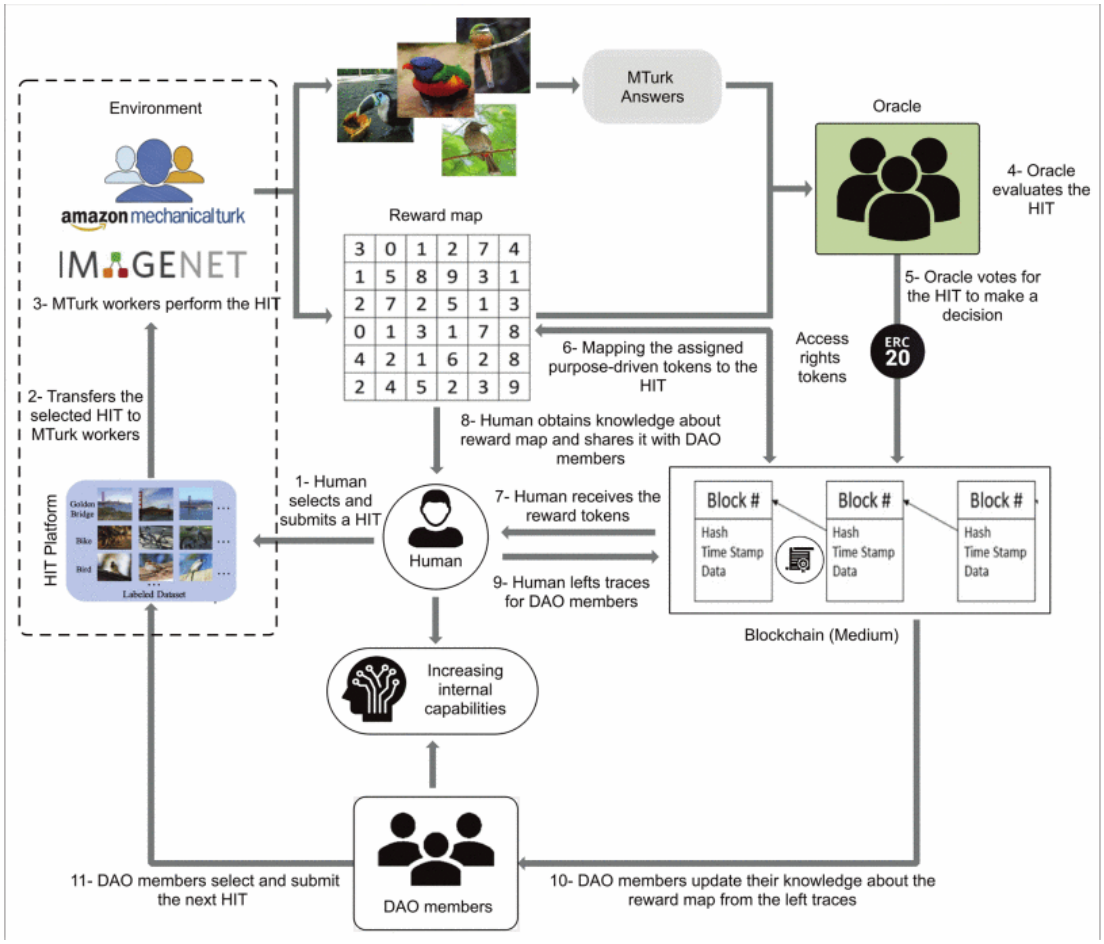


**Figure 2.8** Discovery of hidden token reward mao via Amazon MTurk and on-chaining Oracle.

[Source: Beniiche, A., Rostami, S., & Maier, M. (2022)]

## 2.7 Chapter Summary

Society 5.0 corresponds with the transition of 6G towards a more human-centric approach, capitalizing on Cyber-Physical-Social Systems that engage individuals in interconnected behaviors across cyberspace, physical space, and social realms. It also embraces technologies facilitating a shift from traditional monetary systems to forthcoming non-monetary economies, exemplified by the blockchain-based Web3 token economy and its pivotal role in the emerging DAO framework. Drawing parallels with decentralized blockchain technology, it incorporates stigmergy (a self-organization mechanism observed in social insect societies) to enable indirect communication and coordination among offline agents via traces with feedback loops established within a blockchain-based online environment.

The implemented CPSS-based bottom-up token-engineering DAO framework for Society 5.0 has been validated to enhance both Collective Intelligence (CI) and rewarded purpose-driven tokens through the utilization of stigmergic traces in a blockchain-powered online setting involving crowdsourced Amazon MTurk workers and a validating on-chain oracle. Notably, the convergence of human computation through crowdsourcing and biological mechanisms like stigmergy holds promise for leveraging nature's efficiency (a process known as bioneering) to promote sustainability in blockchain and future 6G networks. This entails embracing Nature-based Solutions (NbS) that

collaborate with nature to tackle societal issues such as climate change and promote human well-being.

**Problems**

1. Define the CPS significance for Society 5.0.
2. Describe the co-evolution of society and industry toward Society 5.0.
3. Explain Society 5.0 with SDG.
4. Outline Society 5.0 from Robonomics to Tokenomics.
5. Explain Society 5.0 as a human-centered society.
6. Detail Society 5.0 with collective intelligence.
7. Describe the Implementation of Society 5.0.

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# Chapter 3

# Transportation 5.0

**Chapter Objectives**

- Learners understand the impact of cyber-physical systems on transportation.
- Learners familiarize the platform of transportation 5.0 in context of cyber-physical systems.
- Learners can describe the evolution of transportation with cyber-physical systems.

The IEEE Intelligent Transportation Systems Society inaugurated a Technical Committee on Transportation 5.0 in 2014. Its objective is to advocate for and facilitate the adoption of cutting-edge technologies, particularly Artificial Intelligence, within transportation. This chapter provides a concise overview of the primary development and discoveries. Key areas of focus include Transportation Foundation Models, Transportation Scenarios Engineering, and Transportation Operating Systems, which have been pinpointed as crucial avenues for advancing the development of next-generation intelligent transportation systems.

## 3.1 Introduction

The relationship between Intelligent Transportation Systems (ITS) and human societies is intricate, involving social structure, transportation infrastructure design, and societal behavior, all of which are interrelated and influence each other. Society's role is as crucial, if not more so, than transportation technologies in shaping the development and evolution of ITS. In established ITS applications like intelligent surveillance and traffic light control, societal and transportation-related human factors have been incorporated as contextual inputs, resulting in reactive responses. The studies often overlooked societal perspectives not because their importance was unrecognized, but due to the immense complexity involved in accounting for social interactions. However, the emergence of the Intelligent Technology Era, also known as the New IT Era, has changed this scenario.

A recent approach known as Transportation 5.0 has been introduced, employing Cyber-Physical Social Systems (CPSS) architecture. Inspired by reality theory, CPSS integrates and coordinates three elements: computational or cyber resources, physical resources, and human or social traits. It stresses the deep integration of social and human dimensions into Cyber-Physical Systems (CPS), establishing a new space with equal status as cyber and physical spaces, rather than merely serving as a backdrop or context. By incorporating Decentralized Autonomous Organization (DAO) into CPS, Transportation 5.0 actively engages society as a participant, proactively interacting with society in ITS processes by leveraging advancements in Artificial Intelligence, large-scale communication and computing, and data technologies.

From the standpoint of social functioning and urban development, the transportation system encompasses all systems facilitating the movement of people and goods within a city. The level of urban development is closely reflected in the quality of a city's transportation system. Similarly, the transportation system significantly influences regional economic structure and urban morphology.

The limited capacity and functionality of transportation systems can constrain the growth potential of cities.

While ITS technologies have garnered significant attention and growth, optimizing a transportation system requires more than just technological advancements. New technologies may introduce additional complexities to existing systems, potentially leading to inefficiencies and degraded performance if not properly designed and optimized. The current transportation system consists of numerous uncoordinated subsystems, each aiming to optimize its performance without considering the overall system performance, resulting in the well-known phenomenon known as the Price of Anarchy. This phenomenon highlights that subsystem optimality does not imply system optimality, and vice versa. For example, the development of personal transportation often conflicts with the need for social welfare due to the high consumption of roadway resources associated with increased demand for personal transportation. Consequently, past transportation planning objectives focused on efficient private transportation have resulted in severe environmental pollution and traffic congestion.

Various everyday scenarios underscore the importance of considering a societal perspective when designing transportation systems. Social activities have increasingly become a primary purpose of trips for many individuals. Despite the COVID-19 pandemic, the proportion of trips involving visiting friends and dining out has risen, highlighting the importance of maintaining a reliable and trackable logistics network.

Studies emphasize the crucial role of humans in all technological fields, particularly in areas where ITS has a significant impact, such as vehicle technologies, automation levels, traveler information management, fleet planning, and traffic management control. Societal perspectives should be integrated early in the ITS testing phase to introduce a new paradigm. Test results could lead to wider public acceptance of the new ITS paradigm, resulting in improved morphology and continuous support for ITS developments. For instance, the adoption of new technologies like autonomous vehicles hinges on public trust. Even though the introduction of these vehicles into urban environments is expected to be gradual, understanding road users' actions and reactions to these vehicles is essential for establishing trust.

The Technical Committee on Transportation 5.0 was established by the IEEE Intelligent Transportation Systems Society (ITSS) during the 17th IEEE International Intelligent Transportation Systems Conference (ITSC) in 2014 in Qingdao, China. Since then, IEEE ITSC has regularly organized workshops on Transportation 5.0 and published numerous technical reports and papers on various topics related to X 5.0 and Parallel Intelligence. This position provides a concise overview of the extensive activities and research conducted over the past decade in this field.

## 3.2 Transportation Systems

### 3.2.1 Socio-technical systems

Socio-technical systems (STS) are systematic arrangements that encompass cybernetic processes, technical components, and human interactions. These intricate infrastructures consist of both social and technological elements that interact with each other in complex and often unpredictable ways. STS comprises four key elements: humans, nature, artifacts, and organizations. Human interactions with nature lead to the creation of artifacts, which in turn contribute to the formation of organizations.

Transportation serves as a quintessential example of an STS. In this system, human interactions with physical space and natural resources result in the construction of human-made objects such as roads

and vehicles. Additionally, humans organize transportation operations, including logistics and public transport services, which represent organizational activities. Developmemt has demonstrated that unilaterally optimizing either society or technology tends to increase the number of unpredictable relationships and may have adverse effects on system performance. Therefore, the socio-technical theory advocates for the joint optimization or design of social and technological systems to ensure they function harmoniously.

Achieving joint optimization in socio-technical systems can be challenging because it requires synchronized changes in both technological advancement and social awareness. If technological development outpaces changes in social awareness, development may be hindered. Conversely, if social awareness exceeds technological development, its impact may be limited. Therefore, studying complex systems like transportation from a socio-technical systems perspective is crucial for understanding how to navigate the interplay between technological progress and social awareness and adapt appropriately.

### 3.2.2 Evolution of Transportation Systems

Viewing transportation through the socio-technical paradigm shifts provides insights into its evolution as a fundamental human necessity, dividing it into four phases. These phases mirror the general trajectory of socio-technical systems development, where advancements in tools and technologies initially drive changes in societal structures, which then influence technological evolution in a reciprocal manner.

**Transportation 1.0:** Alteration of the natural landscape. The emergence of cities and nations necessitated the development of transportation systems. As human and commodity activities expanded beyond traditional tribal societies, new transportation methods and infrastructure became essential for urban and national development. Networks like Rome's road system, China's Qin Zhi Dao, and the Persian Royal Road facilitated transportation within natural environments, shaping regional identities and fostering social interaction.

**Transportation 2.0:** Diversification of transportation modes. Increased familiarity with travel spurred the evolution of transportation methods. Initially driven by the elite, primitive modes such as saddles, carriages, and ships emerged. The industrial revolution introduced modern vehicles like automobiles, trains, and ships, epitomized by Ford's assembly line. Access to personal vehicles became widespread, transforming travel from a luxury to a societal norm and establishing transportation as a cornerstone of modern cities.

**Transportation 3.0:** Coordination of mobilities. With transportation ubiquity, social coordination of various modes became essential for efficient marine, air, rail, and road transport. The focus shifted to resource coordination, leading to standardization efforts and regulatory frameworks such as the Vienna Convention on Road Traffic and Road Signs and Signals.

**Transportation 4.0:** Meeting human needs. As transportation's importance grew, research refocused on fulfilling human needs. Recognizing transportation as a social necessity, efforts centered on aligning systems with societal demands. Safety measures like airbags and seat belts improved personal safety, while electric vehicles reduced environmental impact. Innovations like ride-sharing reduced reliance on private ownership, enhancing public transportation's resource allocation and effectiveness.

### 3.2.3 Artificial Intelligence as a The New Frontier

The evolution of transportation systems has undergone four paradigm shifts, focusing on altering nature, generating artifacts, organizing resources, and meeting human desires. As a socio-technical

system, transportation's complexity has grown significantly from 1.0 to 4.0, posing challenges to achieving substantial improvements through technical advancements alone.

Addressing traffic issues while considering social structural changes can yield remarkably positive outcomes. For instance, innovative business models like bike-sharing have greatly influenced traffic system efficiency despite minimal technical innovations. However, such initiatives may yield unintended consequences without careful planning. For example, the surge in courier delivery services has increased accidents involving non-motorized vehicles. To improve transportation systems, novel approaches that integrate nature, artifacts, organization, and human factors are essential.

Fortunately, advancements in AI technology facilitate this convergence. Intelligent technologies enable the automation of previously human-responsive behaviors, allowing for direct modification of social consciousness. The focus of transportation systems has shifted towards efficiently transforming nature, creating practical artifacts, establishing reliable organizations, and meeting human needs with trustworthiness. These essential aspects can be unified in the new era of Intelligent Technology, enabling synergistic optimization of multiple needs, and accelerating the shift from technology-centered to society-centered paradigms as shown in **Figure 3.1**.

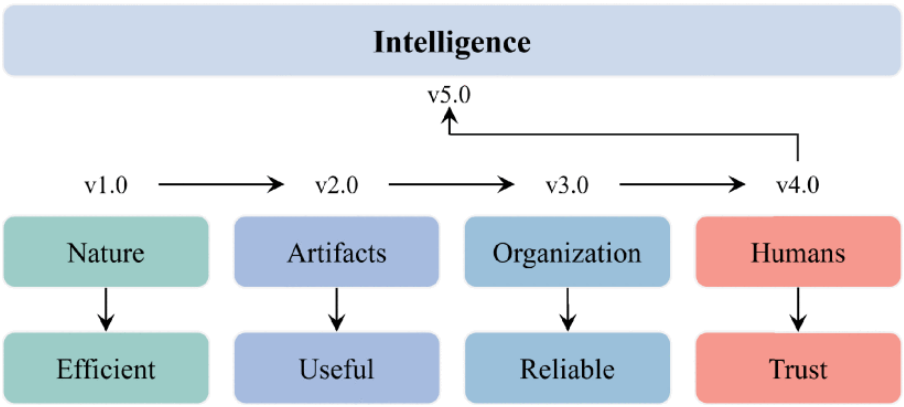


**Figure 3.1** The evolution of transportation systems through four distinct phases.
[Source: Wang, F.-Y., et al. (2023)]

### 3.3 Decentralised Society (DeSoc)

#### 3.3.1 From New Technology to New Social Form

Intelligent technology facilitates the convergence of natural entities, artificial artifacts, social organizations, and human interactions. Here it delves into the global ramifications of technology and envisions potential future societal structures.

The Cyber-Physical Social Systems (CPSS) theory posits three interconnected worlds: the Physical World (World One), the Mental World (World Two), and the Artificial World (World Three), as integrated entity. This framework offers profound insights into the dynamics of socio-technical system evolution. As depicted in **Figure 3.2**, transformations typically initiate in the artificial world, subsequently influencing both the mental and physical realms. The interconnectedness of these three worlds, mediated by the artificial realm acting as a parallel domain, lays the groundwork for future advancements. The contemporary artificial world has undergone substantial metamorphosis, profoundly impacting our mental and physical environments. Accurately recognizing these changes is imperative for the advancement of transportation systems.

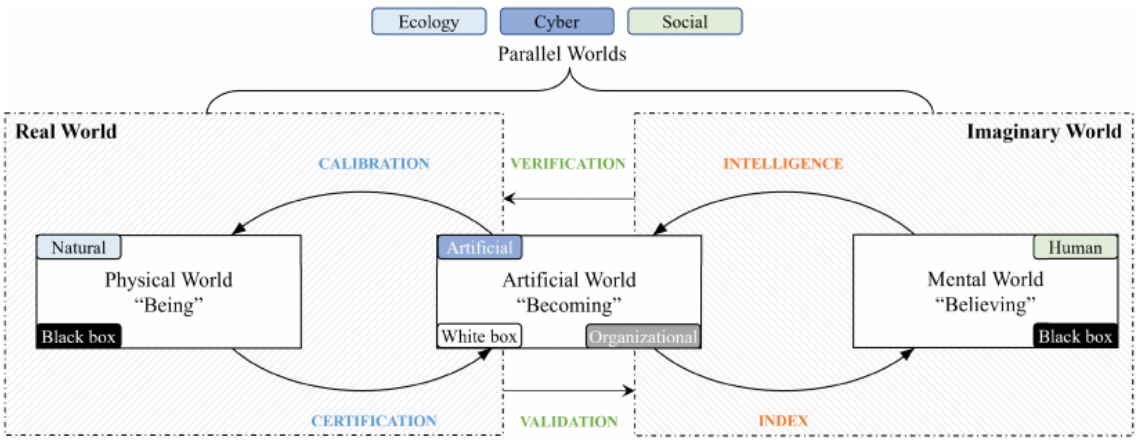


**Figure 3.2** Three worlds in socio-technical systems.
[Source: Wang, F.-Y., et al. (2023)]

### 3.3.2 The Decentralization Trends

As new social structures gradually emerge, the advancement of intelligent technology acts as a catalyst, while developments in energy and communication technologies provide the necessary material and informational exchange infrastructures. It contends that these three technological innovations have fundamentally reshaped the human-made environment and further influenced the current physical and mental landscapes, leading society towards a decentralized trajectory.

**Energy Technology:** The advancement of clean energy technology plays a pivotal role in alleviating tensions between humans and the environment caused by fossil fuel consumption. Additionally, it has propelled the advancement of battery technology. Presently, the widespread adoption of electric vehicles and smartphones is intricately tied to innovations in battery technology. The transition from centralized fossil fuel supply, such as coal and natural gas, to decentralized battery-based energy signifies a shift towards decentralized energy utilization. Importantly, advancements in energy technology lay the groundwork for the development of digital technologies.

**Communication Technology**: Communication technology is an indispensable component of modern civilization in the 21st century, with smartphones leading the way in driving significant advancements. These developments have had profound impacts on modern life. The ubiquitous use of modern communication technologies like WiFi and 5G has seamlessly integrated search engines and e-commerce into everyday activities. Social networks and short videos have supplanted traditional news outlets and leisure pursuits.

**Intelligent Technology:** Web and communication services have spurred the creation of technologies such as recommendation engines, large-scale databases, and application-specific integrated circuits. These innovations have facilitated the processing of vast amounts of data and enabled the development of AI technologies capable of performing various intelligent tasks. Deep learning, among other cutting-edge technologies, has greatly enhanced automation in speech and image recognition, as well as intelligent decision-making. However, these advancements sometimes present challenges for human comprehension.

Initially aimed at enhancing human connectivity and efficiency, these technological advancements have often resulted in unforeseen consequences. While social networks and short videos have accelerated the dissemination of news, they have also exacerbated issues such as information bubbles and the fragmentation of opinions. The widespread adoption of smartphones and online entertainment has made attention one of the most coveted commodities of time. Moreover, these

technological advancements have tangible effects on the physical world. Cities are now teeming with intelligent technology, including facial recognition cameras and autonomous vehicles (AVs). The geographical distribution of the workforce has undergone significant transformations due to internet accessibility and remote work options.

**3.4 The Obstacles of New Social Structure**

The emergence of advanced technological innovations has led to the fragmentation of society, characterized by decentralized information dissemination, diverse influencing entities, and varied value systems. Bitcoin, alongside other decentralized digital currencies, and Non-Fungible Tokens (NFTs) have surged in popularity. Traditional influencers like city mayors have been overshadowed by internet users who can share relevant news instantly, resulting in a shift towards fleeting fame, as epitomized. This phenomenon, known as DeSoc or Decentralized Society, has brought about significant changes affecting the transportation sector.

**3.4.1 Decentralization of Information Channels:**

In the era of Web 3.0, advancements in mobile apps and IoT technology have transformed various entities into potential information channels. While this theoretically offers broader information sources that could enhance traffic management systems, practical challenges such as data silos due to privacy regulations and competition among systems hamper its effectiveness. These barriers hinder the dynamic adjustment of transportation systems to changing conditions. Addressing this requires well-defined and implemented data pricing methods agreed upon by providers and consumers to facilitate collaboration. New industry chains like data collaboration platforms and Data as a Service (DaaS) are crucial for overcoming these barriers.

**3.4.2 Lack of Consensus:**

Diverse perceptions and reactions to phenomena have become more apparent with the fragmentation of information channels. This challenges the traditional consensus-building mechanisms, especially in the context of social issues where contrasting viewpoints are prevalent. While simulation systems have been employed to reach consensus in social engineering, current models often rely on expert-made rules, leading to discrepancies between simulated and actual data. To address this, existing consensus mechanisms should integrate diverse perspectives based on the observer, allowing for local consensus formation on matters of common interest. This paradigm shift replaces a rigid consensus with a more adaptable approach that adjusts to local data granularity and patterns.

**3.4.3 Contradictory Interests:**

Traditionally, conflicts in the transportation sector have been addressed utilizing macro-level data. For instance, the impact of private cars on public transportation has prompted measures like the creation of bus lanes. However, in scenarios where information sources are widely dispersed and consensus is only achievable at the local level, conflicting interests may arise among participants. For instance, drivers often criticize pedestrians for crossing the street, yet they also lament drivers who fail to yield when not driving themselves. Such disagreements are commonplace, especially in situations where competition for resources exists, leading to differing opinions on resource ownership or usage rights.

While macro-level statistics have been useful in mitigating conflicts in transportation, micro-level conflicts have also emerged with the advent of data collection technologies and control devices. Decision-makers in transportation often opt to optimize arterial traffic volumes, sacrificing non-arterial traffic efficiency when faced with limited traffic data, which can be effective. However, the proliferation of mobile apps enabling individuals to predict arrival times poses a risk of significantly increasing traffic on arterial routes, undermining signal optimization strategies.

These examples highlight that solely relying on macro-level statistics and control methods may fall short in addressing intricate social conflicts when there's ample information but no consensus on resource allocation. Instead, a multidimensional control approach is needed to navigate the dynamic game dynamics of social behavior, especially as micro-level factors can substantially alter expected outcomes.

### 3.5 Safe, Secure, and Sustainable ITS

The progression of technology, particularly the Internet and information technology, has spurred decentralization across various facets of society, including information dissemination, societal consensus formation, and interest expression. This transformation has had a profound impact on the conceptualization, planning, and administration of transportation systems, which traditionally relied on experience, theories, and established norms.

Existing centralized transportation systems often encounter numerous hurdles when confronted with the dynamics of a decentralized society. These centralized systems, typically overseen by a single authority, operate under the assumption of relatively uniform public transportation demands. However, in a decentralized setting, they grapple with several challenges in accommodating the diverse preferences and expectations of individuals and communities. These challenges can be classified into three main areas: description, prediction, and prescription.

- **Description:** Centralized systems often struggle to comprehend and adapt to the varied and dispersed data prevalent in a decentralized society. Obtaining timely and efficient information, crucial for swift decision-making and adjustments, becomes a challenge. In a decentralized context, data sources and information exhibit greater diversity, necessitating more robust data collection and analysis methodologies.

- **Prediction:** Centralized predictive models encounter difficulty in accurately capturing the nuances among local areas within the transportation system. Each region may possess unique characteristics and requirements that centralized models may inadequately account for. Consequently, predictions derived from such models may not be as precise or applicable across all regions, leading to suboptimal transportation planning and resource allocation.

- **Prescription:** Centralized approaches lack the precision and efficacy needed to address the varied demands of a decentralized society. A one-size-fits-all approach may yield inadequate solutions for specific contexts or regions, and the implementation of these solutions may face delays due to the bureaucratic nature of centralized systems. Consequently, this can result in reduced efficiency and satisfaction among users of the transportation system.

The hurdles encountered by centralized transportation systems in adapting to a decentralized society underscore the necessity for innovative technologies and methodologies tailored to meet the diverse requirements of individuals and communities. In the era of Transportation 5.0, ITS efficiently leverage communication, information technologies, and AI for data-driven traffic management, monitoring, prediction, and behavior analysis. Advanced technologies like AI, Blockchain, DAO2, and privacy-preserving computing are instrumental in addressing the challenges related to description, prediction, and prescription through the implementation of Privacy Data Collaboration, Transportation Foundation Models, and Decentralized Autonomous Operation and Organization.

AI plays a pivotal role in various ITS applications such as autonomous driving, traffic signal control, traffic flow forecasting, demand modeling, driving behavior analysis, and traffic incident monitoring,

enhancing the efficiency and effectiveness of transportation systems within a decentralized framework. For instance, cooperative driving automation facilitates interaction between vehicles, infrastructure, and other road users to enhance overall system performance. These applications can be seamlessly integrated into a decentralized system powered by Blockchain technology, often referred to as DAO2. DAO2 efficiently manages complex system functions through Smart contracts, executed autonomously without centralized control, transparently recorded on a Blockchain, and incentivized using specialized tokens. Moreover, privacy-preserving computing reinforces the system by enabling data processing and analysis while safeguarding individuals' privacy. This approach ensures data security and privacy, allowing for confidential data handling while enabling computation and analysis. Through the amalgamation of these technologies, the evolution of Transportation 5.0 can advance towards TRUE2, embodying the essential principles of Trust (T), Reliability (R), Usability (U), and Effectiveness + Efficiency (E).

### 3.5.1 Privacy-Preserving Data Collaboration

In the era of Transportation 5.0, advancements in hardware, algorithms, and software systems centered around data technology have ushered in new avenues for development in Intelligent ITS. The scope of traffic data collection has expanded beyond physical space to encompass cyber and social domains, including travel service platforms, social media platforms, and portable mobile devices. The proliferation of data volume and complexity has spurred interdisciplinary works and the emergence of technologies like data mining, natural language processing, and deep learning.

Traditionally, traffic data collection primarily focused on measuring vehicle volume on roads and highways using physical sensors and cameras stationed at various points along roadways. However, conventional data collection methods in physical and cyber realms have limitations in coverage and the ability to capture the entire traffic process and environmental variables. With the advent of digital technology and social media, traffic data collection has evolved to include monitoring social activity, such as tracking visits to location-based services. Social space data complements physical and cyber space data collection efforts and offers valuable insights into transportation perceptions and behaviors, enhancing the accuracy of traffic prediction models.

Leveraging social data collection alongside privacy-preserving computing, blockchain, and distributed computing can enhance transportation data utilization within a broader social context. Decentralized Autonomous Organization (DAO)-based city management presents an efficient approach to optimize data utilization and integrate it with data from other subsystems, fostering a deeper understanding of urban dynamics and enabling the development of multi-system simulations based on data. Introducing a data pricing mechanism could incentivize further data sharing and improve data circulation across various domains. Blockchain technology can establish a secure and decentralized data platform, fostering trust and authenticity in data transactions while enhancing system security.

In essence, the advent of advanced technologies like privacy-preserving computing, blockchain, and cloud-based distributed computing in the era of AI offers novel opportunities for privacy-preserving data collaboration in ITS. Integrating these technologies into ITS can mitigate challenges related to data heterogeneity, real-time processing, and scalability, thereby facilitating the creation of data-driven multi-system simulations and optimizing urban resource allocation for maximal societal benefits.

### 3.5.2 Traffic Foundation Models

Simulation techniques are frequently employed in transportation planning and control decisions, with traffic simulation technology being widely utilized to investigate the operational mechanisms of cities. These simulation models are built upon the traffic foundation model and utilize models of individual agents or groups of agents (such as vehicles or pedestrians) interacting with the infrastructure within the simulated environment. To accurately capture the complexities of urban cities, it is essential to analyze diverse road user behaviors. The Next Generation Simulation (NGSIM) datasets, provided by the USDOT, offer valuable real-world data for studying and understanding the interactions among different road users. However, urban cities are complex and dynamic social systems, where the evolution of the traffic system involves not only interactions among various traffic players but also changes in social structure and form, presenting new challenges for future simulation technology development.

Several simulation models, including macroscopic, microscopic, mesoscopic, and vehicle-level simulation, have been developed to address the challenge of accurately simulating complex large-scale traffic behavior. These models simplify the system by focusing on a single scale, offering different levels of detail and insights into traffic behavior. However, traffic simulation models relying on rule-based methods using pre-existing models, algorithms, and rules face difficulties in managing high-complexity large-scale agent behavior. As urban systems become more complex, simulating real-time traffic responses dynamically becomes increasingly challenging, necessitating more advanced and adaptive simulation methods.

Traffic simulation systems serve as fundamental models for various traffic-related tasks by using computer algorithms and mathematical models to replicate traffic system behavior, providing insights into traffic flow, congestion patterns, and the effects of transportation policies and infrastructure changes. Data-driven traffic simulation models can function as pre-trained models for tasks such as traffic flow prediction and traffic signal control and have been successfully applied in various fields, including visual and natural language processing, and general decision-making.

By employing state-of-the-art methods such as deep neural networks, graph learning, and multi-source data integration, traffic simulation can be transformed into Transportation Foundation models, converting task-specific intelligence into scenarios-oriented generic intelligence. The traffic foundation model serves as a theoretical framework for understanding traffic phenomena and solving scenario-based problems. **Figure 3.3** illustrates a concept of TengYun, one of these models, designed and developed with parallel learning and federated intelligence in TransVerse, addresses challenges of insufficient, contradictory, and inconsistently distributed data through data pre-processing, entity alignment, and scenario engineering. Additionally, it adopts a "pre-training + prompt tuning" approach to training, significantly reducing computational resources and storage required for fine-tuning on edge servers while increasing traffic knowledge utilization. TengYun offers a solution to the challenge of integrating and utilizing transportation data for efficient and effective management and operation.

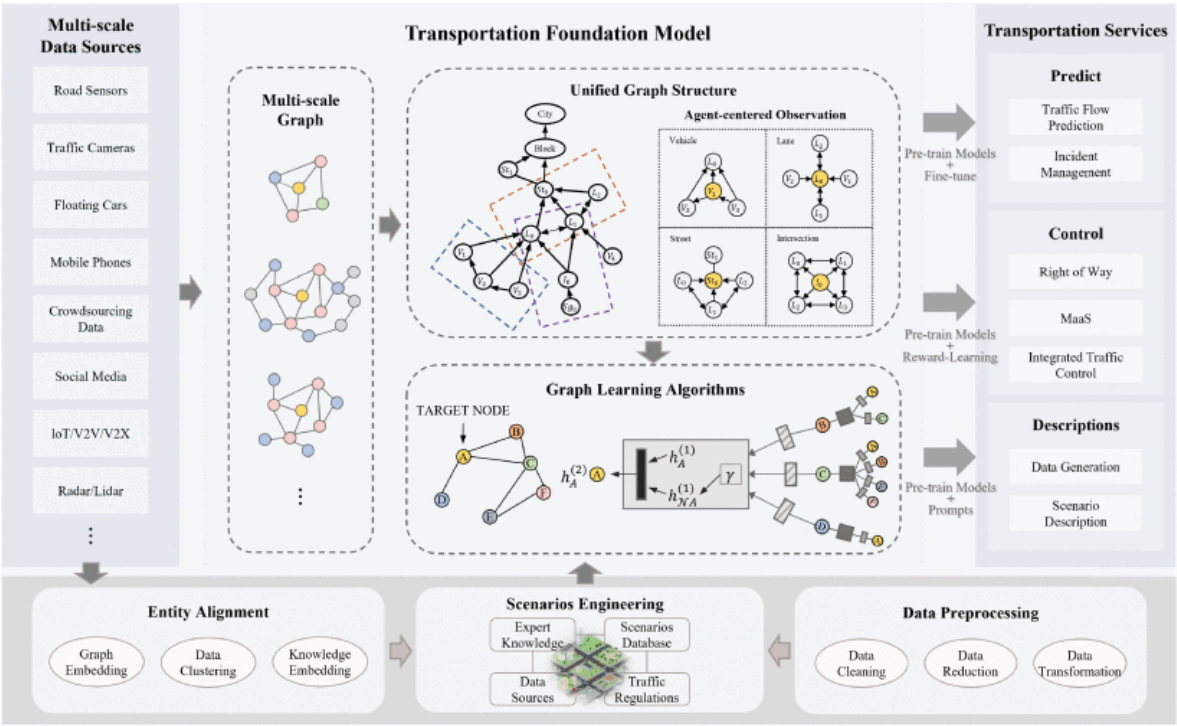


**Figure 3.3** Conceptual framework of the Transportation Foundation Model.
[Source: Wang, F.-Y., et al. (2023)]

TransWorld is an innovative traffic simulation model initially developed by the CAST Lab with the primary aim of constructing Artificial Transportation Systems (ATS) using agent-based technology and object-oriented programming. This model simulates social and behavioral patterns by employing autonomous agents guided by population statistics and behavioral models. Its application is particularly valuable in verifying and validating transportation operations, especially at the logic level. Through interactions among agents, TransWorld can offer a comprehensive depiction of traffic scenarios at various resolutions. The transportation modeling is expected to incorporate advanced technologies and methodologies. These models must possess scalability, flexibility, and expandability to effectively manage the exponential complex growth of transportation systems. Additionally, traffic models should be data-driven, serving as foundational tools to address intricate transportation problems by leveraging real-world data.

### 3.5.3 Decentralized Autonomous Operations and Organizations (DAO2)

ITS is a complex system consisting of multiple subsystems involving various participants. These subsystems operate interactively to meet diverse needs such as commuting and tourism. By gaining a nuanced understanding of the complexity of ITS through data collection, coordination, modeling, and simulation, it becomes possible to predict the behaviors of participants within ITS. The ultimate objective is to manage and control the entire system. ITS control aims to create a safer, more efficient, and sustainable traffic system by striking a balance between traffic demands and infrastructure capacity while considering factors such as comfort, safety, emissions, and energy consumption.

There have been significant advancements in traffic management and control systems aimed at enhancing the performance of traffic infrastructures and vehicles. Various effective traffic control methods have been developed, which can generally be categorized based on response time (ranging from milliseconds to days) and controlled objects (whether infrastructures or vehicles), as outlined in **Figure 3.4**

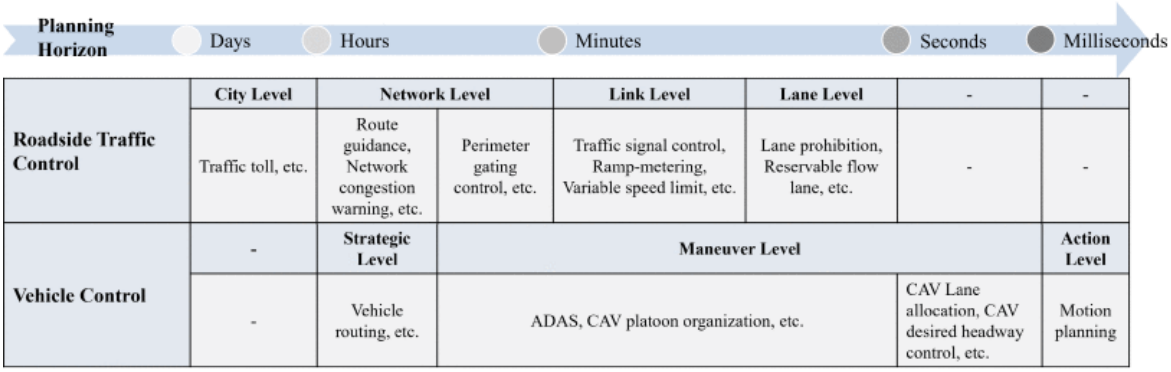


**Figure 3.4** Traffic Control Measures in the Era of Transportation 5.0.
[Source: Wang, F.-Y., et al. (2023)]

Accurately measuring and estimating traffic states are pivotal for implementing more efficient, safer, and sustainable traffic control strategies. With the advent of AI in the era of Transportation 5.0, existing control methods have become theoretically mature, aiming for greater speed, agility, and adaptability. However, the intricate nature of ITS has hindered these methods from realizing their full potential in practice, often leading to the paradox when implemented without coordination. For example, the implementation of green-wave traffic signal control may inadvertently cause traffic congestion on uncontrolled roads, reduce network capacity, and ultimately worsen overall traffic efficiency. Hence, exploring integrated and coordinated control methods that consider participants across multiple ITS subsystems and scales, as well as multiple objectives, presents a significant challenge.

The studies have made strides in multi-scale and multi-objective integrated traffic control, demonstrating its effectiveness in alleviating traffic congestion, ensuring safety, and promoting sustainability. These studies involve integrating and coordinating multiple infrastructure control methods within specific subsystems (highways) or across multiple subsystems (highways and urban roads), managing multiple connected and automated vehicles, and coordinating between road infrastructures and vehicles. Such studies are conducted either in a centralized or decentralized scheme. The centralized scheme assumes perfect knowledge of all controlled participants' states to formulate a generalized objective summarizing each participant's objectives. Conversely, the decentralized scheme controls participants based on their individual objectives, which are linked to the observation and prediction of their connected participants' states. While the centralized scheme faces challenges in scalability, stability, and security, limiting its ability to handle numerous participants with diverse attributes, decentralized control methods compromise on optimality. The emergence of Blockchain technology and DAO2 offers promising solutions to develop integrated and coordinated traffic control systems in a trustworthy, reliable, useful, and efficient manner.

By adopting a DAO2-based system, coordinated control across multiple participants and subsystems can be realized through a set of smart contracts. This decentralized approach, supported by Blockchain technology, ensures security, transparency, and facilitates seamless sharing of traffic data among various subsystems, including vehicle location, travel speed, and traffic signals. Smart contracts automatically process this data and execute appropriate actions to enhance traffic conditions, promoting a community-driven autonomy that upholds principles of mutual benefit, transparency, and safety.

For instance, under this framework, traffic signals can dynamically adjust based on real-time data such as vehicle location and speed, optimizing traffic flow and reducing congestion. These smart contracts can also cater to the objectives of other participants, such as ensuring the safety of

pedestrians and cyclists, by monitoring their behavior through real-time sensor data and taking necessary actions, like adjusting traffic signals, to achieve mutually beneficial outcomes. Moreover, Blockchain technology ensures security and transparency within the ITS ecosystem. For example, when implementing a smart ticketing system for public transportation, the DAO2-based integrated control approach can effectively mitigate ticket fraud, reduce administrative expenses, and concurrently address other objectives like alleviating traffic congestion through decentralized and tamper-proof record management.

The fusion of ITS and blockchain technology offers the potential for more efficient, safer, and sustainable traffic control. Through integrated and coordinated control mechanisms facilitated by Blockchain technology and DAO2, the traffic system can better cater to people's travel demands while simultaneously reducing congestion, enhancing safety, and fostering the sustainable development of cities.

### 3.5.4 HANOI

The direction of Intelligent Transportation Systems (ITS) is supported by three fundamental technologies: Privacy-preserving Data Collaboration, Traffic Foundation Models, and DAO2 as illustrated in **Figure 3.5**. These technologies are poised to address the descriptive, predictive, and prescriptive needs of Transportation 5.0, which is characterized by decentralization. Through Privacy-preserving data collaboration, data can be aggregated from diverse sources, while the Foundation Model can establish a cohesive consensus among fragmented social entities. DAO2 aligns the interests of all stakeholders to maximize societal benefits. Compared to Transportation 4.0, Transportation 5.0 involves a larger number of participants, necessitating broader technical capabilities, including IoT, blockchain, and intelligent technologies.

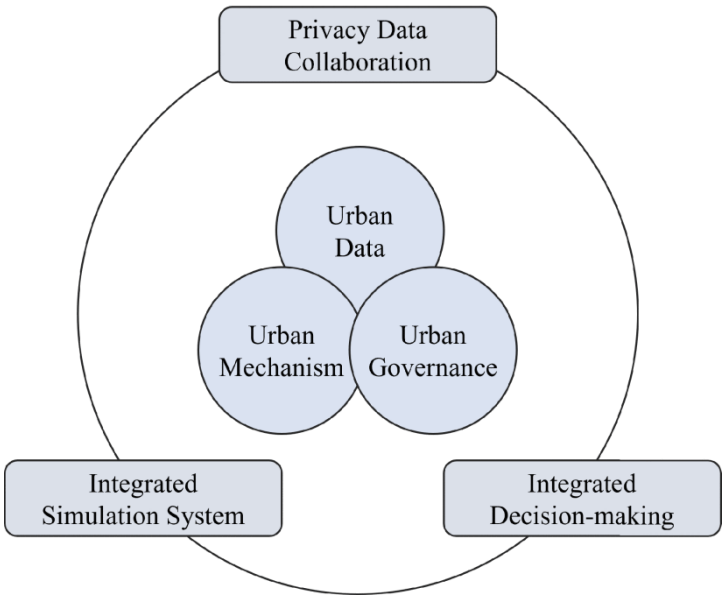


**Figure 3.5** Illustration of the three cornerstone technologies.
[Source: Wang, F.-Y., et al. (2023)]

Essentially, the essence of these three technologies lies in achieving social consensus. Starting from the basic consensus on methods of information disclosure, it gradually progresses to a consensus on overall status awareness, forming agreement on the behavior of each entity in local time and space,

and finally culminating in a series of long-term consensuses on behavioral norms and resource exchange ratios. The first three consensuses primarily impact the social subsystem of transportation, while the latter long-term consensus extends beyond transportation, facilitating an organic integration of transportation with other social subsystems.

While the specific forms and implementation paths of these consensuses still require further research, their ultimate goal is believed to be the achievement of TRUE2 for the overall system, encompassing the four key indicators of Trust (T), Reliable (R), Usable (U), and Effective + Efficient (E). Furthermore, it aims to ensure safety in the physical world (Safety Index), security in the information world (Security Index), sustainability in the ecological world (Sustainability Index), optimization of individual needs and rights (Sensitivity Index), high-quality services for everyone (Service Index), and intelligent infrastructure for everyone (Smartness Index) in the 6S society. Therefore, the attainment of "6I" intelligence is necessary, which includes Cognitive Intelligence and Parallel Intelligence at the technical level, Crypto Intelligence and Federated Intelligence at the operational and management level, and Social Intelligence and Ecological Intelligence at the organizational level. Ultimately, this intelligence forms HANOI, a fusion of human intelligence (H), artificial intelligence (A), natural intelligence (N), and organizational intelligence (OI). **Figure 3.6** illustrates the six types of intelligence and indexes that constitute HANOI.

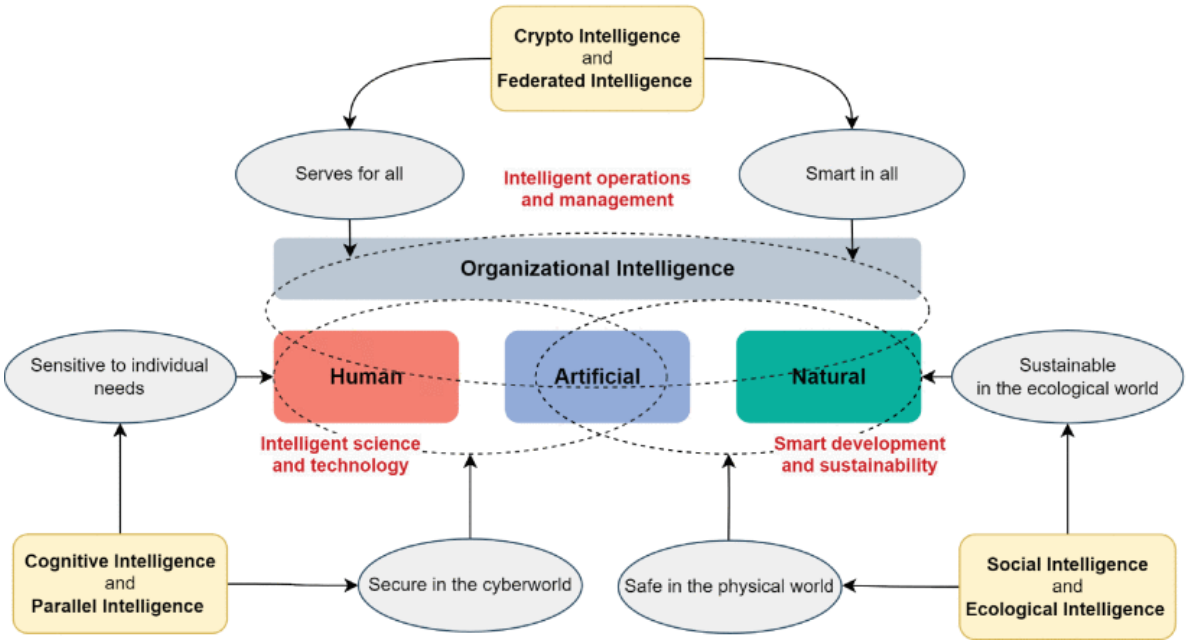


**Figure 3.6** The six types of intelligence and indexes.
[Source: Wang, F.-Y., et al. (2023)]

### 3.6 Scenarios and Systems

Apart from fundamental technologies and tool systems, emerging transportation modes like Mobility as a Service (MaaS) and autonomous driving are also shaping up to accommodate shifts in social structures. These future scenarios of ITS provide the guidance for the evolution of transportation in the coming years.

### 3.6.1 Social-Participated AI Test and Scenario Engineering

The effective deployment and commercialization of Intelligent agents, such as Autonomous Vehicles (AVs), demand comprehensive testing procedures. However, the expansion of AI tests has faced challenges due to insufficient relevant data and repetitive test scenarios.

Inspired by the concept of DAO2, AI testing should not be limited to a single vehicle type or a confined area. Instead, socially inclusive AI tests should be embraced, wherein testing occurs in diverse contexts involving numerous connected vehicles, conventional vehicles equipped with data collectors, and all traffic participants (including bicycles and pedestrians). Scenario Engineering (SE) encompasses the integration of scenarios and activities within a specific temporal and spatial scope, encouraging all actionable AI to participate in the design, certification, and verification process. SE ensures that AI systems are better aligned with their original testing objectives by avoiding repetitive scenarios and generating more valuable ones. Parallel learning is proposed as a valuable tool for AI testing and scenario engineering. DeCAST within the TransVerse platform was developed following the DAO2 principle, as depicted in **Figure 3.7**. Through parallel learning, the evaluation and development of AVs can be significantly expedited.

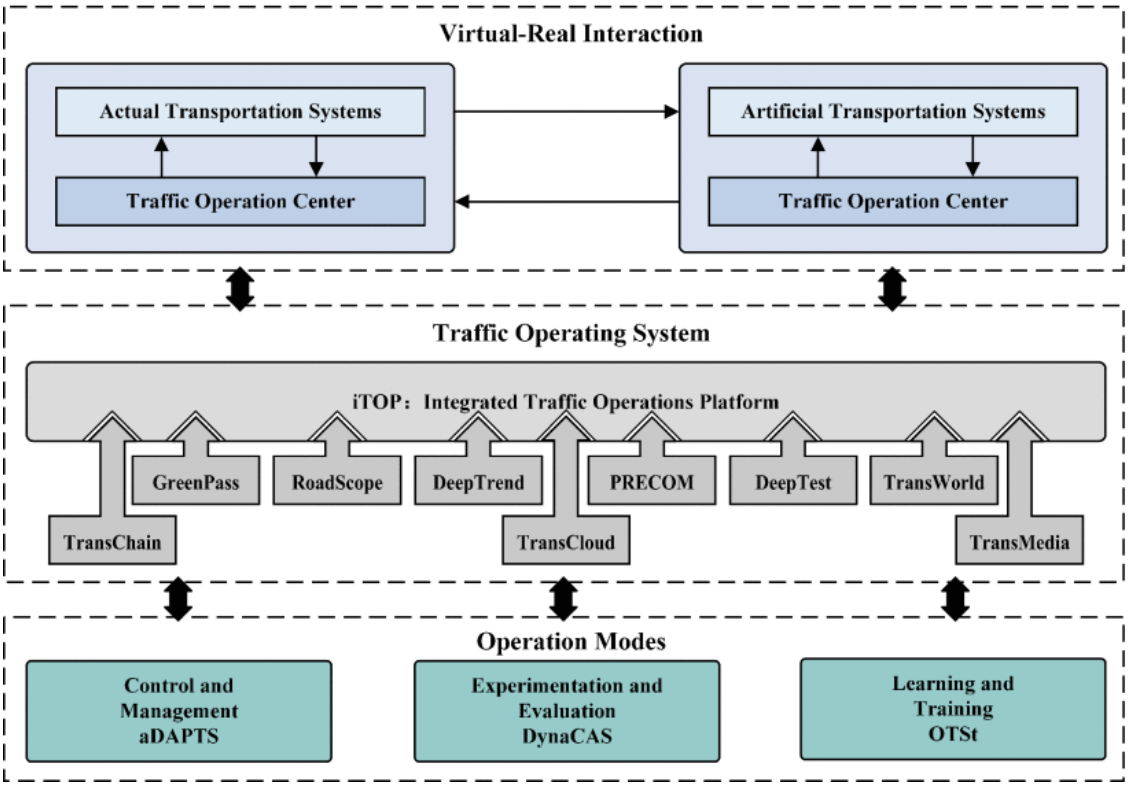


**Figure 3.7** The platform architecture of DeCAST.
[Source: Wang, F.-Y., et al. (2023)]

Acquiring a substantial volume of data is crucial for the AI testing methodology to generate comprehensive scenarios, particularly in mixed-traffic environments. These comprehensive scenarios, in turn, can alleviate the bottleneck in the development of autonomous driving technology. To achieve this objective, an integrated testing platform is essential, connecting the virtual simulation test field, human-driven driving simulator, and actual test field. This integrated setup establish a closed-loop process for developing, testing, and advancing new technologies. The proposed simulation-driven AI has the potential to fulfill the requirement for the Try-Test-Adjust design policy when integrating virtual and real data collected.

### 3.6.2 Trans-Scale Control and RoW-Based Traffic System

The existing limited scope of traffic light control has become a focal point of research concern, as signal lights are currently positioned solely at intersections and expressway ramps, potentially leading to conflicts. Introducing the concept and technology of Right of Way (RoW) in traffic interactions could serve as a crucial innovation in addressing the challenges associated with traditional traffic control.

To effectively optimize the use of constrained road resources, an efficient traffic control system must confront the following challenges:

- Precisely determining vehicle arrival times at intersections to deploy appropriate control signals.
- Ensuring seamless integration of RoW distribution and communication throughout the entire driving process.
- Accurately measuring and managing the movement of each vehicle on the road.

The emergence and progress of V2X (Vehicle-to-Everything) technology present novel opportunities to tackle RoW ownership issues. This technology establishes a network that connects humans, vehicles, roads, and other transportation elements, enabling ubiquitous information sharing. However, the transportation system faces hurdles due to the lack of a unified control objective for coordinated subsystem control. Addressing this challenge in traffic systems across various agents at different scales necessitates a new concept known as "Generalized Right of Way." This concept entails a fundamental attribute granting permission to occupy specific travel resources for a specified duration. By leveraging this concept, a trans-scale traffic control system can be developed to tackle fragmented control strategies.

As urban intermodal transportation demand continues to evolve, the limitations of single-scale control methods are gradually becoming apparent, constraining the ability to integrate multi-scale schemes to achieve control objectives. Recent studies have explored the cooperation of trans-scale traffic control tasks, which is a critical issue in ITS. However, developing a unified control mechanism from the perspective of maximizing social resource allocation and appropriately coordinating the utilization of multiple control modes requires further in-depth research.

The RoW facilitates seamless transitions between different subsystems and scales within the traffic system by quantifying the impact of one aspect on all others. Based on the unified control objective (RoW), a collaborative mechanism involving multiple agents for trans-scale traffic control can be established. This mechanism allows for a scenario of multi-agent joint control, tailored to each agent's resource consumption percentage and control effectiveness.

The RoW can be utilized in exchange for various assets such as currency, carbon emissions, and energy consumption rights to establish a tradable system. By integrating the transportation subsystem with carbon sink trading systems and Location-Based Services (LBS), this framework enhances resource allocation based on user data and various travel resources. Through collaborative control of all elements within a complex traffic system and abstracting numerous social interactions as generalized usage rights, a unified quantitative method for resource recycling mechanisms can be established. Additionally, a cross-system decision-making scheme can optimize overall social benefits by allocating social resources.

As a notable example of traffic control based on RoW theory, the Traffic Operation Recommendation for Controlling Hangzhou Road Networks (TORCH) serves as a best practice. TORCH has been successfully implemented on the Hangzhou road network, enabling city-level traffic control at over

1,000 intersections. This system has notably enhanced the capacity to manage traffic congestion incidents by two to three times, as depicted in **Figure 3.8**.

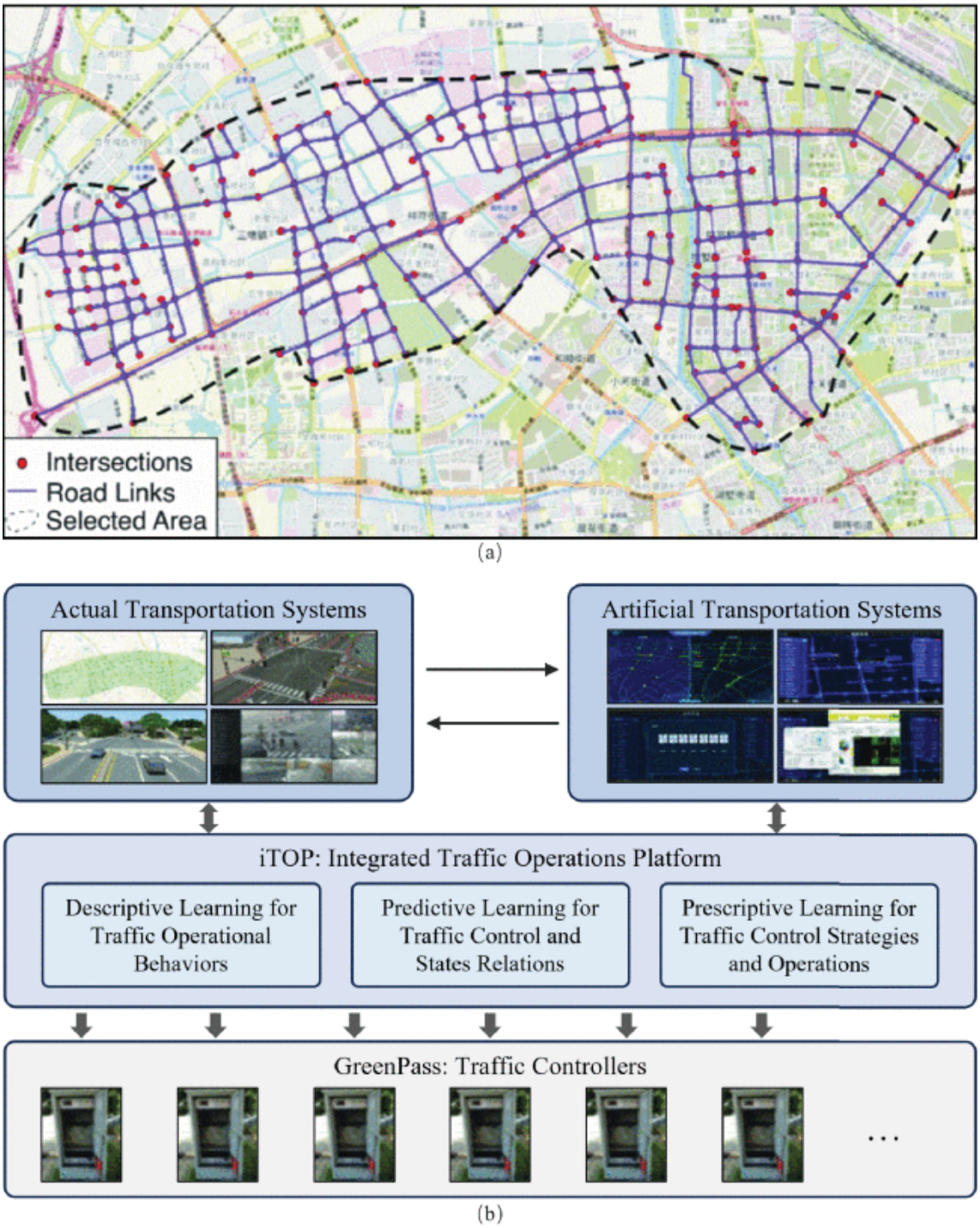


**Figure 3.8** Traffic Operation Recommendation for Controlling Hangzhou Road Networks (TORCH) (a) The case study area, and (b) The architecture.
[Source: Wang, F.-Y., et al. (2023)]

Proactive collision prevention has been explored by establishing a set of decision criteria for Autonomous Vehicles (AVs) to efficiently ascertain the Right of Way (RoW). To enhance driving safety for AVs, three essential principles and devised a rule-based, nine-step communication-decision framework is outlined, depicted in **Figure 3.9**. These decision criteria are designed to be

straightforward and rapidly processed with minimal communication, enabling mutual understanding of behaviors and intentions between human drivers and AVs.

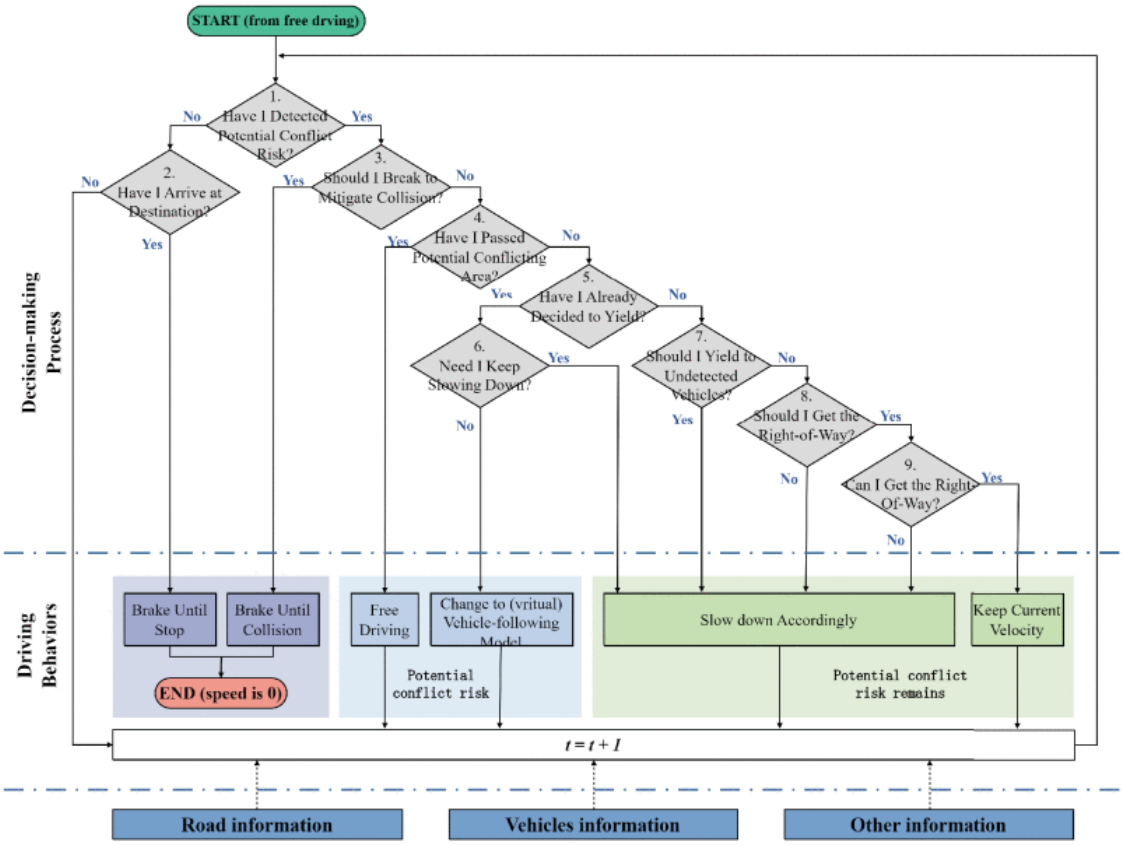


**Figure 3.9** Flowchart of the communication-decision model for RoW in AVs.
[Source: Wang, F.-Y., et al. (2023)]

### 3.6.3 MaaS and Human-Oriented Operating Systems

MaaS represents a novel approach in transportation, consolidating various mobility services from different providers by exchanging data, streamlining intermediation, and offering customers seamless service and a unified payment interface through a continuous pipeline. While there are various interpretations of MaaS, they generally share the vision of shifting from vehicle ownership to enabling users to access shared transportation modes on a per-trip basis. Many cities worldwide have embraced MaaS, leading to numerous practical studies on its implementation and research exploring its business models. For city administrators, MaaS presents an opportunity to develop and manage comprehensive transportation systems and services holistically, rather than dealing with each transportation service separately.

A novel system is required to seamlessly integrate transportation into social life, offering a unified, user-centric interface that aligns with people's behaviors and preferences, and leveraging human feedback to enhance its underlying agent system. Some scholars propose calling such a system a Human-oriented Operating System (H2OS). Similar to computer software and hardware operating systems, H2OS is a complex system comprising multiple components capable of virtualizing transportation resources, parallelizing transportation requests, and implementing transportation planning into real-world operations.

The transportation environment's H2OS encompasses various components, including traffic data collection, processing, and storage modules, traffic request management modules, resource scheduling modules, and more. Through collaborative efforts among these components, H2OS can virtualize and optimize transportation resources, making transportation smarter and more efficient. A central aspect of H2OS is its unified interface, which enables users to easily access transportation resources and conduct planning and scheduling tasks.

In designing H2OS, it is advisable to adopt a decentralized architecture, offering numerous advantages. For instance, it enhances H2OS's resilience against local failures or attacks. Moreover, as new nodes join the network, they can contribute their resources, facilitating H2OS's scalability. This architecture also enhances H2OS's ability to allocate and optimize transportation resources more effectively by leveraging distributed computing and real-time data processing for improved decision-making. Additionally, privacy and security can be bolstered as users' data is distributed across the network rather than centralized. This decentralization fosters transparency and accountability, as all network participants can access the system's transactions and operations.

### 3.7 Chapter Summary

It summarizes to underscore the ongoing transformation in Intelligent Transportation Systems (ITS) from a technology-driven focus to one centered around society. This shift is propelled by the adoption of Cyber-Physical-Social Systems architecture and parallel systems methodology, which provide innovative solutions to current transportation challenges. These methodologies are swiftly advancing and being implemented across three critical domains: Privacy-preserving Data Collaboration, Traffic Foundation Models, and Decentralized Autonomous Operation and Organization.

The success ITS practices validates the vision and related assertions of the ITSS TC for Transportation 5.0. As ITS development continues, emerging scenarios like social-participated AI testing, Right of Way (RoW)-based traffic control, and Mobility as a Service (MaaS) are pivotal in propelling ITS towards a society-centric architecture. This significant transition will not only reshape the ITS landscape but also profoundly influence the organization of related sectors such as urban planning, energy, and the environment, steering transportation systems towards objectives centered on human welfare and sustainability.

**Problems**

1. Explain the CPS significance for Transportation 5.0.
2. Describe the evolution of transportation systems.
3. Figure out Transportation 5.0 with the Decentralised Society.
4. Describe Transportation 5.0 with the obstacles of new social structure.
5. Analyze the conceptual framework of the Transportation 5.0
6. Describe Transportation 5.0 with the safe, secure, and sustainable ITS.
7. Describe the six types of intelligence and indexes.
8. Define Transportation 5.0 with the scenarios and systems.

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# Chapter 4

# Cyber-Physical System Architectures

**Chapter Objectives**

- Learners understand cyber-physical systems architectures for an industry domain.
- Learners become familiar with the basic cyber-physical systems architectures.
- Learners can describe the cyber-physical systems architectures for an industry 4.0.

The industrial landscape is undergoing rapid and exponential transformations, driven by the emergence of various technologies and the ever-growing demand. Consequently, there is a proliferation of processing devices and systems within industrial architectures. Connectivity between entities, seamless integration of physical and virtual operations, interactivity, interoperability, self-organization, and intelligent decision-making are crucial for unlocking the full potential of Industry 4.0 (I4.0). Cyber Physical Systems (CPS) and the Industrial Internet of Things (IIoT) play pivotal roles in the evolution of I4.0. These technologies are actively exploring to adapt to this digital revolution, developing IIoT systems and CPS architectures capable of connecting diverse network devices across different Information and Communication Technologies (ICT) systems, virtualizing company assets, and facilitating integration with other manufacturing sectors and enterprises. This chapter presents the primary CPS architecture models deployed in industrial settings, highlighting their essential characteristics, technologies, and interrelations. It underscores the objectives, advantages, and contributions to the introduction of IIoT in I4.0. Additionally, this conducts CPS and IIoT works, identifying the predominant technologies utilized in the alignment with the key features of I4.0, namely vertical and horizontal industrial integration. The chapter outlines the requirements for addressing issues, limitations, gaps, and adaptations in CPS architectures to enhance their suitability for the I4.0 landscape.

## 4.1 Introduction

The increasing demand for enhanced production, efficiency, and quality in industrial products has spurred the collaborative development of new technologies to keep pace with the rapid evolution of production processes. Historically, the First Industrial Revolution in the eighteenth and nineteenth centuries mechanized water and steam energy production. The Second Industrial Revolution in the twentieth century introduced electricity into factories, alongside mass production, while the Third Industrial Revolution saw the emergence of Computer Numeric Control (CNC) machines, robots, industrial automation, and information technology.

In the 21st century, the advent of the Fourth Industrial Revolution, commonly known as Industry 4.0 is witnessed. Originating in Germany, Industry 4.0 aims to efficiently automate production systems. The pervasive presence of the Internet in various domains has facilitated a connected and smart world, giving rise to the Internet of Things and Services, which connects information, objects, people, and resources. For instance, Smart Grids have emerged in the energy sector, while solutions for Smart Health have been developed in healthcare. From a manufacturing perspective, this technological advancement is encapsulated by Industry 4.0.

Industry 4.0 deployment is characterized by key features, including horizontal integration across value networks, which involves integrating information technology systems at different stages of manufacturing and business planning processes for data exchange within and between companies. Additionally, there is end-to-end digital integration of engineering throughout the value chain, as well as vertical integration and networked manufacturing, which converge information technology systems at various hierarchical levels to deliver comprehensive solutions. These aspects underpin the Smart Factory paradigm, which integrates the physical and digital realms by creating smart products and processes capable of revolutionizing conventional value chains, thereby forming Cyber-Physical Systems.

Consequently, the merging of the Internet of Things and Services with Cyber-Physical Systems in Industry 4.0 will profoundly impact industrial processes through the convergence of Information Technology (IT) and Operational Technology (OT) to facilitate connected factories. In this context, a challenge lies in developing a reference architecture model to provide technical specifications and standards for integrating and implementing these technologies. Furthermore, there is ongoing discussion on how Cyber-Physical Systems and other emerging technologies can be effectively deployed in the Industry 4.0 environment to ensure both vertical and horizontal integration, as well as to enable interoperability among different companies and sectors within the industry.

In response to the reference architecture, numerous studies have been conducted from the perspective of Cyber-Physical Systems (CPS) within the realm of Industry 4.0 (I4.0), aiming to establish standardized frameworks for their application in the industrial sector. A range of CPSs in the context of Smart Manufacturing have been undertaken, focusing on various aspects. Communication between entities is explored by encompassing Unmanned Aerial Vehicles (UAV) networks, wireless connectivity, Ethernet, Time-Sensitive Networking (TSN), and 5G mobile networks. These delve into security and privacy considerations in CPS systems, including analysis of security vulnerabilities in blockchain technology. They examine emerging technologies relevant to CPSs, such as cloud computing, mobile robots, wireless sensors, and Software Defined Networking (SDN). It provides CPS approaches in general, presenting paradigms on CPS origins and concepts, as well as discussing CPS technology standards and characteristics applicable to future Smart Factories.

Existing literature primarily focuses on specific issues and topics within the context of CPS, without adequately addressing their implications for I4.0 or discussing how they align with its key features. At present, this current situation offers the entire CPS architecture within the framework of I4.0, shedding light on current CPS initiatives in industrial settings and their potential alignment with the key features of I4.0, such as vertical and horizontal integration. This unique perspective has been explored and the main contributions are as follows:

- The primary CPS reference architecture models in I4.0, emphasizing their key objectives, existing industrial technologies, standards, and protocols, with a focus on platforms like Open Platform Communications United Architecture (OPC UA). It includes the 5C Architecture, Reference Architectural Model Industrie 4.0 (RAMI 4.0), and Industrial Internet Reference Architecture (IIRA).

- The current CPS solutions developed for industrial settings, accompanied by a detailed analysis and discussion of how these initiatives relate to the reference architecture models and their potential to fulfill the key features of I4.0, such as vertical and horizontal integration.

- The limitations and open issues within current CPS projects are highlighted along with potential improvement to ensure the advancement of this technology in industrial environments and its alignment with the practical implementation of I4.0 key features.

### 4.2 Background Foundations

This part aims to provide the essential concepts to enhance the detail. It will include the principles of Industry 4.0 and Industrial Internet of Things (IIoT), CPS technology.

#### 4.2.1 Industry 4.0 and IIoT

Envisioned as part of the High-Tech Strategy 2020 Action Plan in 2011, Industry 4.0 represents a strategic initiative of the German government aimed at transforming manufacturing processes. This initiative seeks to revolutionize manufacturing by integrating various pillars that facilitate the convergence of the physical, digital, human, and biological realms, thereby fostering the development of new technologies within industrial settings, as depicted in **Figure 4.1**. One of the pivotal pillars within Industry 4.0 is the integration of the Internet of Things and Services into factory operations, also referred to as IIoT (Industrial Internet), Internet of Everything, and Internet 4.0, marking the onset of the fourth industrial revolution.

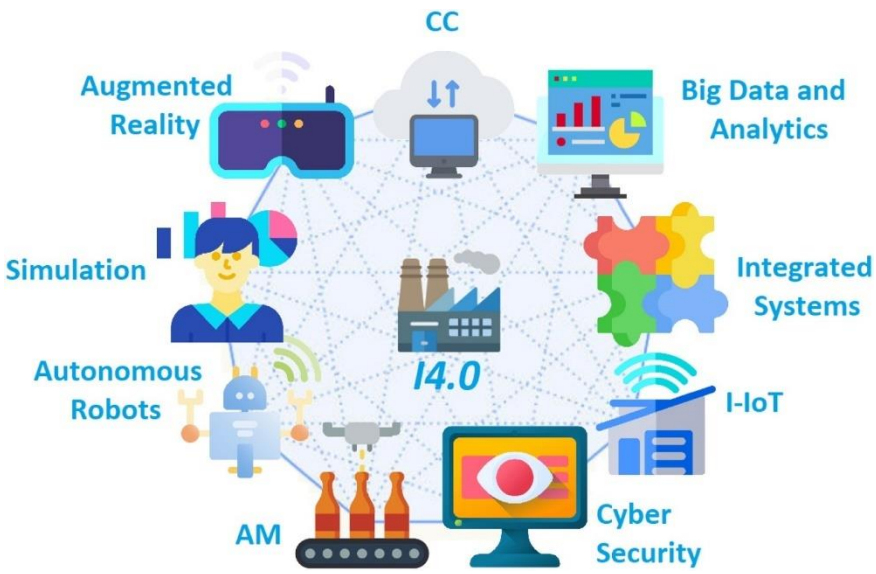


**Figure 4.1** The pillars of the Industry 4.0.
[Source: Pivoto, D. G. S., et al. (2021)]

IIoT plays a significant role in the industrial landscape by introducing concepts and technologies that facilitate the establishment of a network comprising industrial devices. These devices encompass sensors, sophisticated industrial robots, and actuators, interconnected through communication technologies that enable systems to swiftly and easily monitor, analyze, transmit, collect, and modify data. Consequently, the Industrial Internet facilitates the realization of Industry 4.0's key features, including horizontal integration through value networks to support companies' business strategies, end-to-end engineering by seamlessly integrating the digital and physical realms across the entire value chain, and vertical integration by networking manufacturing systems.

The combination of IIoT with Industry 4.0 yields numerous benefits for industrial environments, such as the convergence of Information Technologies (IT) and Operational Technologies (OT). This convergence entails the integration of manufacturing control systems and data storage, computing,

and communication. Whereas OT traditionally comprised hardware and software systems for controlling shop floor processes, they were typically not integrated into a network or larger computerized system. Presently, the IT-OT convergence enables OT components to directly communicate with other machines and centralized servers, facilitating information exchange through an IT network.

Furthermore, this integration leads to a reduction in the number of required operations, enhanced asset performance and utilization, minimization of asset cycle costs, expedited decision-making processes, and the transformation of product purchase and sale into service-based models, thereby expanding business opportunities and fostering the emergence of new manufacturing business models. Consequently, this state focuses on the essential prerequisites for establishing factories that incorporate global networks integrating assets, storage systems, and production processes in the form of CPS.

Despite the myriad benefits associated with the implementation of IIoT and Industry 4.0, the scheme is inherently complex due to the extensive digitization and networking of involved companies, leading to the proliferation of architectures devised by various aspects and potential challenges related to communication networking and system interoperability.

**4.2.2 Cyber-Physical Systems**

One of the primary technologies underpinnings I4.0 and CPS was initially conceptualized by American scientist Hellen Gil in 2006 at the National Science Foundation. CPS encompasses several concepts also found in the Industrial Internet of Things (IIoT), serving as a bridge between virtual spaces and physical reality by integrating networking, computing, and storage. This integration facilitates the creation of interactive industrial environments, leading to the emergence of Smart Factories where uniquely identifiable smart products can be in real-time.

CPSs are automated distributed systems that integrate physical reality with communication networks and computing infrastructures. Diverging from traditional embedded systems, CPSs focus on networking various devices for I4.0 purposes. Essentially, they comprise a control unit capable of managing sensors and actuators that interact with the physical world, processing acquired data, and exchanging them with other systems and cloud services via a communication interface. In essence, CPSs can be regarded as systems capable of transmitting and receiving data from devices through a network.

An essential characteristic of CPSs is their ability to acquire information and services in real-time, irrespective of their location, facilitated by providing Internet access to manufacturing machines. Beyond real-time communication, ensuring stability, reliability, efficiency, and security in operations is imperative. Accordingly, one of the objectives of I4.0 is to furnish high-level security support across all layers of CPS architecture, safeguarding confidential information while ensuring data anonymity. In the I4.0 context, CPSs extend their coverage beyond machines and products to encompass clients, service providers, and inventories, ensuring seamless interaction across all executed areas.

CPSs find applications across various domains including manufacturing, healthcare, renewable energy, smart buildings, transportation, agriculture, and computer networks. In manufacturing, CPSs facilitate auto-monitoring, production control, and real-time information sharing. In healthcare, they enable real-time remote monitoring of patient's physical conditions. In renewable energy, sensors facilitate network monitoring and control to ensure reliability and efficiency in energy consumption. In smart buildings, CPS interaction with smart devices can reduce energy consumption while enhancing protection, safety, and comfort for occupants. In transportation, CPS enables communication between vehicles and infrastructure to share information such as traffic intensity,

congestion locations, and accidents for accident prevention and congestion mitigation. In agriculture, CPS collects weather and resource data like irrigation and humidity, enhancing precision in agricultural management systems. Finally, in computer networks, CPS aids in understanding system and user behaviors in virtual environments.

Among the existing architectural references for CPS, the 5C Architecture stands out as a widely used reference model during the development of CPSs. With the advent of the fourth industrial revolution and the proliferation of data and industrial devices, additional reference architectures have been developed, such as RAMI 4.0 in the manufacturing sector for device virtualization in the value chain and IIRA for industry integration and cooperation with a focus on IIoT.

### 4.3 CPS reference architecture models

As delineated in the preceding, implementations of I4.0 and IIoT encounter several limitations, including deficiencies in security support, connectivity, standardization, and interoperability among devices. To tackle these shortcomings, various reference models for CPS architecture have been standardized and it delves into the principal CPS reference architectures. The methodology employed for selecting these architectures is associated with widely adopted CPS architectures and thorough works on key I4.0 and IIoT initiatives worldwide. Among the noteworthy initiatives are Platform Industry 4.0, a collaborative effort involving companies aimed at driving the digital transformation of manufacturing in Germany, and the Industrial Internet Consortium (IIC), which comprises a collaborative council of industry senior executives focused on advancing the technologies necessary for accelerating the growth of the industrial internet. Based on the adopted methodology, it presents the 5C Architecture, RAMI 4.0, and IIRA models, offering a succinct description of their functionalities while shedding light on the implementation challenges inherent in CPS concepts within each architecture. Furthermore, their details explore the interrelation among these reference architecture models, along with the existing standards and protocols implemented to ensure their proper functioning, elucidating both emerging and legacy technologies, their key facilitators, and the security perspective.

#### 4.3.1 5C Architecture

The 5C Architecture is grounded in models of automation processes and revolves around a data acquisition model for industrial devices. This architecture comprises five levels for system operation, as depicted in **Figure 4.2**.

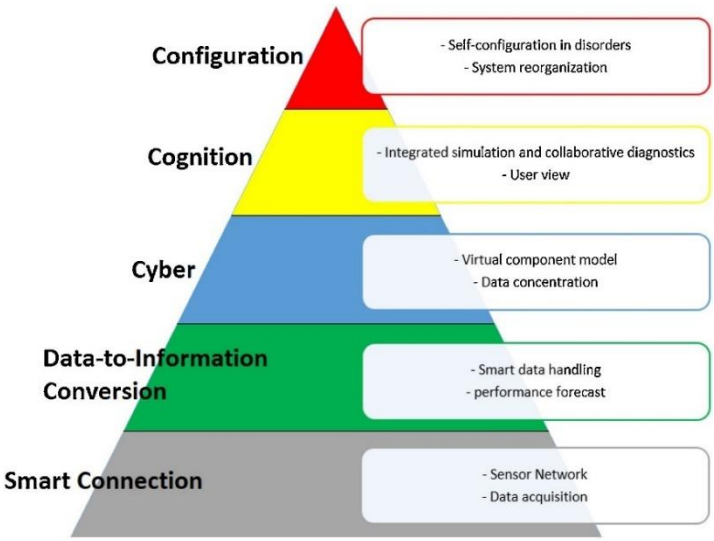


**Figure 4.2** 5C Architecture of CPS.
[Source: Pivoto, D. G. S., et al. (2021)]

The levels of the 5C Architecture are outlined in **Table 4.1**. Despite offering an implementation framework for CPS ecosystems and containing valuable guidelines, the 5C model overlooks some fundamental characteristics crucial for its application in the I4.0 context. Primarily, it is imperative to consider the information flow not only vertically but also horizontally between products and machines, where they can be processed by client specifications.

**Table 4.1** Overview of the 5C architecture levels.

| | |
|---|---|
| Connection | Integration of the physical devices connected in a communication network. |
| Conversion | Conversion from monitored device data to information, to understand them and apply to the physical world. |
| Cybernetic | Use of information for the device virtualization. It is also the level responsible for the communication among assets. |
| Cognition | Functions of monitoring and prognostics for failure prediction and maintenance optimization. |
| Configuration | Transmission from the virtual to the physical world makes the machines self-adjusting and self-adaptive. |

Moreover, it is crucial to anticipate a model capable of facilitating connectivity among clients and service providers across industries, as I4.0 services need to be integrated with the Internet alongside controllers, machinery, products, and other objects. These services encompass tasks like inventory management, freight transport requests, and procurement. Through the virtualization of factories, these processes and services can be automated, enabling the emergence of the Internet of Services (IoS), a fundamental pillar of I4.0.

Given that existing I4.0 architectures are not entirely comprehensive within the realm of Smart Factories, additional reference models have been developed to address current needs and establish standardization for I4.0, such as RAMI 4.0 and IIRA. These architectures incorporate CPS concepts, which will be expounded.

### 4.3.2 RAMI 4.0

RAMI 4.0 stands as an Architecture Reference Model for Industry 4.0, conceived through the collaborative efforts of Platform Industry 4.0 to establish communication structures and a standardized language within the factory environment, complete with its vocabulary, semantics, and syntax. This standardized language facilitates the integration of IoT and services within the context of I4.0, linking them seamlessly with the broader world. Functioning as a Service Oriented Architecture (SOA), RAMI 4.0 amalgamates IT components to advance key aspects of I4.0, such as horizontal integration among factory networks and plants, and vertical integration within a factory, spanning from products at one end to the Cloud at the other.

This architecture is depicted through a three-dimensional map comprising three axes, referred to as hierarchy levels, product lifecycle, and architecture layers, providing a structured approach to address Industry 4.0 concerns and ensuring mutual understanding among all stakeholders involved in the manufacturing process. **Figure 4.3** illustrates the three-dimensional model of RAMI 4.0.

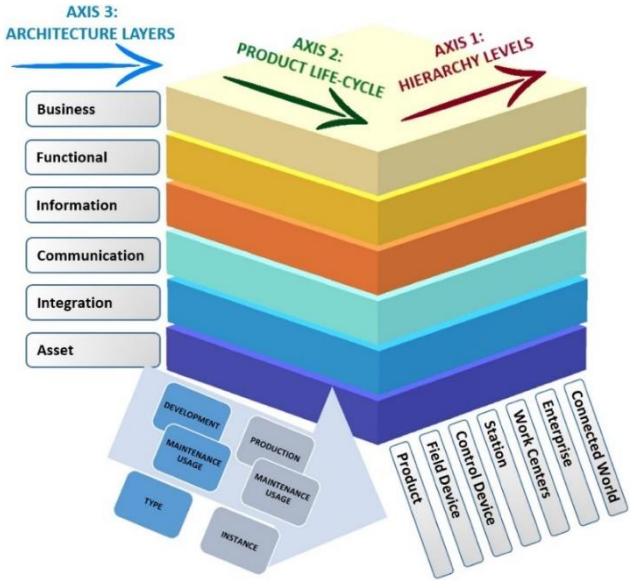


**Figure 4.3** Three-dimensional model of the RAMI 4.0.
[Source: Pivoto, D. G. S., et al. (2021)]

Axis 1, overseeing hierarchy levels, seeks to depart from the Industry 3.0 paradigm, characterized by specialized hardware infrastructure with limited functionalities, hierarchical communication models, and isolated products. In the realm of I4.0, the aim is to promote the concept of flexible machines and systems, with distributed functions across the network ensuring interaction and communication among all stakeholders, while products are viewed as integral components of the architecture.

Axis 2, governing the product lifecycle, delineates assets within the value chain from inception, through development and maintenance, to production, utilization, and upkeep. Assets encompass objects of value to an organization, such as devices or equipment.

Axis 3 is dedicated to the development of the CPS concept, the focal point of this article, and will be elaborated upon subsequently. It encompasses the Architecture Layers of RAMI 4.0, as delineated in **Table 4.2**

**Table 4.2** Overview of the Architecture Layer of the RAMI 4.0.

| | |
|---|---|
| Asset | Representation of physical things in the real world. These things can be components, hardware, documents and human workers. |
| Integration | Transition from the physical to the virtual world. It represents the visible assets and their digital capacities, consequently providing control via computers, making it possible to generate events for themselves. |
| Communication | Standardized communication from services and events or data to the Information Layer, and from services and control commands to the Integration Layer. It focuses on transmission mechanisms, networks discovery and the connection among them. |
| Information | Description of services and data that can be offered, used, generated or modified by the technical functionality of the asset. |
| Functional | Description of the logical functions of an asset, such as its technical functionality, in the context of I4.0. |
| Business | Organization of the services to create business processes and links among different ones, supporting business models under legal and regulatory constraints. |

The vertical axis of the architecture layers serves to depict the physical components of the industrial network under consideration, including devices, equipment, and machinery and correlates them with their corresponding virtual representations known as Industry 4.0 Components (I4.0C), which provide detailed descriptions of CPS properties.

I4.0C are globally and uniquely identifiable objects endowed with communication capabilities, each consisting of an asset and an administration shell (AS) containing pertinent management information. Additionally, they encompass the technical functionalities of assets, housing all relevant data and information. The AS serves as a standardized interface for communication networks, facilitating the connection of physical entities to the I4.0 framework. I4.0C can be associated with assets such as equipment, machinery, or products in the asset layer, while the AS resides in the information, functional, and business layers. For instance, an asset like a machine embodies its physical aspect, while its corresponding AS represents its digital counterpart. Moreover, all administration shells (digital twins) within the system are overseen by a superior system administration shell (SAS), responsible for coordinating their intercommunication.

### 4.3.3 Overview of IIRA

IIRA developed by IIC is an open architecture built upon IIoT standards with a strong emphasis on promoting interoperability among industries. This model is structured around four viewpoints aimed at identifying and categorizing the common concerns of an IIoT architecture. Through systematic analysis and documentation, the model addresses these concerns and produces models and other relevant information associated with each viewpoint.

The four viewpoints are as follows: (i) business viewpoint, (ii) usage viewpoint, (iii) implementation viewpoint, and (iv) functional viewpoint.

- Business viewpoint delineates the participants involved in IIoT systems along with their respective business views, values, and objectives.

- Usage viewpoint outlines the expected functionalities of the IIoT system in fulfilling its intended business objectives.

- Implementation viewpoint identifies the requisite technologies necessary for implementing the functional components, including communication protocols and life-cycle procedures such as topology, structure, and technical distribution and description of components.

- Functional viewpoint zooms in on the functional components and their interrelationships and interactions with both internal and external elements in the environment.

**Figure 4.4** illustrates the architecture of the functional viewpoint, encompassing crosscutting functions and systems characteristics.

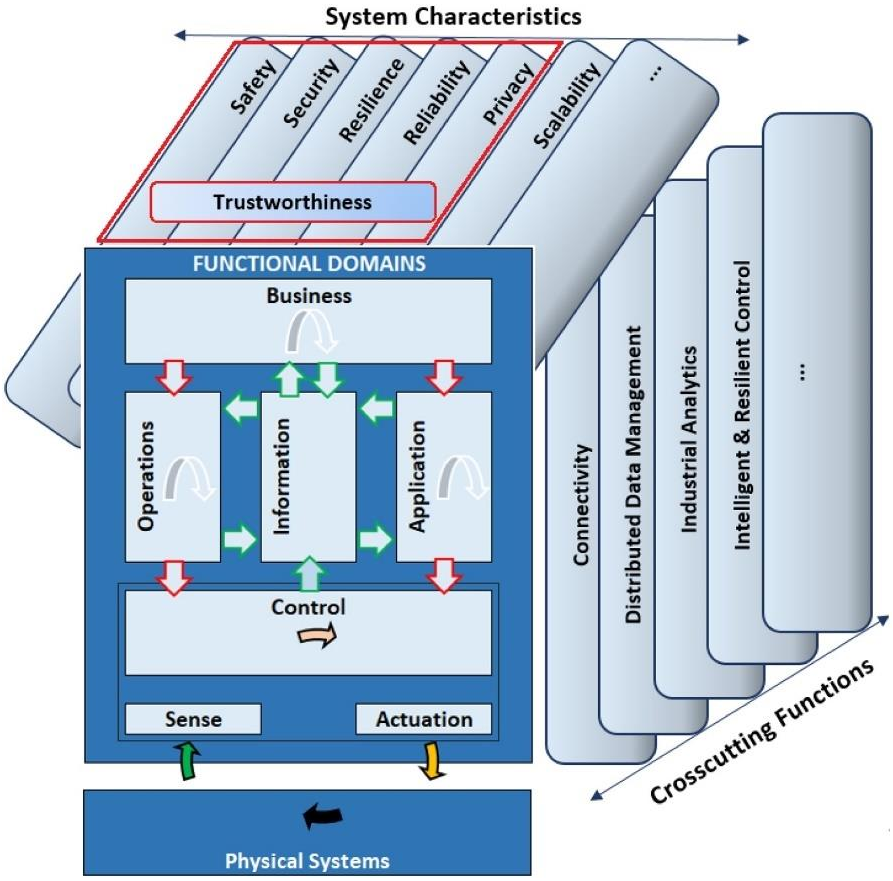


**Figure 4.4** IIRA functional domains, crosscutting functions, and system characteristics. [Source: Pivoto, D. G. S., et al. (2021)]

As depicted in **Figure 4.4**, the functional viewpoint comprises five distinct domains, delineated in **Table 4.3**, namely control, operation, information, application, and business. These functional domains are tasked with elucidating the primary functions of the system. Additionally, there are crosscutting functions aimed at facilitating these domains and system characteristics, which denote the properties or emergent behaviors of the integrated components within an IIRA system. Among the crosscutting functions, the connectivity function plays a pivotal role in establishing connections among the system functions, thereby ensuring seamless interaction and full functionality.

**Table 4.3** The domains of the IIRA.

| | |
|---|---|
| Control | Functions for industrial control systems, such as: the sensor data reading and writing; communication among sensors, actuators, controllers, gateways and other devices; abstraction of the devices through the representation of a virtual entity; interpretation of data collected by sensors and other devices; operation management of control systems, such as configuration and firmware/software updates; and the execution of control logic for the understanding of the states, conditions and system's behavior. |
| Operation | Functions for prognostics, management, optimization and monitoring of the systems in the Control Domain, such as: configuring, recording and tracking assets; management commands transmission; detection and prediction of problem occurrences through real-time monitoring of assets; predictive analysis of IIoT systems based on historical data operating and performance; reduction of the energy consumption for the system optimization. |

**Table 4.3** The domains of the IIRA (cont.).

| | |
|---|---|
| Information | Functions for domain's data collection, and then the data transformation, modeling and analyzing to acquire high-level system-awareness. It includes a set of functions responsible for data collection of operation and sensor states in all domains; and a set of functions for data modeling and analytics. |
| Application | Functions capable of implementing application logic while performing specific business functionalities. This domain applies: a set of rules with specific functionalities required in considered use cases; and a set of functions whose application can expose their functionalities to other applications that consume them; or user interfaces for human interactions. |
| Business | End-to-end operation of IIoT systems, integrating them with specific business functions of traditional or new system types. |

### 4.3.4 Correlation among 5C Architecture, RAMI 4.0 and IIRA

An analysis of the correlation is entailed among the architecture reference models, emphasizing their primary objectives and the interoperability among them. Firstly, it is essential to note that although these architectures incorporate CPS concepts, their objectives vary. The following points outline the primary goals and the envisaged development scenarios for each architecture:

- The 5C Architecture primarily focuses on asset data acquisition and processing, typically utilized in embedded systems and smaller industrial environments. It represents one of the initial CPS architectures disseminated in the literature.

- Developed from the smart grid architecture model (SGAM), RAMI 4.0 aims to adapt CPS architecture to the I4.0 context. It delineates the operational framework for a manufacturing plant, with a strong emphasis on the manufacturing sector and integration throughout the product lifecycle, encompassing the company's value chain.

- IIRA, with its prominent IIoT proposition, is grounded on ISO/IEC/IEEE 42010 standards. It delineates the development of IIoT systems, focusing on various sectors' concerns, including product operation and maintenance, business aspects, and notably, interoperability among industries.

The functional mapping among the 5C architecture, IIRA, and RAMI 4.0 is illustrated in **Figure 4.5**. This figure demonstrates similarities among the architectures, with domains from IIRA mirroring similar functions with the respective levels from the 5C Architecture and layers from RAMI 4.0. Additionally, there exists correlation and interoperability among these reference models.

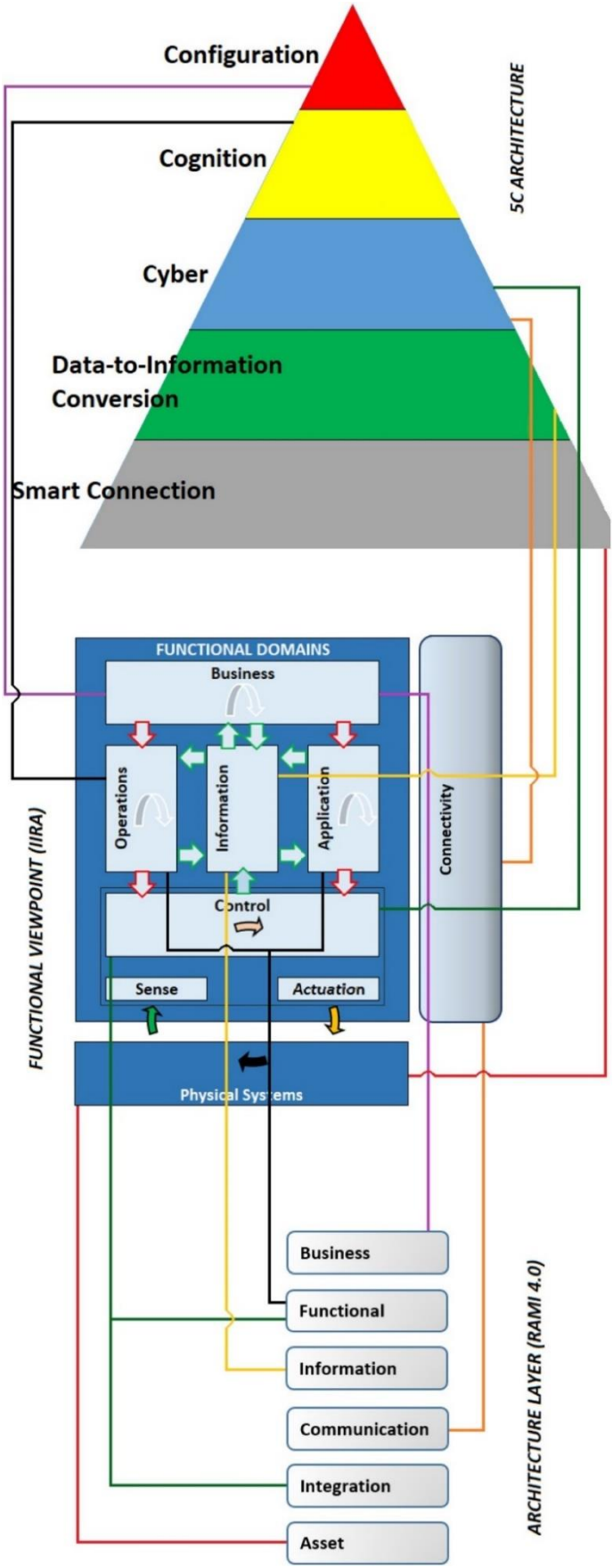


**Figure 4.5** Functional mapping among 5C Architecture, IIRA and RAMI 4.0. [Source: Pivoto, D. G. S., et al. (2021)]

However, RAMI 4.0 and IIRA have garnered more attention in the industrial community because these architectures are primarily focused on I4.0 initiatives, fostering the development of applications, services, and business concepts for inter-industry integration and the broader manufacturing sector. Ensuring interoperability between RAMI 4.0 and IIRA necessitates certain fundamental concepts, including standardized functions and semantics, as well as unique identifiers for properties and assets. Consequently, identification, networking, semantics, and functional mapping emerge as pivotal concepts for facilitating interoperability between IIoT and Industry 4.0 systems. For instance, IIoT systems' (IIRA) operation and maintenance services may require technical data concerning materials, components, and the entire manufacturing process of a product, which are typically available from manufacturers (RAMI 4.0). Standardizing parameters such as these enables both RAMI 4.0 and IIRA architectures to recognize the same product and access its corresponding data, thus facilitating interoperability between the two systems.

### 4.3.5 Standards and Protocols for CPS architectures

This part provides details of industrial standards and protocols utilized in CPS architectures to align with the requirements of I4.0. It also discusses enabling new technologies in legacy systems and addresses system security considerations. **Table 4.4** presents an overview of the standards and protocols commonly employed in CPS architectures, based on the structure of reference.

**Table 4.4** Architecture reference models and related standards and protocols.

| Function description | Architecture reference models | Standards and protocols |
|---|---|---|
| Physical Industrial Asset | RAMI 4.0 Asset Layer<br>IIRA Physical System5<br>C Smart Connection Level | ISO/TS 14649-201, IEC 61360 |
| Virtual representation of assets and functions for industrial control systems | RAMI 4.0 Integration and Functional Layers<br>IIRA Control Domain5<br>C Cybernetic Level | ModBus, ISO 15926, ISO 15746 |
| Standardized communication for data, assets and services | RAMI 4.0 Communication Layer IIRA Connectivity Crosscutting Function 5C Cybernetic Level | FC 2616 (HTTP), IEC 61784, IEC 29182-1, RFC 7540 (HTTP2), TCP, UDP, IP, 6LoWPAN, CoAP, MQTT, DDS, IEC 62541 (OPC UA), Web Services, oneM2M, TSN, 5G |
| Data processing for collecting, transformation, modeling and analyzing | RAMI 4.0 Information Layer<br>IIRA Information Domain<br>5C Data-to-Information Conversion Level | IEC 62714, IEC 24760, ISO 19629 Semantics: SPARQL, RDF(S), OWL, RIF/SRWL |
| Runtime environment for applications, assets technical functionality, in addition to management and maintenance functions | RAMI 4.0 Functional Layer<br>IIRA Application and Operation Domains<br>5C Cognition Level | IEC 62337, ISO 19629 |
| Business functions and support to business models | RAMI 4.0 Business Layer<br>IIRA Business Domain5<br>C Configuration Level | ISO 19439, B2MML, ISO 22400, ISO 13374, ISO 15704 |

Concerning physical devices, ISO/TS 14649-201 and IEC 61360 play pivotal roles in specifying machine description data elements and establishing a framework for defining characteristic properties of industrial components, respectively.

To aid in asset virtual representation, ISO 15926 offers an ontology for planning processes at process plants. For industrial control system functions, the serial ModBus protocol, utilized in programmable logic controllers (PLCs), and ISO 15746 are instrumental in integrating advanced process control for manufacturing systems.

A suite of standards facilitates data processing and conversion from industrial data to information. IEC 24760 defines terms for identity management in information systems, while ISO 19629 structures semantic concepts for capturing and exchanging manufacturing process information. IEC 62714 provides a solution for industrial data exchange in the automation markup language (AML) format. Semantics commonly used in CPS systems for I4.0 include resource description framework (RDF), ontology web language (OWL), SPARQL Protocol and RDF query language (SPARQL), and rule interchange format/semantic web rule language (RIF/SRWL). ISO 19629 and IEC 62337 are recommended for describing asset technical functionality and commissioning electrical, instrumentation, and control systems in the process industry, respectively.

Standards supporting business functions and models encompass ISO 19439 for model-based enterprise engineering, ISO 22400 for key performance indicators (KPIs) in manufacturing operations management, ISO 13374 for condition monitoring and diagnostics of machines, ISO 15704 for enterprise-reference architectures and methodologies, and business-to-manufacturing markup language (B2MML) for linking enterprise resource planning (ERP) and supply chain management systems with manufacturing systems.

Communication standards, delineated according to the ISO/OSI model, include application-level protocols like hypertext transfer protocol (HTTP), HTTP 2, constrained application protocol (CoAP), and message queue telemetry transport (MQTT). Transmission control protocol (TCP) and user datagram protocol (UDP) constitute the transport network, with internet protocol (IP) serving as the common protocol for the network layer. 6LoWPAN facilitates IPv6 over low-power wireless personal area networks while emerging technologies like time-sensitive networking (TSN) and 5G are also noteworthy. Standards such as IEC 61784 and IEC 29182-1 are pertinent for ethernet-real-time-enabled industrial communication networks and sensor network characteristics.

For complete interoperability among function descriptions and protocols, The Industrial Internet Consortium (IIC) identified the data distribution service (DDS), web services, oneM2M, and OPC UA as potential IIoT connectivity core standards. DDS functions as a data-centric middleware standard facilitating connectivity between industrial components, while web services are designed for human-user interaction interfaces. oneM2M enables efficient and secure intercommunication among applications hosted on connected machines, devices, and enterprise systems. OPC UA is considered a core standard for both RAMI 4.0 and IIRA architectures and is essential for CPSs in the I4.0 context.

OPC UA stands as a Service-Oriented Architecture (SOA) communication protocol facilitating data exchange between industrial control systems and enterprise levels, enabling component interoperability as delineated in Table 4.4. Within the architecture reference models discussed earlier, OPC UA corresponds to RAMI 4.0's communication layer, IIRA's connectivity crosscutting function, and 5C's cybernetic level, serving as a crucial technology for ensuring industrial vertical integration and interconnecting the entire CPS architecture.

This platform-independent standard supports communication among diverse systems and devices via client/server or publish/subscribe communication models. In the OPC UA client/server model, communication utilizes OPC UA Binary, OPC UA XML, and JavaScript programming language (JSON) data encoding standards to construct request/response messages. These messages are

transmitted via OPC UA connection protocol (UACP), OPC UA TCP, simple object access protocol (SOAP) over HTTP, OPC UA HTTPS, and web sockets transport protocols depending on the application. Conversely, OPC UA publish/subscribe (Pub/Sub) employs message mappings to define network message structure and encoding, including UADP and JSON as payload representations in transport protocol mappings for publishing messages via OPC UA UDP, OPC UA Ethernet, advanced message queuing protocol (AMQP), and message queuing telemetry transport (MQTT).

For PLC-level applications, OPC UA can be combined with an automation markup language (AML). AML, based on XML, describes data and information exchange, while OPC UA governs the exchange process. AML integrates existing XML data formats like CAEX (IEC 62424) for object topologies, PLC Open XML (IEC 61131) for discrete behavior, and COLLADA (ISO/PAS 17506) for geometries and kinematics. The integration of these technologies follows the DIN SPEC 16592 standard, merging AML engineering data with OPC UA online information.

In scenarios with one-to-many communication, managing the vast volume of resource allocation poses challenges. The OPC UA publish/subscribe specification offers a solution. This specification accommodates data exchange between publishers and subscribers through broker and broker-less concepts, as shown in **Figure 4.6**. In the broker scenario, a middleware acts as an intermediary between publisher and subscriber, facilitating data exchange using AMQP or MQTT protocols. Conversely, in the broker-less scenario, network infrastructure delivers messages via UDP multicast groups, ensuring lower latencies.

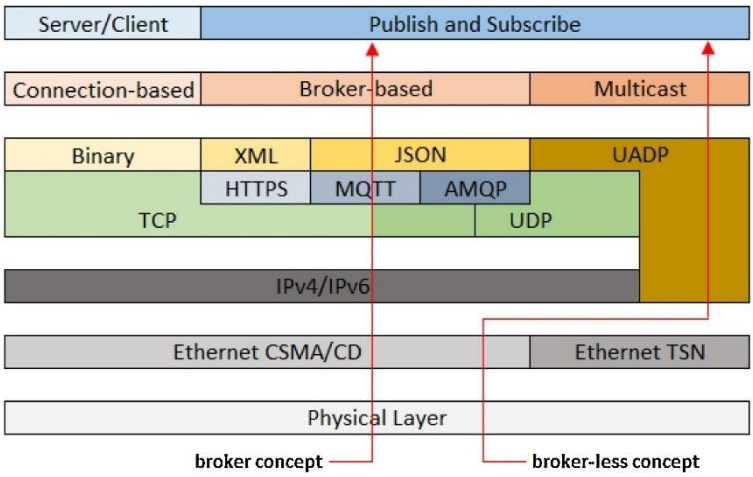


**Figure 4.6** Broker and broker-less concepts for OPC UA Pub/Sub.
[Source: Pivoto, D. G. S., et al. (2021)]

To ensure interoperability among diverse systems, standards, and protocols, gateways are implemented as forwarding components, facilitating the connection of various networks. Typically, gateways are categorized into core gateways, which connect via core connectivity standards like DDS, Web Services, oneM2M, and OPC UA, and non-core gateways, which link specific technologies used in architecture layers to a core connectivity standard.

Core gateways facilitate communication among systems utilizing different core standards in their respective architectures. For instance, in the context of OPC UA, several solutions have been proposed. The Open Management Group (OMG) and OPC collaborate on the development of the OPC UA/DDS Gateway, bridging DDS and OPC UA bidirectionally by mapping DDS to the client/server and lightweight OPC UA UDP Pub/Sub models. Additionally, according to the oneM2M Organization, the interaction between OPC UA and oneM2M can be achieved through the

interworking proxy application entity (IPE), supporting OPC UA interface and mapping OPC UA data models to oneM2M resources. Moreover, OPC UA clients can connect to OPC UA servers via HTTP. On the other hand, non-core gateways encompass commercially available solutions bridging OPC UA with various industrial protocols like ModBus, Profibus, and foundation Fieldbus.

In addition to commercial solutions, the details highlight several research endeavors related to OPC UA gateways, including a universal edge gateway for legacy equipment, smart OPC UA/DDS gateway for interoperability, OPC UA/ModBus gateway for energy recovery system identification, power and cost-reduced OPC UA gateway for IIoT platforms, OPC UA-based gateway supporting different fieldbus protocols, OPC UA gateway solution for the automotive industry, and OPC UA server serving as a gateway for sharing CAN network data.

Despite the benefits of interoperability and the vast data volume of industrial devices connected to the Internet, security emerges as a critical concern within the I4.0 research community. To address this issue, transport layer security (TLS) is widely employed in the industrial environment, ensuring private connections through symmetric cryptography, authentication using public-key cryptography, and reliability through message integrity checks, thus preventing undetected loss or data alteration during transmission.

TLS cryptographic protocol is not only implemented in new technologies like OPC UA but can also be applied to legacy ones such as ModBus TCP. Given that the ModBus protocol lacks a communication validation mechanism between master and slave devices, the inclusion of TLS mitigates this deficiency by preventing attackers from issuing arbitrary commands, offering a robust security solution.

### 4.4 CPSs for Industry 4.0

Based on the reference architecture models for Industry 4.0 and IIoT presented, several works have emerged to develop CPS structures in the factory environment. A thorough analysis of the current industrial CPS works has been conducted to identify their gaps, propose solutions, and offer suggestions for ensuring key features of Industry 4.0.

To select state-of-the-art CPS, the works are extensive literature across various proposes contributing scientific developments related to CPS in the context of Industry 4.0. The exclusion criteria focused on prioritizing CPS works. This timeframe was chosen because the first widespread CPS reference architecture in industrial environments was the 5C Architecture (created in 2013). It allows us to track the evolution of CPS architectures before and after the emergence of these reference models for Industry 4.0.

To narrow on CPS works in the Industry 4.0 context and discuss how they contribute to industrial vertical and horizontal integration, the keywords are employed known as D1-D8 Dimensions. These dimensions encompass various aspects enabling CPS to meet the key features of Industry 4.0. The dimensions are categorized as follows:

**Table 4.5** The D1-D8 Dimensions keywords utilized in I4.0.

| CPS concepts on I4.0 | Dimension | Technology | Description |
|---|---|---|---|
| I4.0 base technologies | D1 | IIoT | IIoT is the infrastructure that allows CPSs to be networked, being an industrial network of unique identifiers assets connected via Internet for exchanging data in real time. |
| | D2 | Cloud Computing | Cloud Computing is used in the I4.0 context for data storage and computing capacity, supporting a more robust industrial system. |
| | D3 | Big Data | Given the emergence of IIoT and a huge volume of networked devices, Big Data is the technology for analysis and interpretation of large volume of data of great variety. |
| I4.0 Vertical Integration | D4 | Semantics | Semantic models offers the access to information in the context of the real world in a consistent way. |
| | D5 | ID/Loc | ID/Loc is a proposal adopted in the IIoT scenario, and consists in how to uniquely identify and locate the assets connected in the network. |
| | D6 | Digital Twins | Digital Twins is a digital abstraction of a physical entity to virtualize assets, working as a detailed simulation of them and allowing to users device acting in the real world through the virtual one. |
| I4.0 Horizontal Integration | D7 | SOA | SOA allows the extension of industrial services concept to clients and servers, and it can be applied for integrating different companies through development of services and applications as cloud services. |
| | D8 | Connectivity | Due to the multitude of IT systems that hamper collaborative efforts and information sharing among companies, Connectivity refers to communication concepts, standards and protocols for reaching the horizontal integration. |

D1 (IIoT), D2 (cloud computing), and D3 (big data) as I4.0 base technologies dimensions, representing technologies crucial for supporting smart factories in the industrial scenario.
D4 (semantics), D5 (ID/Loc), and D6 (digital twins) as dimensions for the emergence of I4.0 vertical integration, encompassing technologies and concepts enabling integration across industrial hierarchical levels. D7 (SOA) and D8 (connectivity) as dimensions for I4.0 horizontal integration, comprising technologies and solutions for digitizing the entire supply and value chain, integrating different companies and clients.

These dimensions evaluate concepts from the perspective of data exchange and collaboration across corporate borders, enhancing the existing IT link between suppliers and customers, which is pivotal for digital information sharing and horizontal integration.

The CPS solution has been proposed as a SOA-based manufacturing resources virtualization model (MRVM) and manufacturing resources service composition. As a result, the project comprises the I4.0 features of manufacturing digitization and details of the implementation process.

The development of the architecture of a domain name system (DNS) has been able to translate unique identifiers (IDs) of physical objects to addresses of objects in the network, providing name resolution to support ID and Locator decoupling, being considered in modern mobility-friendly architectures, such as the MobilityFirst project and NovaGenesis product.

The CPS extension in an embedded system using the Cerebot 23MX7 edge microcontroller as a gateway was developed to connect to the cloud via HTTP and with a coffee machine via controller area network (CAN) communication. An Android application and a website for CPS operation have been created for data exchange with the machine by accessing the cloud via smartphone, making it possible to identify defective or depleted products.

The architecture based on OPC.Net specifications has been proposed, allowing the client to participate in the industrial processes. In addition, a data server module was created for sending and receiving data from the sensor network via Zigbee and Fieldbus in smart buildings and CANopen and Modbus in industrial environments. In addition, a human-machine interface (HMI) application enables customers to read sensor information and send commands. As a benefit, the integration of new fieldbuses into the OPC.Net server did not require an upgrade or recompilation of the entire application.

The CPS-based network architecture has been proposed so that autonomous vehicles could transport electrical devices identifiable via QR Codes to stations named testing areas. The network architecture was divided into the main control network layer for device monitoring based on TCP/IP and UDP and a ZigBee wireless network; the intermediate interaction layer for data communication and multimedia equipment; and the station network layer or accessing the subnets of the various stations to connect to the intermediate layer. The network, based on SOA and Java 2 enterprise edition (J2EE) showed an improvement in electrical equipment detection efficiency.

An approach has been proposed to semantically represent Industry 4.0 device information with an RDF-based administration shell using a uniform resource identifier/internationalized resource identifier (URI/IRI) identification scheme. Unified access to information has been done through SPARQL. A semantic AS from a servo motor controller was generated and intend to expand AS vocabulary to a wider range of devices.

A European project aimed at optimizing and manufacturing asset processes called Cloud Collaborative Manufacturing Networks (C2NET) was proposed for building cloud-enabled tools to

optimize the supply chain of small and medium-sized manufacturing and logistics assets based on collaborative demand, delivery, and production plans. The C2NET is a layered architecture with cloud infrastructure, based on concepts of everything as a service (XaaS), infrastructure as a service (IaaS), platform as a service (PaaS) and software as a service (SaaS). The project has been tested in the automotive, metallurgical, dermo-cosmetic, and original equipment manufacturer (OEM) sectors, proving its efficiency.

A CPS architecture proposed based on the 5C model has been created and tested on a workbench divided into 5 stations with parts production modules: distribution, testing, handling, processing, and classification of parts. Each module consisted of sensors and actuators, a PLC, a local computer for reading data through the Festo Inc. OPC server (Codesys V2.3), and a library of the OPC client for C# available from the OPC Foundation website. Local computers also communicate with the central computer responsible for creating the system virtual model of the system, developed in C# object-oriented language to analyze the conditions of the smart objects, such as actuation failure, usage time, and informing users about maintenance needs.

Based on the 5C Architecture, the framework expanded the knowledge model to an 8C architecture by adding alliance, client, and content guidelines. Alliance is responsible for integrating the value chain and production chain among different parts of production processes; the Client is focused on its participation in the production process, giving rise to quality of service (QoS) improvement services; and the Content allows the extraction, storage, and traceability of the product. The project is beneficial for the development of smart factories.

A novel architecture of a large-scale digital twin platform named uDiT (universal Digital Twin) platform was developed with flexible data-centric communication based on OMG DDS and co-simulation functions based on a functional mockup interface (FMI). The platform has the scheme to abstract devices through the representation of its virtual entity. It also supports data sharing by entities in any format and interworking functions for a large number of digital twins and physical systems.

The SOA in smart manufacturing products have developed for a tool turret. Some services have been developed by OPC UA server, such as discovery, reading, stakeholder link, and subscription creation, using a trial version of a C++ Software Development Kit (SDK). An OPC UA information modeling for customers to data reading and writing has been implemented through the MTConnect standard. The project has been compiled on a Linux-based platform and transferred to a Raspberry Pi for sensor and actuator control. The developed OPC UA server application has been tested by a client, noting factory devices' capacity to describe themselves, their status, and offer their functionalities.

The NodeI4.0 project has been developed, which consists of an embedded prototype capable of adding the 5C architecture smart connection level to any legacy system. The hardware has analog inputs and digital output circuits, as well as an ESP8266-01 module for Internet connection and a PIC18F2550 microcontroller for the transmission of I/O variables from serial communication. A configuration page is generated for activating read and write commands, making it possible to send data to the server via request HTTP protocol. The prototype resulted in efficiency for systems whose response requirement is above 50ms.

A scalable SOA called Cyber-Physical Manufacturing Cloud has been developed, in which every manufacturer in an industry owns machines monitored by controllers that communicate with their local server via TCP/IP and MTConnect protocols. The controllers can also send data to the cloud via HTTP protocol, responsible for communication between the cloud and consumers. The architecture provides cloud services in a pub/sub model, virtualization through web-accessible Representative

State Transfer (RESTful) web services, and applications management for customers to perform cross-platform internet manufacturing operations. Tests with a large-scale operational prototype demonstrated the viability of monitoring and executing cloud operations and manufacturing processes over the Internet.

A European project called Cloud-Based Rapid Elastic Manufacturing (CREMA) has been approached. Its main principles are manufacturing virtualization, interoperability, optimization, and collaboration of cloud manufacturing processes, ensuring the integration of the stakeholders. CREMA incorporates CPS technologies, including support for RDFS and OWL 2 semantics, assets and services abstraction and virtualization, Cloud Computing, and Big Data. The results have been targeted so that manufacturing orchestrations among organizations and integration of distributed resources were allowed, making manufacturing processes more efficient.

The SITCHEN 4.0 framework has been proposed, which is a multi-level, point-of-view engineering method for CPS modeling based on RAMI 4.0 standardization and network semantics. The project describes abstraction levels for CPS embodied in physical and virtual worlds; CPS types represented through views; viewpoints for specifying notations, languages, and model types for constructing a view type; and definition of RDF and OWL network semantic standards to build and represent viewpoints. Models can be transformed into CPS instances and be used as the main application that generates dynamic or on-demand executable code (PLCs) with Industry 4.0 standard interfaces, such as OPC UA, MQTT, AMQP, and PLCopen XML.

The CPS architecture based on the 5C reference consists of 5 modules: Configuration, Intelligence; Cybernetics, Conversion, and Communication. The architecture uses OPC UA protocol via XML and system information management. Tests were implemented in a Smart PD3 industrial teaching plant with a PLC transmitting its data via ModBus TCP/IP and a Raspberry Pi 3 connected to the PLC's ethernet network. In addition, an HTTP standard page was created to publish data containing events such as samples and conditions of equipment running in the plant. The results showed data accuracy.

A SOA architecture for equipment discovery in manufacturing processes has been designed based on the RAMI 4.0 reference model, including AS and unique IDs on devices. It can provide components to enable communication among products and equipment. A web service capable of providing a mechanism similar to the DNS for locating equipment to process is also offered. Based on the RAMI 4.0 model, the architecture was developed using the Production Flow Schema (PFS)/Petri Net (PN) technique and applied in a modular production system, showing its efficiency.

A test-driven resource virtualization framework for smart factories is proposed to create digital twins to easily represent their manufacturing assets. The proposed framework specifies the digital twin hierarchy, the information to be modeled, and the modeling methodology. A case study was performed in an international company to create digital twins for all their manufacturing resources. The obtained results showed that the proposed resource virtualization framework is efficient in virtualizing complex factory setups in cyberspace.

A cloud-based CPS is presented for adaptive shop-floor scheduling and condition-based maintenance. The proposed CPS consists of different modules (monitoring, adaptive scheduling, condition-based maintenance), which have been developed in a cloud environment supported by different I4.0 and IoT paradigms. It can be highlighted the cost-effective monitoring; reliable real-time data collection, processing, and analysis from the shop floor; and an adaptive decision-making system. A real-case study from a high-precision mold-making industry was performed in order to validate the work, proving its efficiency and future works include energy consumption estimation and predictive maintenance planning.

A Cyber-Physical Machine Tools (CPMT) Platform based on OPC UA and MTConnect is proposed for efficient data communication among machine tools and software applications. The method used was based on a generic OPC UA information model for CNC machine tools and the interoperability between OPC UA and MTConnect was reached through an interface capable of transforming MTConnect information model and its data to their OPC UA counterparts. Different applications were developed, such as a conceptual framework for a CPMT-powered cloud manufacturing environment, and results showed that the CPMT Platform can improve production efficiency and effectiveness in manufacturing.

### 4.5 Chapter Summary

Given the significance of CPS architectures developed for Industry 4.0 and their disparities in ensuring interoperability among Cyber-Physical Systems, this chapter conducted an in-depth detail of CPS architecture reference models, their associated standards and protocols, and the interrelations among them, with a focus on IIoT as a primary pillar in the scenario. Additionally, the experimental CPS architecture projects analyzed the architectural dimensions utilized in CPS design while striving to meet the key features of Industry 4.0. The content identified gaps and limitations for enhancing the architectures, along with offering potential suggestions for vertical and horizontal integration of CPS endeavors. Given the importance of industry in the economy, these viewpoints can contribute to the advancement of burgeoning economies, fostering improvements in processes, products, and value generation.

A noteworthy aspect is an imperative need to expand the deployment of cloud computing and big data solutions, particularly in addressing the Industry 4.0 requirements for managing vast data flows generated by swarms of IIoT devices. Furthermore, the introduction of technologies and concepts facilitating both I4.0 vertical and industrial integration, such as semantic-rich orchestration (SOA) and contextualization, ID&Loc splitting, and digital twins for data modeling and device representation based on unique identifiers, is essential. This facilitates the co-creation and co-development of applications and services within company ecosystems. Finally, cybersecurity remains a formidable challenge to ensure the privacy of users and industrial data. It is imperative to incorporate other emerging technologies into the design of Industry 4.0 reference architectures and CPS projects, such as WSN, 5G, blockchain, and the future internet, to ensure that industrial CPSs remain abreast of technological advancements. Additionally, there is a need to explore clearer and more unified standardization solutions capable of ensuring interoperability among different industrial systems.

**Problems**

1. What is the foundation of the cyber-physical system architectures?
2. Describe the 5C CPS architecture model.
3. Give the potential elements of the RAMI 4.0 CPS architecture model.
4. Characterize the IIRA CPS architecture model.
5. Describe the key dimensions of CPS architecture in connection in Industry 4.0.
6. Detail the CPS architecture based on OPC.Net.
7. Explain the CPS architecture based on OPC UA framework.

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# Chapter 5

# Industry 4.0 as a Smart Factory

**Chapter Objectives**

- Learners understand cyber-physical systems architectures for Industry 4.0.
- Learners become familiar with the cyber-physical production systems.
- Learners can describe the cyber-physical production systems for smart factories.

The fourth industrial revolution has been realized through the effective integration of the Internet of Things (IoT) and the Internet of Services (IoS) with other emerging technologies. This achievement has been particularly significant in advancing cyber-physical systems (CPS). In the realm of manufacturing, CPS, in conjunction with existing enabling technologies, acts as a crucial link between manufacturing and information technology (IT), giving rise to smart factories that are reshaping the global market, societal dynamics, and economic development. This transformative process extends beyond traditional industries, bringing improvements in adaptability, energy and resource efficiency, accuracy, reliability, safety, user-friendliness, scalability, and intelligence. However, it requires thoughtful consideration of technical challenges associated with the development of CPSs, including wireless networking, reliability, complexity, security, and data protection, to attain the desired performance levels. Furthermore, the success of this industrial revolution lays the foundation for efficient and strategic management operations. The most notable advancements in computer science, information, and communication technologies are embodied by CPS. These systems comprise collaborative computational entities intricately linked to the physical world and its ongoing processes. They simultaneously provide and utilize data access and processing services available on the Internet. Cyber-physical production systems (CPPS), leveraging advancements in computer science, information, and communication technologies alongside manufacturing science and technology developments, have the potential to drive the fourth industrial revolution, often referred to as Industry 4.0.

## 5.1 Introduction

The progression of Information and Communication Technology (ICT) has introduced several emerging technologies into the manufacturing landscape. The Internet, particularly IPv6, with its expansive address space, facilitates the networking of powerful autonomous smart objects, leading to the convergence of the physical and cyber worlds, forming what is known as a cyber-physical system (CPS). CPS represents large-scale, interconnected, complex, and heterogeneous systems, where operations are monitored, coordinated, and controlled by computing, communication, and components interacting with the physical environment as shown in **Figure 5.1**.

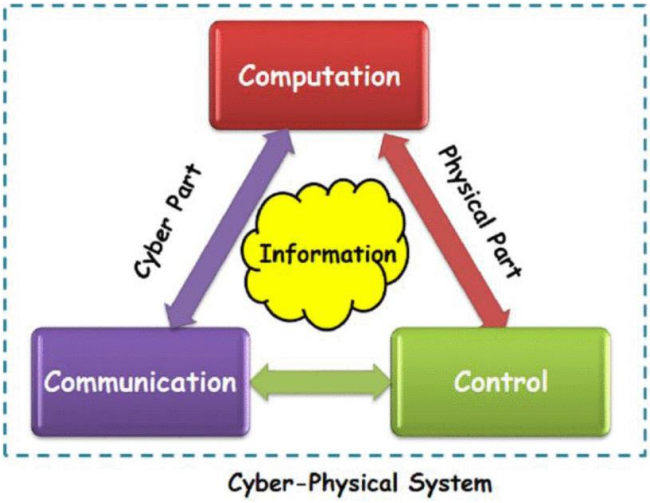


**Figure 5.1** Computation, communication, and control (3Cs) in CPS.
[Source: Sinha, D., & Roy, R. (2020)]

In contrast to traditional standalone embedded systems, CPS focuses on networking multiple devices, allowing physical processes to influence computations and vice versa through a closed-loop feedback control path as shown in **Figure 5.2**. It represents an evolved version of embedded systems capable of transmitting and receiving data over wired and wireless networks, enabling on-demand access, intelligent analysis, and automated tasks from any location.

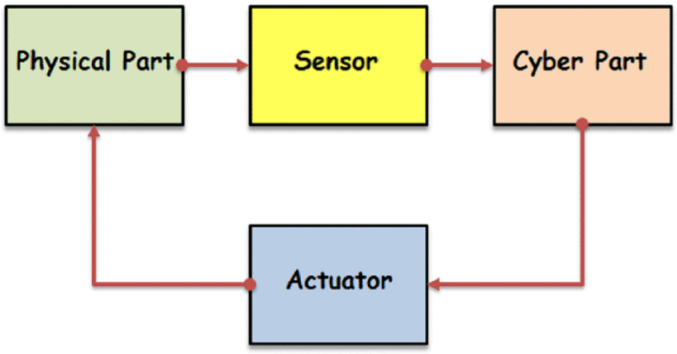


**Figure 5.2** Closed-loop networked control cyber-physical system.
[Source: Sinha, D., & Roy, R. (2020)]

CPS finds applications in diverse domains, promising transformative impacts in areas. While past industrial revolutions have brought advancements, current industries face sustainability challenges, contributing to environmental degradation and energy crises. Additionally, issues like poor adaptability, material waste management, and high production costs hinder organizational growth.

The need for a radical shift towards smart production and resource utilization has given rise to the concept of the smart factory, integrating the virtual and physical worlds through emerging technologies like CPS, Internet of Things (IoT), Internet of Services (IoS), and cloud computing. This has led to the fourth industrial revolution, often referred to as Industry 4.0, driving global initiatives like the "High-Tech Strategy 2020 Action Plan" in Germany and the "Industrial Internet" from General Electric in the USA.

The application of CPS in industrial production systems has resulted in cyber-physical production systems (CPPS), where traditional manufacturing is integrated with intelligent machines and high-

speed processors. This integration enhances fundamental production processes, improves resource usage, and facilitates decentralized decision-making.

However, CPS faces challenges related to the heterogeneity and complexity of its components, necessitating the modeling and analysis of cross-domain interactions. From a managerial perspective, the adoption of CPS in manufacturing infrastructure enhances flexibility, robustness, and adaptability, contributing to value creation, efficient supply chain management, and increased competitiveness.

The realization of CPS-based smart factories requires a workforce and management with the foundational knowledge of CPS and related technologies. Continuous training and awareness programs are crucial to ensuring the proper deployment and maintenance of CPS in industrial environments. Although the adoption of Industry 4.0 practices is progressing, there remains a need for comprehensive training and awareness to bridge the gap between existing technologies and the vision of the fourth industrial revolution.

The tends to focus solely on technical or managerial aspects of CPS-based production systems, but this article uniquely merges both perspectives. It provides operational managers with insights into the structural and operational functionality of CPS in the manufacturing industry.

In contrast to the fixed production lines of traditional factories, a smart factory integrates related corporations, geographically distributed production sites, and a chain of activities such as customer demand, product design, production planning, manufacturing, after-sale services, maintenance, and recycling horizontally, vertically, and end-to-end. This integration occurs seamlessly through the exchange of information and resources. The International Society of Automation (ISA) proposed the ISA-95 architecture, also known as the 5C architecture, to categorize various tasks of Cyber-Physical Systems (CPS) within a smart factory. **Figure 5.3** depicts this architecture and its designated functionalities. The focus of this structure is primarily on the vertical integration of the plant.

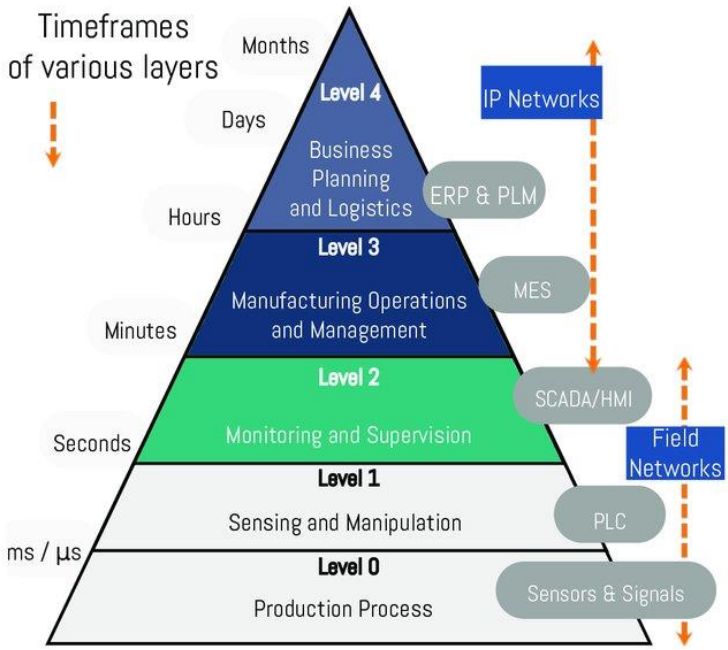


**Figure 5.3** The ANSI/ISA-95 model architecture.

[Source: Katti, B. (2020)]

Subsequently, a modified cyber-physical system architecture to enhance both vertical and horizontal integration in smart factories. This modification involves the addition of three extra facets, known as 3C facets, to the existing 5C architecture. These facets are Coalition, Customer, and Content, as shown in **Figure 5.4**. Coalition integrates the value chain, product chain, and supply chain, facilitating the exchange of production-related information among different parties to collaboratively produce specific products dynamically and timely. The Customer facet incorporates the roles of customers into the production processes of CPS-based smart factories, allowing for the design and development of customized products based on customer orders and feedback. Lastly, the Content facet involves the extraction, storage, and retrieval of all types of product-related data, including product specifications, raw materials used, product storage locations, customer information, and after-sale service records. However, the 8C architecture is suggested to be superior to the 5C hierarchy, particularly for the production of customized products and comprehensive traceability throughout the entire lifecycle of these products.

CPS within the smart factory facilitates communication and negotiation among smart entities, allowing for the reconfiguration of resources in response to changing system dynamics. This reallocation of resources automatically reorganizes the flowline that connects them, resulting in a highly flexible, reconfigurable, and context-aware manufacturing system. Unlike traditional closed systems, the conveyor belt in a smart factory remains open-ended without specific input-output terminals, allowing for easy adaptation to various production routes.

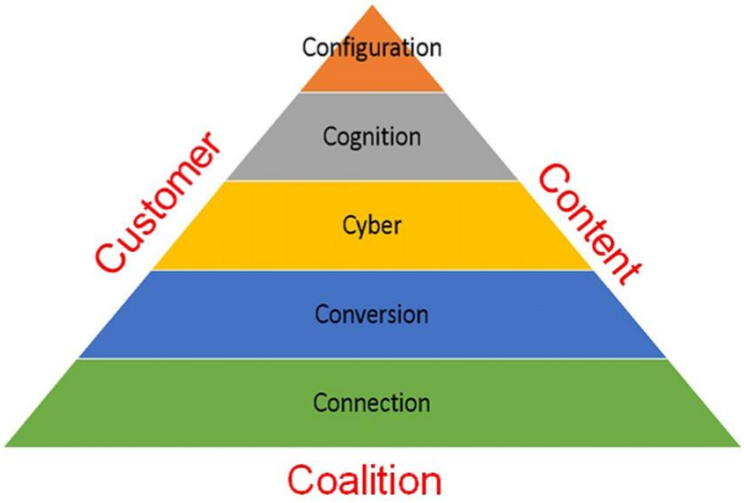


**Figure 5.4** The CPS 8C architecture.

[Source: Jiang, J-R. (2018)]

The industrial CPS within the smart factory forms a closed-loop system comprising supervision, computation, and control. A network of physical artifacts, such as smart products and intelligent machines, is monitored and controlled by logical systems like computers, software, and algorithms. This interaction occurs through a closed-loop networked control system, as illustrated in **Figure 5.2**. The physical and cyber components are interconnected via an Industrial Wireless Network (IWN), supported by the cloud layer. The IWN can rapidly adapt to the dynamic nature of the smart factory, accommodating changes such as the addition of new machines or the replacement of faulty ones through a plug-and-play method. In the smart factory, products are affixed with editable RFID tags containing process requirements, which are updated during production. Machinery and automated

carriers equipped with RFID readers interact with the products, enabling automatic organization of machines and rerouting of the production line.

Contrary to misconceptions, a smart factory does not imply an unmanned workshop. Humans play a central role in the CPS loop, making decisions, optimizing processes, designing and planning, installing and manufacturing, updating, servicing, and maintaining Cyber-Physical Production Systems (CPPS). In smart factories, both computers and humans from geographically distributed areas can participate in different levels of production processes through the Internet and various user interfaces such as computers, laptops, tablets, and smartphones. This collaborative approach, often referred to as social manufacturing, ensures the harmonious coexistence of CPS and human involvement in smart factories.

## 5.2 Smart Factory

### 5.2.1 Achieved Features

The objective of the intelligent factory is to establish extensive, adaptable, robust, reliable, and secure networks of CPSs, addressing inherent challenges to enable flexible, resource-efficient, and profitable on-demand manufacturing. CPSs have the potential to revolutionize our production processes and the manufacturing industry, featuring the following characteristics:

- **Interoperability:** All components and information systems within an individual CPS, as well as across CPSs within the same production plant or different production facilities, can connect, communicate, and exchange information, knowledge, modules, and expertise through high-speed Internet, Industrial Wireless Network (IWN), and the cloud.

- **Virtualization:** Virtual replicas of the physical plant and shop floor are generated and simulated to validate the entire design and manufacturing process. This approach optimizes resource utilization, estimates setup and production costs, assesses risks and environmental impacts, and identifies corresponding safety measures.

- **Modularity:** Modularity involves decomposing system components into smaller, independent yet interlocked subsystems that can be easily and quickly combined or reconfigured using a plug-and-play method. A smart factory should exhibit high modularity, enabling the swift integration of modules to meet manufacturing objectives, produce different products or variants, or scale up production volume. Modularity in a smart factory facilitates real-time responsiveness to changing market dynamics, customer preferences, improved product quality at reduced costs, shorter time-to-market, and overcoming internal system errors and malfunctions.

- **Distributed Control:** In large-scale and complex production processes, central control becomes challenging. Distributed control and coordination involve embedded computers providing cyber capabilities (networking, scheduling, data processing, and computational capacity) in each physical component. This enables independent decision-making and local information exchange to continuously track or update the entire system.

- **Flexibility:** ICT-driven digitization allows virtualization of the entire shop floor, physical processes, and machinery even before they are put into action. Open production lines and integrated organizational hierarchies enhance manufacturing flexibility, enabling companies to respond rapidly and efficiently to dynamic market demands, resource supplies, contemporary challenges, competitions, or last-minute changes in customer orders.

- **Personalization:** Social manufacturing encourages the production of highly flexible, personalized products and services. Human involvement in the design, sale, and production or improvement of on-demand products by providing ideas, opinions, and feedback enhances personalization.

- **Real-Time Response:** Customizing product design and manufacturing processes based on customer demand or swiftly dealing with device inclusion, replacement, or malfunctioning at any point during production is essential for real-time response.

- **Self-Maintenance:** Features like self-learning, self-diagnosis, self-coordination, and self-updating make CPS reliable against disruptions, allowing it to maintain performance or handle faults autonomously.

### 5.2.2 Case Studies

Case 1: BASF SE, a leading global chemical production company, is developing a smart factory prototype under the "German Research Centre for Artificial Intelligence (DFKI)" in Kaiserslautern. This prototype specializes in the production of customized shampoos and liquid soaps. In this innovative setup, each soap container, equipped with an RFID tag, communicates wirelessly with intelligent machines. It provides instructions on the specific type of soap to be produced, including details such as fragrance, color, bottle design, cap color, quantity, and labels. When a customer places an order, the automated factory line dynamically adjusts its protocols to manufacture the unique product according to the online order. The entire setup and manufacturing process are automated, and precise, and result in products of exceptional quality with minimal waste.

Case 2: WITTENSTEIN Bastian's "Future Urban Production" facility in Fellbach, Germany, hosts the "Milk Run 4.0," a prototype of a smart factory focusing on optimizing intralogistics. It achieves this by introducing a demand-driven milk run system between various delivery and pick-up locations, eliminating the need for routine service. In this setup, intelligent product carriers or logistics operators utilize barcodes and scanners to monitor the status, pick-up points, and delivery addresses for orders. Once the order-based customized products are ready for pick-up, these intelligent operators receive notifications and are authorized to collect the workpieces, initiating the milk run as per demand. This approach reduces the frequency of milk runs, decreases delivery times, and alleviates employees from unnecessary and burdensome workloads. This creates a mutually beneficial situation for both customers and the industry, enhancing customer satisfaction while improving vehicle capacity utilization, resource efficiency, environmental sustainability, and cost-effective production and service management.

### 5.2.3 Prospective Benefits

Successful integration of cutting-edge technologies, marked by groundbreaking innovations in the manufacturing industry, brings substantial advantages and business prospects to the industries of the modern era. Key contributions made by smart factories in the context of Industry 4.0 include:

- **Efficient Resource Management:** Smart factories, operating on a demand-driven model, consistently optimize production planning and supply chain management to maximize the utilization of available resources or external services. This strategic approach minimizes the wastage of valuable raw materials and reduces the likelihood of generating hazardous byproducts during manufacturing or mass production. This enhances overall system productivity, making the production process both cost-effective and sustainable.

- **Resilient Manufacturing Processes:** The flexibility of production lines and the intelligence of machinery in smart manufacturing systems create a fault-tolerant and resilient system that can withstand unforeseen events and potential failures. Information sourced from various channels, containing real-time updates on ongoing processes, machine conditions, market demands, and customer feedback, is stored and analyzed for strategic decision-making in the future. Cloud-based data storage allows Cyber-Physical Systems (CPS) or Industrial Internet of Things (IIoT) to monitor, diagnose, predict, and proactively upgrade themselves, ensuring agile and robust production under Industry 4.0.

- **Reduced Human Intervention**: Smart manufacturing, being fully autonomous and self-regulating, operates with minimal or zero manual intervention. This minimizes the occurrence of human errors and their associated consequences throughout the design, planning, and production phases. The reduced reliance on human input decreases the computational and decision-making burden on engineers and management personnel. Furthermore, it liberates labor from arduous routine tasks, enhancing work quality and fostering a harmonious relationship between employees and employers within the smart factory environment.

- **Smart Customized Products:** In a flexible manufacturing environment, smart products are optimally developed by assembling intelligent components, and undergoing thorough testing in laboratories to ensure safety throughout their lifecycle. These products, identifiable by RFID tags, interact with their surroundings, communicate their status at each lifecycle stage, and possess capabilities for data storage, computations, error handling, and self-maintenance. Fully customized, affordable, and high-quality, these products meet the requirements of both the enterprise and the market.

- **Enhanced Customer Experience**: Smart manufacturing systems empower customers, as products are produced based solely on customer demand and feedback. Customers can even alter their orders at the last minute, with manufacturers committed to delivering high-quality end products quickly and with added value, ensuring customer satisfaction. After-sales services, product maintenance, and customer support provided by smart factories are easily accessible and consistently maintain high standards. Additionally, products can be recycled once they are discarded by customers, emphasizing the customer-centric philosophy of the smart factory.

### 5.2.4 Challenges and Solutions

Smart hardware, software, their controller, high-bandwidth Industrial Wireless Network (IWN), cloud computing, and big data analytics are essential components for implementing time-critical and safety-critical Cyber-Physical Systems (CPSs) in the next-generation smart factory. The numerous technical and managerial challenges associated with this implementation and potential solutions are elaborated below:

### 5.2.5 Technical Challenges

- **Intelligent Decision Making and Negotiation:** Cutting-edge research in various branches of Artificial Intelligence (AI) has yielded promising outcomes, such as ontology and the contract net protocol (CNP). Ontology facilitates collaborative problem-solving by sharing knowledge bases, while CNP, a task-sharing protocol in Multi-Agent Systems (MAS), empowers smart machinery to autonomously make decisions and negotiate for the development of intelligent products.

- **High-Speed IWN Protocol:** Uninterrupted, 24/7 connectivity with high reliability is essential for robust and efficient smart factory operations. The evolving 5G technology aims to meet the high-speed Machine-to-Machine (M2M) communication requirements of Industry 4.0. Various technologies like mm waveform, WiFi, optical communication, and MIMO can be employed for reliable, high-data-rate, and low-latency communication. Different standards, such as IEEE 802.15.3, 802.15.4, and modified versions of IEEE 802.11, can be used based on application requirements.

- **Industrial Big Data Handling**: Instead of collecting random data and then filtering them, a predetermined decision on what data to collect, their characteristics, storage location, collection method, and efficient utilization should be made. This proactive approach streamlines the data collection process and enhances the usefulness of the data.

- **Malfunction Restraints:** Monitoring and recording the machine's state, operational history, and task processing times allow for anticipatory problem identification. This information helps in taking preventive measures well in advance, identifying performance limitations, operational congestion, and load imbalances.

- **Cyber-Physical Interface and Control Mechanism**: Formal methods, like model-checking technology employing differential equations and stochastic processes, can be suitable for dynamic modeling and analysis of large-scale, complex, self-organized manufacturing systems. This facilitates appropriate control methods by enabling interaction between cybernetic and physical components.

- **Security:** Security measures, including encryption, authorization, software verification, certification of high-confidence software, high-fidelity simulation, and secure cloud storage, are crucial for smart factory applications. Robust prevention measures are necessary to counteract potential threats like denial of services (DoS), deception attacks, and anomaly-based intrusions.

### 5.2.6 Managerial Challenges

- **Initial Investment:** The incompatibility of new smart factory infrastructure with traditional production systems demands higher efforts and costs for planning and implementation. Challenges include a lack of managerial experience in budget estimation, transparency on standardization, limited cooperation, coordination, openness, and trust among firms, and difficulty in coordinating machinery and supply chain integration. Initiatives to enhance awareness, visibility, and collaboration, along with encouraging high-end research, can help overcome these barriers.

- **Competitive Market Scenario**: Intense competition among companies necessitates embracing technological advancements and improving marketing strategies. The rapid growth of technology and new market entrants pose challenges to small and medium enterprises (SMEs). To survive, companies need to focus on innovations, real-time tracking of market demands, resource availability, and customer feedback, achieved through seamless integration of manufacturing with value chain, service chain, business models, and customer engagement.

- **Value Creation:** Industries are emphasizing value creation to enhance the quality and worth of goods and services. Value creation is vital for gaining a competitive edge. Cyber-Physical

Systems (CPS), along with Information and Communication Technologies (ICT), create a network to produce competitive and fully customized products. Managers focus on efficient, creative, and systematic value creation processes to generate profits for stakeholders.

- **Supply Chain Management:** Smart factories, under Industry 4.0, prioritize a demand-driven supply chain management model, focusing on customer preferences. Challenges include timely collection of orders and feedback, continuous tracking of resource availability, logistics management, and efficient resource usage. Managers employ intelligent tools, such as AI and ML, for digitally modeling initial product design, optimizing resource handling, and monitoring and controlling the interconnected process flow for supply chain management.

- **Unavailability of Skilled Workers**: The transformation in technological paradigms requires structured training for employees in smart factories. Competencies needed include technical, methodological, social, and personal skills. Identifying, recruiting, and employing suitable candidates is crucial. Industry-oriented collaborative research, curriculum revisions, vocational training, e-learning, AI/ML literacy programs, and hands-on workshops are necessary to bridge the gap between education and the requirements of smart factories. Strategic Human Resource Management (HRM) plays a pivotal role in the development and success of companies in this context.

### 5.2.7 Impact

The cusp of a new industrial era is marked by the convergence of modern technologies such as high-speed internet, the Internet of Things (IoT), Internet of Services (IoS), big data handling, cloud computing, and artificial intelligence (AI) & machine learning (ML). These technologies, combined with physical, digital, and biological systems, are ushering in breakthrough innovations through the implementation of Cyber-Physical Systems (CPS) in smart factories under the umbrella of Industry 4.0.

The amalgamation of the physical and cyber worlds is steering manufacturing processes toward a sustainable model, poised to address global challenges and reshape our way of life. This transformation is accompanied by the widespread adoption of emerging technologies across the global manufacturing landscape. Industry 4.0 has become a top priority for many companies and research and development endeavors.

Smart factories, integral to Industry 4.0, empower plant managers with real-time insights into the shop floor. Instant decision-making and task control during production fosters a more flexible, customized, and autonomous manufacturing system. The maturation of research in "Big data" allows for the automated analysis of vast datasets from diverse activities, extracting valuable information without human intervention. This evolution is propelling smarter supply chains, production processes, and products.

However, the advent of intelligent robots potentially taking over human jobs in future factories raises concerns about income inequality and unemployment. The fear of permanent job losses due to automation may result in widespread panic, leading to rumors about wealth concentration at the top, and exacerbating social and economic disparities. The concept of "creative destruction" is met with skepticism by some.

Social manufacturing is anticipated to enhance the competitiveness of the manufacturing industry. The dynamic market necessitates increased flexibility and responsiveness to manage higher product

complexity and global supply chains. Traditional production and logistics processes may become obsolete, triggering societal shifts, including potential challenges in agriculture, migration, and urban overcrowding.

The fundamental question arises: Will Industry 4.0 be a boon or bane, and what measures can be taken to prevent future unemployment? While Industry 4.0 redefines work, workplace environments, health, safety, autonomy, customization, and flexibility, concerns persist regarding its impact on employment. Automation, expected to eliminate low-skilled, repetitive jobs, also promises to create new opportunities, particularly for skilled professionals. Job seekers must adapt to technological advancements to stay relevant, necessitating modifications to institutional structures, practical job-focused education, and encouragement of hands-on experience.

The evolution of Industry 4.0 is a dynamic process. Developed countries lead the industrial revolution, with developing nations following suit. The initial focus is on enhancing labor expertise, increasing productivity, reducing production costs, and addressing societal challenges. Thoughtful solutions to these challenges present immense opportunities for global business growth. The success of Industry 4.0 is contingent on navigating the complexities of the labor market and fostering cooperative partnerships among various stakeholders.

## 5.3 Cyber-physical systems in manufacturing

### 5.3.1 Technological Advancement and Management

A smart factory represents a fully integrated and collaborative system that dynamically adapts to the factory environment, supply network, customer demands, and market scenarios in real time. The development process within this environment involves numerous technical and managerial steps. Various emerging technologies such as IoT, IoS, wireless sensor-actuator networks, data mining, big data handling, cloud computing, edge computing, 5G/6G communication, AI, ML, multi-agent systems, advanced robotics, blockchain, 3-D printing, virtual and augmented reality, and digital twins are key components of Industry 4.0. Their integration in industrial automation leads to machine-to-machine interaction, cyber-physical production systems, smart factories, smart products, and transformative changes in e-commerce, business development, and marketing within the manufacturing industry.

Smart machines, enabled by powerful computers and AI, emerge as autonomous, highly flexible, self-organized, and reconfigurable manufacturing systems resembling humanoid intelligence. In Industry 4.0, cloud-assisted industrial wireless networks support the production-oriented cyber-physical system, connecting smart artifacts and the Internet. These artifacts communicate to create a dynamically reconfigurable and self-organized system adaptable to various customized product types. Cloud computing, with virtualized server-network resources, offers scalable storage and computing power. As intelligent manufacturing generates substantial data, big data analytics in the cloud aids in data synchronization, proactive diagnosis, operational predictions, production process improvement, supply chain analysis, and product quality maintenance. This enhances the efficiency of production machinery, resource utilization, energy conservation, and after-sale services.

Numerous information systems and cognitive components connected to a common cloud form the basis of the Internet of Things (IoT) and Internet of Services (IoS). IoT enables interaction among various devices through RFID, digital addressing schemes, facilitating system-wide coordination, improved decision-making, and process optimization. In Industry 4.0, the smart factory implements a production-oriented CPS, integrating machines, production activities, warehouses, logistics, and social requirements through emerging information technologies to establish IoT and IoS. In addition

to technical advancements, managers play a crucial role in CPS-based smart factory systems. They inform top-level management and stakeholders about technological advancements, convince them to invest in Industry 4.0 compliant organizations, and manage knowledge, funds, resources, and waste materials. Managers oversee customer demands, efficient production systems, product safety and quality, time-to-market, and after-sale services. They act as intermediaries between the factory and customers, ensuring employee welfare, providing continuous training, and strategizing for new value creation and supply chain management. Overall, CPPS in the smart factory integrates business and engineering domains, operating in an adaptable, resource-efficient, and environmentally friendly manner. This not only impacts the industry but also transforms our networked lives and work methodologies.

### 5.3.2 Interaction between CS, ICT, and Manufacturing Automation

Examining the evolution of computer science, information and communication technologies (ICT), and manufacturing science and technology reveals a parallel progression as illustrated in **Figure 5.5**. Advancements in computing paved the way for the numerical control of machine tools and robotics, with the microprocessor serving as the cornerstone of computer numerical control (CNC) systems. Additionally, the application of computer graphics gave rise to computer-aided design (CAD) systems. The integration of computer networks became indispensable for modern manufacturing systems, particularly computer-integrated manufacturing (CIM) systems, which relied on database storage. Innovations in artificial intelligence (AI) and machine learning (ML) significantly contributed to the development of intelligent manufacturing systems (IMS). Robotics benefited from computer vision algorithms for environment and object recognition tasks. The advent of the Internet revolutionized collaboration among humans, between humans and systems, and between different systems, facilitating concepts like concurrent engineering (CE), extended enterprises (EE), supply chains (SC), and production networks (PN).

The application of multi-agent systems facilitated agent-based manufacturing and holonic manufacturing systems (HMS). Wireless communication, sensor networks, and the Internet of Things (IoT) enabled the development of high-resolution manufacturing systems and tracking solutions in production processes. Embedded systems played a crucial role in implementing smart automation solutions and product-service systems, while semantic web solutions promoted interoperability in manufacturing. Cloud computing introduced cloud services for manufacturing through the use of ontologies, while grid computing led to grid manufacturing. The advancements in computer science and ICT significantly contributed to advancements in production. However, this progress was not unilateral, as the complexity and importance of production presented new challenges for various disciplines. This interplay between disciplines led to a convergence between the virtual and physical worlds, shown in **Figure 5.5**, inspiring further innovation and development.

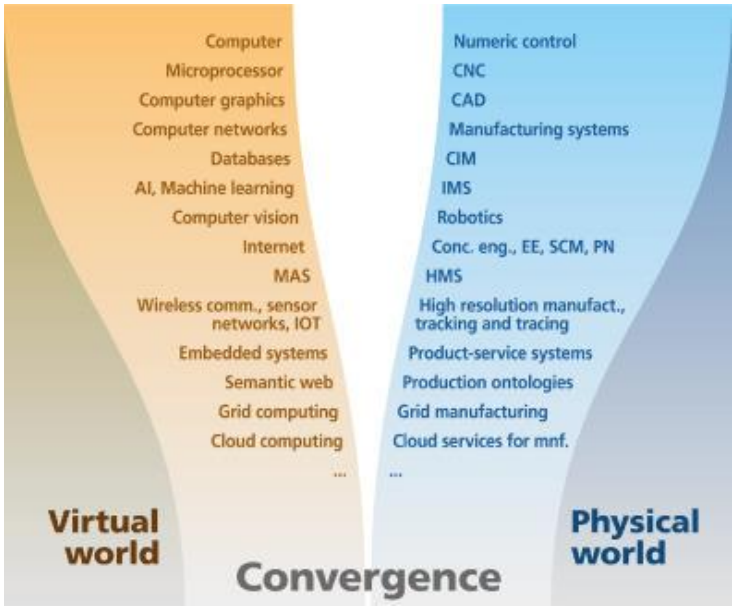


**Figure 5.5** Interplay between CS, ICT, and manufacturing.
[Source: Monostori, L., et al. (2016)]

### 5.4 CPPS Architecture

CPPS comprises autonomous and cooperative components and subsystems interconnected based on contextual relevance across all production levels, spanning processes, machinery, and production and logistics networks. Three primary characteristics distinguish CPPS:

- Intelligence (smartness): CPPS elements possess the capability to gather information from their environment and operate autonomously.
- Connectivity: CPPS exhibits the capacity to establish and utilize connections with other system elements, including humans, for cooperation and collaboration, as well as access to knowledge and services accessible on the Internet.
- Responsiveness to internal and external changes: CPPS demonstrates agility in adapting to changes occurring within the system and in its external environment.

Modeling the operations and predicting the emergent behavior of these systems present a range of fundamental and application-oriented challenges, particularly concerning the control of various system levels. The central question revolves around exploring the relationships among autonomy, cooperation, optimization, and responsiveness.

The integration of analytical and simulation-based approaches is poised to become increasingly significant. Addressing the challenges of managing sensor networks, handling large volumes and high rates of data, and addressing issues related to information retrieval, representation, and interpretation, with a focus on security considerations, is essential. Additionally, novel methods of human-machine communication must be developed to establish CPPS effectively.

CPPS represents a departure from the traditional automation pyramid paradigm. Even predating Industry 4.0, highlighted how the automation pyramid, which previously defined industrial and automation IT architecture, is transitioning towards a new architectural model.

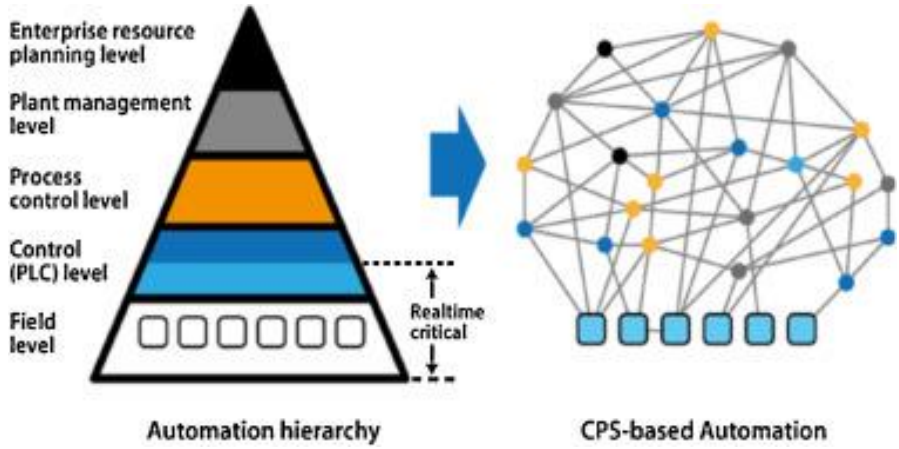


**Figure 5.6** ISA-95 as a 5C architecture for industrial cyber-physical system.

[Source: Monostori, L., et al. (2016)]

With CPS having progressed further, while the traditional control and field levels persist, featuring common PLCs near technical processes to ensure optimal performance for critical control loops, a more decentralized operational approach characterizes CPPS at higher levels of the hierarchy as depicted on the left side of **Figure 5.6**.

The core assumption, namely that a CPPS comprises two primary functional components, is visually represented on the right side of **Figure 5.6**. The lower component is tasked with advanced connectivity, facilitating real-time data acquisition from the physical realm and information feedback from the cyber domain, while the higher-level component encompasses intelligent data management, analytics, and computational capabilities that form the cyber domain.

The 5C architecture delineates five levels in a sequential workflow manner, illustrating the construction of a CPPS from initial data acquisition through analytics to final value creation as shown in **Figure 5.7**. Additionally, the figure provides examples from the realm of process, machine, or system-level monitoring. In a CPPS framework, the smart connection level (Level 1) embodies the physical space, while Levels 2-4 represent the pure cyber domain, and the configuration level (Level 5) facilitates feedback from the cyber domain to the physical realm.

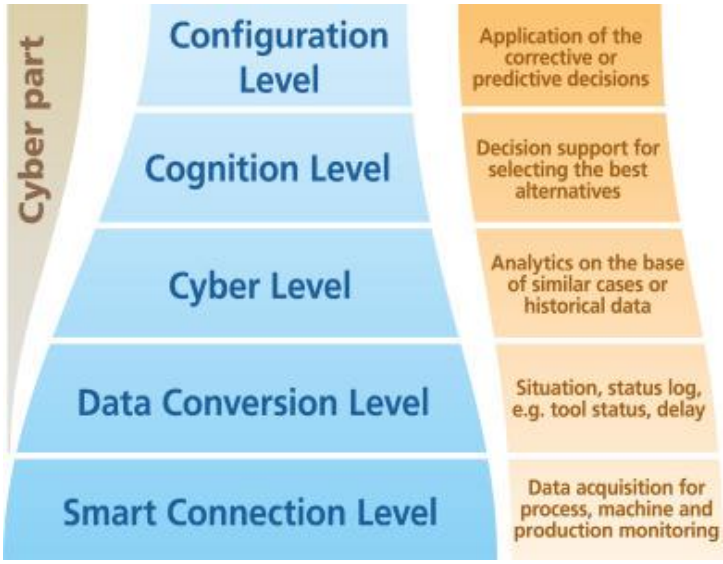


**Figure 5.7** 5C architecture for implementation of CPPS.

[Source: Monostori, L., et al. (2016)]

CPPS holds a particularly prominent and central position. The strategic initiative Industry 4.0 underscores Germany's status as having one of the most competitive manufacturing industries globally and being a leader in the manufacturing equipment sector. The implementation of three key features of Industry 4.0 was prioritized: Horizontal integration through value networks, end-to-end digital integration of engineering across the entire value chain, and vertical integration and networked manufacturing systems.

### 5.4.1 CPS and CPPS as fundaments for Industry 4.0

Anticipations for CPS are diverse, and occasionally overstated, including robustness across all tiers, self-organization, self-maintenance, self-repair, self-X capabilities, safety enhancements, remote diagnosis capabilities, real-time control functionality, autonomous navigation capabilities, transparency improvements, predictability enhancements, efficiency optimizations, and model correctness.

Through CPS, the anticipation is for the emergence of new business models and services that could potentially revolutionize various aspects of our lives. The potential application areas are vast, including air and ground traffic, discrete and continuous production systems, logistics, medical science, energy production, and the infrastructure that surrounds us, among others. By leveraging cyber-physical approaches, these advancements could lead to the development of smart cities, production, communication, logistics, and energy systems, as well as smart homes, ultimately contributing to an enhanced quality of life. In the context of creating a new quality of life, one might refer to the concept of a cyber-physical society, which encompasses not only the physical and cyber spaces but also human, social, and cultural spheres.

Many envision CPPS as the catalyst for the fourth industrial revolution. The first industrial revolution was marked by the invention of the first mechanical loom in 1764, the second by the Ford assembly line in 1913, and the third by the introduction of the first PLC in 1968. It is anticipated that CPPS could usher in a similar transformative leap forward as these breakthrough inventions.

Industry 4.0 represents a new approach to organizing and controlling entire value-adding systems, as illustrated in **Figure 5.8**. The primary objective is to meet individual customer needs while maintaining the efficiency of mass production. As such, it impacts all areas, from order management and research and development to manufacturing, delivery, and the recycling of produced goods. The digitization of production, facilitated by cyber-physical production systems, forms the foundation for these new opportunities. Therefore, all involved resources, including workers, products, resources, and systems, need to be integrated as smart, self-organized, cross-corporate, real-time, and autonomously optimized entities.

**Figure 5.8** Industry 4.0.

[Source: Monostori, L., et al. (2016)]

In the context of global supply networks, machinery, warehousing systems, and production facilities are evolving into CPPS. These systems will interact autonomously, exchanging information and controlling each other independently within what is termed a smart factory. Smart factories offer numerous potentials, such as the ability to fulfill individual customer requirements, manage dynamic business and engineering processes, and optimize decision-making processes. Following the principles of Industry 4.0, the productivity and efficiency of resources can be continually enhanced. Ultimately, Industry 4.0 enables companies to develop new avenues for value creation and innovative business models.

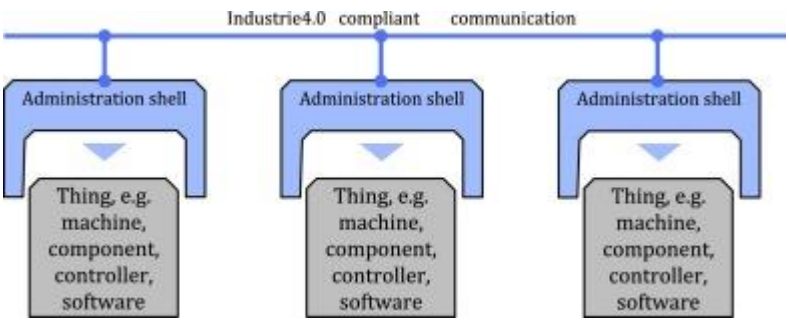


**Figure 5.9** I4.0 component.

[Source: Monostori, L., et al. (2016)]

One development in CPS within manufacturing is outlined in the standardization documents of the national Industry 4.0 platform, known as the "I4.0-component." This concept describes an object

paired with an administration shell, which transforms it into an intelligent object as presented in **Figure 5.9**.

This explanation leads to a globally distinctive virtual depiction of various types and instances of objects. These I4.0 components are depicted within a reference architecture and interact with one another through communication that adheres to I4.0 standards. The standardization process in Germany is still in progress, with the I4.0 concepts being aligned with existing standards.

### 5.4.2 Roots of CPPS in Manufacturing

Many revolutions are notable precursor events that foreshadow significant changes. Several past advancements in manufacturing will be outlined as the foundations of CPPS, with a particular focus on findings reported by the International Academy for Production Engineering (CIRP).

The concept of Intelligent Manufacturing Systems (IMS) was introduced in a speculative prediction. In another, IMSs were delineated as the subsequent generation of manufacturing systems that, drawing on findings from artificial intelligence (AI) development, were anticipated to address previously unforeseen challenges using incomplete and imprecise information. Machine learning (ML) methods were identified as pivotal in this context. The utilization of pattern recognition techniques, expert systems, artificial neural networks, fuzzy systems, and hybrid AI approaches in manufacturing was seen as sequential components of a process. Additionally, agent-based (holonic) systems were highlighted as promising tools for managing complexity, changes, and disruptions in production systems.

While the earlier concept highlighted the intelligent nature of such systems, the World-wide IMS Programme adopted a more expansive perspective. It aimed to establish the foundation of manufacturing science and technology for the next century through extensive international cooperation. To effectively recognize various situations occurring during production, the implementation of sensing, multisensory integration, fusion techniques, and suitable monitoring solutions at the process, machine, and system levels is essential. CIRP has a rich tradition in this critical area, regularly presenting the latest advancements and research challenges, particularly in closely related mechatronic systems for machine tools.

The concept of Biological Manufacturing Systems (BMS) aims to address dynamic changes in external and internal environments throughout the product lifecycle, drawing inspiration from biological principles such as self-growth, self-organization, adaptation, and evolution. The models of BMS at the operational level focused on system reconfiguration. Computer simulations utilizing the principle of self-organization demonstrated that the proposed model exhibited adaptive behavior in response to changes in product demand caused by external factors and malfunctioning manufacturing cells as internal factors, offering the potential for dynamic reconfiguration of manufacturing systems.

Reconfigurable Manufacturing Systems (RMS) offer the advantage of providing precisely the required capacity and functionality precisely when needed. As a result, an RMS can function as both a dedicated system and a flexible one, transitioning between the two as required. Compared to flexible manufacturing systems, RMSs are more effective in supporting the introduction of new system elements and modifying existing ones. Additionally, RMSs can rapidly integrate new technologies and functions.

Beyond the evident economic advantages, considering the pressing demands for environmentally and health-conscious manufacturing practices, reconfigurability can be viewed as a critical feature for production enterprises. The notion of the Digital Enterprise or Digital Factory, which involves digitizing a majority of technical and business processes is considered a fundamental requirement

for enabling control decisions. However, to effectively manage the high dynamics inherent in processes and demand, real-time feedback from production is essential. Addressing these challenges involves tightly integrating the digital and physical realms and incorporating data mining procedures. Models based on discrete event simulation (DES) of production can be utilized in various operational modes as depicted in **Figure 5.10**:

- Offline validation involves conducting sensitivity analyses of schedules against uncertainties before execution (a).
- Online anticipatory recognition aims to identify deviations from planned schedules by running simulations in advance for short-term actions, supporting situation recognition and proactive operation (b).
- Online analysis of potential actions and minimizing losses post-disturbance constitutes reactive operation (c).

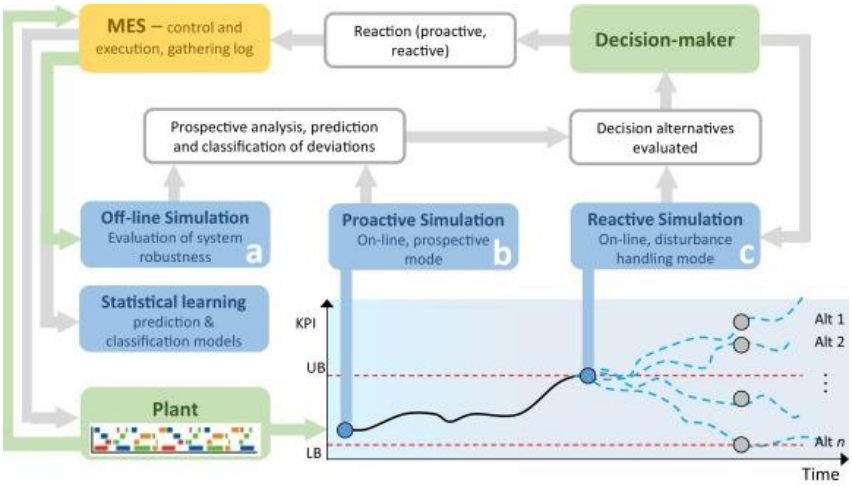


**Figure 5.10** Plant-level active disturbance by reactive & proactive operation modes of simulation.

[Source: Monostori, L., et al. (2016)]

The Holonic (or agent-based) manufacturing systems (HMSs) are comprised of autonomous, intelligent, flexible, distributed, cooperative agents or holons. The PROSA reference architecture for HMSs as depicted in **Figure 5.11** identifies three fundamental types of holons: resource, product, and order holons. Additionally, staff holons are envisioned to support the basic holons in carrying out their tasks. PROSA, enhanced with coordination and control mechanisms inspired by natural systems (such as food foraging behavior in ant colonies), ensures that process plans are executed effectively under changing conditions, while continuously predicting the workload of manufacturing resources and lead times of products. This design empowers product instances to autonomously drive their production, allowing for decentralized coordination. Unlike many decentralized setups, the manufacturing execution system (MES) anticipates future behavior and takes proactive measures to prevent impending issues. Therefore, one of the most promising aspects of HMSs is their ability to bridge the gap between fully hierarchical and heterarchical systems. Agent-based approaches offer a natural means of implementing Cyber-Physical Production Systems (CPPS).

In assembly systems, autonomous processes also rely on agents. These approaches support the realization of plug-and-produce (Plug-and-Work) production systems, where various elements are seamlessly integrated into a complete production system without requiring manual configuration

efforts. The primary objective of these developments is to establish an easily manageable agent platform that provides guidelines and enables a rapid, platform-neutral implementation of agent technology.

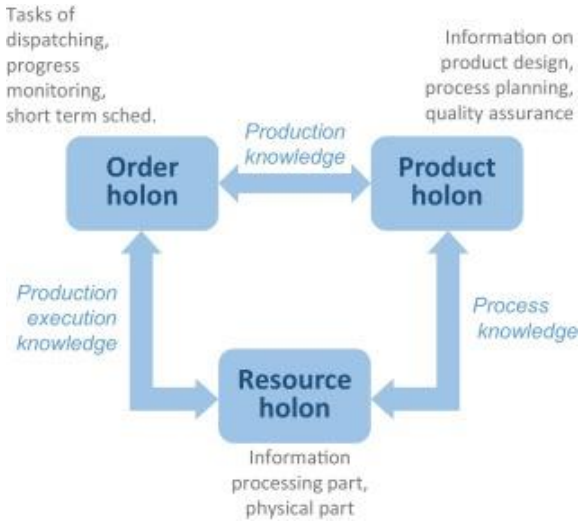


**Figure 5.11** The PROSA reference architecture.

[Source: Monostori, L., et al. (2016)]

Gentelligent components possess the capability to collect information throughout their lifecycle and store and communicate this data. The term "gentelligent" is derived from "genetic" and "intelligent", indicating components with genetically intelligent properties akin to biology. The genetic information of a component includes fundamental data necessary for identifying or reproducing a component, such as geometric descriptions or material data. This information is stored in the component as static, unalterable data and can be inherited from a previous component generation. Additionally, the components contain manufacturing data which may be augmented by quality data. The intelligence of a gentelligent component arises from its technical ability to autonomously collect data during utilization, such as forces and temperatures, and process and store them. This is achieved by integrating appropriate materials and sensors into the component. All data stored in the component can be communicated to the user on demand or read out when the component is disassembled or replaced. The collective data is inherently linked to the gentelligent component and can be recalled at any time. Thus, the gentelligent component is characterized by inherent sensory properties and the ability to store and communicate component-specific data.

With the emergent synthesis methodologies for manufacturing, environmental conditions change due to agents' interactions as they compete or cooperate for the same resources or to achieve a given goal. This interaction alters the behavior of the agents themselves. Complex Adaptive Systems (CAS) exhibit highly structured collective behavior over time through the interaction of simple subsystems, often without centralized control. Key characteristics of complex adaptive systems include dynamics involving interrelated spatial and temporal effects, correlations over long length- and time scales, strongly coupled degrees of freedom, and non-interchangeable system elements. Both the CAS and its environment co-evolve to maintain a state of quasi-equilibrium, on the edge of chaos.

Designing CAS presents challenges such as nonlinear phenomena, incomplete data and knowledge, combinatorial explosion of states, dynamic changes in the environment, and the frame problem. The central issue is creating an artefactual system that achieves its purpose in unpredictable conditions. Addressing such problems solely with existing principles like analysis and determinism proves difficult.

Synthesis constitutes a crucial aspect of problem-solving processes throughout the lifecycle of artifacts, commencing with design, traversing phases of planning, production, consumption, and culminating in product disposal. Emergence assumes a pivotal role in addressing challenging problems encountered during synthesis. A primary concern pertains to the attainment and timing of completeness in the description of the environment and specification of the artefactual system's purpose. Difficulties in synthesis, stemming from incomplete information regarding the environment and/or specification, can be classified into three categories:

- **Class I:** Problems with complete description: In scenarios where all information regarding the environment and specification is provided, the problem is fully described. Nonetheless, finding an optimal solution can be challenging.
- **Class II:** Problems with incomplete environment description: While the specification is complete, information about the environment is lacking. Since the problem remains incompletely described, managing the dynamic properties of the unknown environment proves challenging.
- **Class III:** Problems with incomplete specification: In this case, both the environment description and the specification are incomplete. Consequently, problem-solving initiates with an ambiguous purpose, necessitating significant human interaction.

When delving into CPPS and its implementation, one inevitably confronts Class II and Class III problems.

The concept of Changeable Production Structure recognizes that as manufacturing firms become increasingly interconnected globally and market dynamics evolve, the entirety of the factory must be taken into account, including assembly, logistics, and even the site and buildings. Within this context, the term “changeability” serves as an overarching concept encompassing various types of flexibility across different levels and aspects of a factory.

The notion of co-evolution of products, processes, and production systems represents a significant paradigm shift. It acknowledges the continuous challenges manufacturing entities face due to constantly changing external factors, such as new regulations, materials, technologies, services, communication methods, and escalating pressures on costs and sustainability.

The increasing complexity of manufacturing, technological advancements, and market uncertainties resulting from globalization have become fundamental residues of contemporary industrial landscapes. With the advent of CPPS, complexity management in engineering and manufacturing is poised to gain greater importance. This entails addressing how to mitigate the negative impacts of complexity while leveraging its positive aspects.

Industrial Product-Service Systems (IPS2), also known as hybrid products, represent a concept that acknowledges the dynamic interplay between products and services throughout the product lifecycle. Smart products, empowered by CPS technologies, epitomize the next generation of intelligent, agile, flexible, and networked products.

Open-architecture products (OAP) introduce a novel product class featuring a fixed platform and interchangeable modules. Customers can tailor OAPs to their requirements by integrating modules

into the platform. Realizing open products necessitates the development of cyber-enabled tools that provide design interfaces and methods to manage user participation while ensuring product quality and safety.

Cloud computing is poised to play a crucial role in actualizing CPPS. Cloud-enabled prognostics for manufacturing are particularly promising, as they facilitate the timely acquisition, distribution, and utilization of information from machines and processes across geographical boundaries. Effective prognostics can enhance accuracy and reliability in predicting resource requirements, maintenance schedules, and equipment remaining service life.

Legacy systems pose challenges to the incremental implementation of CPPS solutions in existing manufacturing systems or the transition of traditional systems to become Industry 4.0 ready. Similar challenges emerged with the introduction of the holonic approach. The concept proposes a communication gateway and information server to integrate production systems into an Industry 4.0 environment, even in the absence of Industry 4.0 interfaces at the time of their manufacture.

The manufacturing landscape is succinctly captured which introduced the concept of Cooperative and Responsive Manufacturing Enterprises (CORME). Alongside this analysis, the output provides practical insights into the potential and challenges of adopting the CPS approach in production.

Manufacturing operations are no longer conducted in isolation; instead, enterprises must navigate dense networks of interactions with both their counterparts and their socio-ecological surroundings. Moreover, they must continuously reconcile the divide between their perceptions of reality and the actual circumstances they face. In essence, enterprises must rely on a model of reality while constantly refining and adapting that model.

The main challenges are substantial, as they arise directly from the inherent conflicts between competition and cooperation, local autonomy and global coordination, design, and emergence, planning and adaptability, as well as uncertainty and the abundance of information. It becomes clear that balanced resolutions consistently emphasize cooperation and responsiveness. It was underscored and substantiated through a series of industrial case studies that research in production engineering must incorporate findings from related disciplines and leverage a wide array of contemporary information and communication technologies. Collectively, this approach enables the effective facilitation of cooperation and responsiveness, which are crucial for fostering competitive and sustainable manufacturing.

### 5.5 Chapter Summary

In Industry 4.0, the manufacturing industry is poised for a significant transformation, presenting numerous challenges in adopting smart and eco-friendly practices to meet the global demand for cost-effective, customized, and high-quality products. The concept of smart manufacturing finds its realization through industry-centric Cyber-Physical Systems (CPS) within the framework of Industry 4.0. Leveraging emerging information technologies, CPS is integrated into smart factories, enabling smart artifacts to communicate and adapt dynamically for flexible and sustainable production of various customized products. Industrial Big Data, collected from a multitude of geographically distributed smart objects, is relayed to the cloud layer via the Industrial Wireless Network (IWN). Effective analysis and processing of this big data emerge as the cornerstone for Industry 4.0, facilitating system-wide communication, coordination, prediction, and control. This leads to optimized resource utilization, enhanced system performance, improved production efficiency, superior product quality, and profitable business development. Consequently, traditional work

patterns and protocols are undergoing evolution or complete transformation, necessitating a workforce with explicit skills and training, thereby opening avenues for new job types.

Despite the initial challenges such as technical complexities, a shortage of skilled workforce, and potential social unrest during the implementation of smart factories, these issues can be resolved through the application of existing technologies, coupled with induced technical advancements and the growth of industry leaders. Engineers and researchers are diligently working to comprehend the dynamics of smart manufacturing, contributing new technical inventions to bridge the gap between theoretical concepts and practical applications. It identifies and addresses the shortcomings in existing business strategies and human resources, motivating employees and shareholders to embrace the positive aspects of technological transformation. Customer behavior is a pivotal factor influencing the survival of any industry, necessitating a clear understanding of target clients by top management before establishing smart factories. Initiating value creation and feedback collection on products even before their launch is crucial.

Despite drawbacks and controversies, the application of CPS in manufacturing has far-reaching implications, extending beyond the industrial framework to impact human lifestyle, education systems, social norms, communal development, economic growth, and the environment. To prepare factories for Industry 4.0, it is imperative to address crucial issues such as managing CPS connectivity and interface handling, Industrial Wireless Network (IWN) design, tactile internet, informatics, big data analytics, cloud and edge computing, virtual reality, blockchain technology, additive manufacturing, HRM 4.0, knowledge management, industrial value creation, supply chain management, lean manufacturing, six sigma model development, consumer behavior studies, and global market analysis.

**Problems**

1. Detail the importance of the cyber-physical system for Industry 4.0.
2. Describe the closed-loop network control for cyber-physical systems.
3. Explain the ANSI/ISA-95 model architecture.
4. Give the significance of the smart factory.
5. Describe the challenges of the smart factory.
6. Specify the cyber-physical system in a manufacturing process.
7. Describe the interaction between CS, ICT, and manufacturing automation.
8. Characterize the cyber-physical system in smart manufacturing.
9. Describe the architecture of a cyber-physical production system (CPPS).
10. Explain the PROSA reference architecture.

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# Chapter 6

# Cyber-Physical-Social Systems

**Chapter Objectives**

- Learners understand cyber-physical-social systems architectures.
- Learners become familiar with the cyber- physical-social systems.
- Learners can describe the cyber-physical-social systems for architectures and standards.

The prevailing trend in the modern world is the transformation of traditional systems and mobile devices into intelligent systems and smart devices. In this context, cyber-physical systems (CPSs) and the Internet of Things (IoT) have emerged to meet contemporary needs. To facilitate parallel interactions between the human world and computer networks, IoT, in conjunction with wireless mobile communication and computing, presents both future opportunities and challenges. The construction of a novel cyber-physical-social system (CPSS) is highlighted, emphasizing the consideration of human factors in system operation and management. This chapter provides a detail contributing to the development of CPSSs. Key aspects of CPSSs are identified, covering the evolution from CPSs to CPSSs, architecture design, applications, standards, real-world case studies, enabling techniques, and networks for CPSSs. To establish a foundation for the development of the smart world, a virtualization architecture and an integrated framework, computing, and networking for CPSSs are presented. Simulations show the performance improvement and the discussion leads to issues, challenges, and potential solutions for CPSS areas.

## 6.1 Introduction

The advent of innovative technologies is profoundly transforming various aspects of people's lives. However, these advancements pose challenges to traditional physical devices. Traditional information systems, often based on closed embedded devices, struggle to meet the demands of interactive, controllable, and extensible physical devices. Consequently, cyber-physical systems (CPSs) have emerged as a dominant trend, gradually replacing traditional information systems.

CPSs are characterized as intelligent systems, embedded sensors, actuators, and controllers to facilitate interaction between the physical and cyber worlds. Typically comprising three layers—perception, transport, and application—CPSs acquire perceptive information, transfer data among system elements, and make decisions based on analyzed results. These systems find applications in diverse fields such as transportation, factories, electric vehicles, and smart grids.

As network applications in traditional embedded information systems advance, the concepts emphasize integrating networks with human society, giving rise to cyber-physical-social systems (CPSSs). CPSSs, also known as association systems, integrate computing, physics, and human resources, enabling coordination across cyber, physical, and social domains. These systems support self-synchronization, parallel execution, and supervisory control in physical, information, cognitive, and social domains, offering an ideal paradigm for designing smart environments.

In contrast to CPSs, CPSSs incorporate humans as integral components, considering human factors during system operation. Through intelligent human-computer interaction, CPSSs involve humans in the loop, viewing them not only as service consumers but also as service providers. However, integrating social spaces poses challenges, as humans exhibit variability in task execution, sometimes deviating from instructions. Despite being less reliable than computers, humans excel in adapting to dynamic environments and generating innovative solutions. CPSS designers must consider these human characteristics to facilitate interaction among people, computers, and devices.

This scheme explores existing works related to CPSSs, providing insights focused solely on CPSs. Many existing works that concentrate on specific application fields or interesting topics, this detail spans various aspects of CPSSs, including their development, architecture design, applications, enabling techniques, and challenges. The unique focus on integrating CPSs with social space distinguishes this chapter from others in the field.

## 6.2 CPSS Development

An introduction to cyber-physical-social systems was initially achieved in 2010. This concept is emphasized considering social and human dynamics as integral components in the design of CPSs. This integration effectively coordinates cyberspace, the physical world, and human resources within CPSSs, marking the advent of an era characterized by smart enterprises and industries. CPSs have yielded remarkable technical solutions across various application domains, and the discussion on CPSSs has resurfaced. The situation is now focusing on individual human beings as essential components of CPSs, marking a paradigm shift from traditional CPSs to CPSSs, also known as enhanced living environments (ELEs). This potential will delve into the roles humans can play and how they can be integrated into the loop of CPSSs.

### 6.2.1 Human Function Description

With the widespread acceptance of CPSSs, intellectuals are delving into how human function within this framework. Understanding the purpose of humans in CPSSs is crucial. Humans in CPSSs are akin to users in existing systems, often seen as consumers accessing services and information. However, humans in CPSSs can also be seen as service providers, contributing to the system, or assisting other users.

1. **Citizen Sensing and Citizen Actuation**

The concepts of citizen sensing and social actuation describe how humans function as service providers in CPSSs. Citizen sensing focuses on collecting information and extracting valuable insights, utilizing citizen sensors for data collection and reporting. Citizen actuation aims to generate actionable items, using citizen actuators to influence the surrounding environment. **Figure 6.1** illustrates the feedback loop of citizen sensing and citizen actuation. The first stage involves data acquisition, where state information is collected and processed with a richer context. The second stage is information retrieval, allowing users to access information through visual representations like graphs, videos, and warnings. The third stage involves user feedback, reflecting the insights reported by users. The fourth stage is action, where users carry out their actions or make choices. Subsequently, these actions and choices influence the system, initiating a new feedback loop.

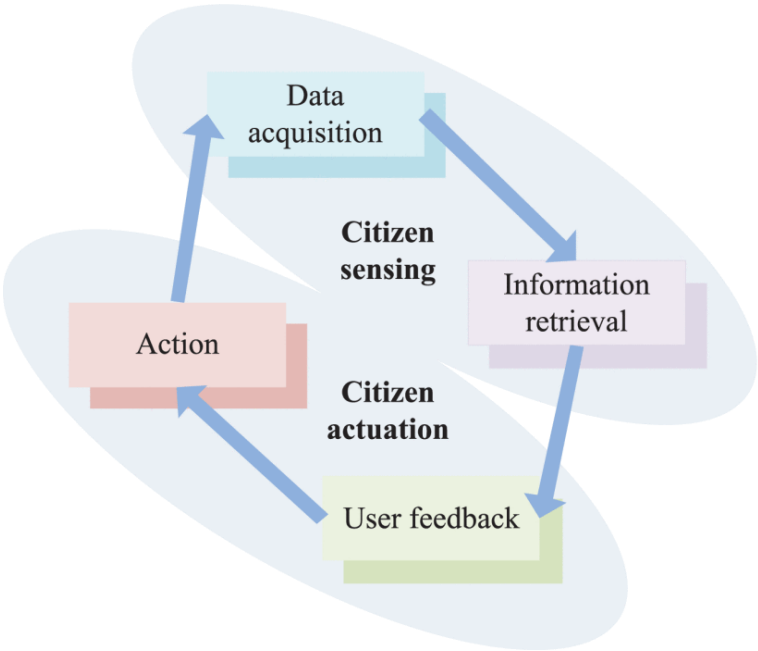


**Figure 6.1** Feedback loop of citizen sensing and citizen actuation.
[Source: Zhou, Y., Yu, F. R., Chen, J., & Kuo, Y. (2020)]

Consider a scenario in citizen sensing where a group of citizen sensors might report surrounding physical environments with varying degrees of uncertainty. A confidence-aware truth-finding scheme is formulated as a constraint optimization problem. This scheme takes into account different degrees of user confidence and uncertainty, effectively determining source reliability and claim correctness. This approach undergoes extensive simulations, demonstrating performance advantages compared to other baseline methods.

A joint citizen sensing and actuation platform for energy management is integrated with a social media application. They assert that citizen actuation enhances energy utilization, with experiments showing an average reduction in energy usage. Subsequently, a citizen actuation framework where tasks assigned by CPSSs are delegated to suitable occupants. The method for selecting occupants is based on social media profile features to accomplish tasks.

### 2. Crowdsourcing and Crowdsensing

With citizen sensing and citizen actuation, crowdsourcing and crowdsensing serve as fundamental building blocks, representing the intersection of things and human-based techniques. Crowdsourcing involves acquiring services and ideas from a group of people. Solutions from crowdsourcing rely on crowd wisdom, often leading to superior results compared to decisions made by individuals or computers. Crowdsensing employs a similar principle to enhance sensing area coverage and data quality through the inertial sensors of human mobile devices, eliminating the implicit cost of traditional sensor networks.

To support the social applications of crowdsourcing and crowdsensing and enable a distributed data analytic platform for CPSSs, CARDAP is introduced. Defined as a scalable, energy-efficient, generic, distributed, and extensible component-based data analytic platform, CARDAP incorporates on-the-move activity recognition and data delivery strategies based on real-time data mining. It is designed for mobile crowdsensing applications, offering advantages in terms of energy, resource, and processing efficiency.

Note that in many existing smart environments, users are often excluded from the control loop, potentially causing disengagement. For instance, heating systems and automated windows in smart buildings are typically centrally controlled without user input. Human contribution is pivotal in CPSSs, marking the evolution from CPSs to CPSSs. Now, having elucidated the role of humans in CPSSs, attention turns to the characterization of human behavior.

### 6.2.2 Human Behavior Description

In traditional systems, designed to meet user requirements where users are perceived as service consumers, it is essential in CPSSs to understand the dynamic behavior of user participation when they serve as service providers. Such as when a person will engage in CPSSs when they will disengage, how they will be identified during participation, what tasks they can handle, what qualifications they need for these tasks, how to communicate with them, and when their task performance terminates. Additionally, the dynamic nature of humans, including sudden interruptions and innovative solutions, must be considered during the design of the behavior description model. The key aspects of designing this model for CPSS operation can be summarized as follows:

- Access of a person
- The person's identity from a system perspective
- Tasks the person can handle
- Qualifications for task accomplishment
- Communication methods with the person
- Termination of task performance by the person

The model should also accommodate the dynamic nature of humans, allowing for sudden interruptions and innovative solutions. With the human behavior description model, tasks can be assigned based on individual abilities, facilitating the integration of humans into CPSSs.

To motivate individuals to participate in CPSS operation and management positively, analyzing user-related data from the behavior description model is necessary. This includes metrics such as user access duration and the quality report, reflecting user indicators like credibility, influence, academic level, or professional quality. Consequently, users can be classified into different groups with varying levels of these indicators. Users in higher-level groups may receive greater rewards or higher-quality services, while those in lower-level groups may face penalties, encouraging positive contributions to system operation and management.

### 6.2.3 Insights

The creation of an intelligent environment relies not only on modern technologies but also on the natural resources provided by its inhabitants. In essence, both "things" and "humans" are essential components for transforming smart environments into even more intelligent ones. Humans can benefit from advanced technologies, enjoying intelligent services, while also contributing to the enhancement of business intelligence. With the evolution of CPSs, CPSSs emerge as a fundamental approach to realizing a more intelligent environment. CPSSs gather information from humans and cater to people with user awareness. In that way delves into the current developments of CPSSs and sheds light on potential future trends. This potential encompasses various aspects, including but not limited to the social dimension of CPSSs.

## 6.3 Architecture Design

The schemes initially present the existing architecture of CPSSs with a detailed description. Subsequently, the motivation and requirements are explored for equipping CPSSs with wireless network virtualization, followed by the use of a virtualized CPSS architecture. Next, to enhance the ubiquity of CPSS computation services and facilitate scalable content retrieval and delivery, an

integrated framework is introduced involving caching, computing, and networking for CPSSs. The performance is evaluated and analyzed using the architecture, providing insights.

### 6.3.1 Existing Architecture

**Figure 6.2** illustrates two prevalent layered architectures of existing smart systems, with **Figure 6.2(a)** and **Figure 6.2(b)** depicting the details of the Industrial Internet (also known as Industry 4.0) and Internet of Things (IoT) protocols, respectively. Here, the industrial Internet protocol can be considered as the industry standard for a CPS-based application. As depicted in **Figure 6.2(a)**, the Industrial Internet architecture comprises five distinct layers:

1. The connection layer manages precise data acquisition from direct sensor inputs, controllers, or enterprise manufacturing systems in physical environments.
2. The conversion layer transforms raw sensor data into useful information, achieving self-awareness of physical components.
3. The cyber layer retrieves valuable information from the lower layer, serving as a central information hub for data processing.
4. The cognition layer provides comprehensive system knowledge through information gathered from the lower layer, enabling intelligent decision-making through big data analytics.
5. The configuration layer delivers smart and adaptive control to machine networks based on intelligent decisions.

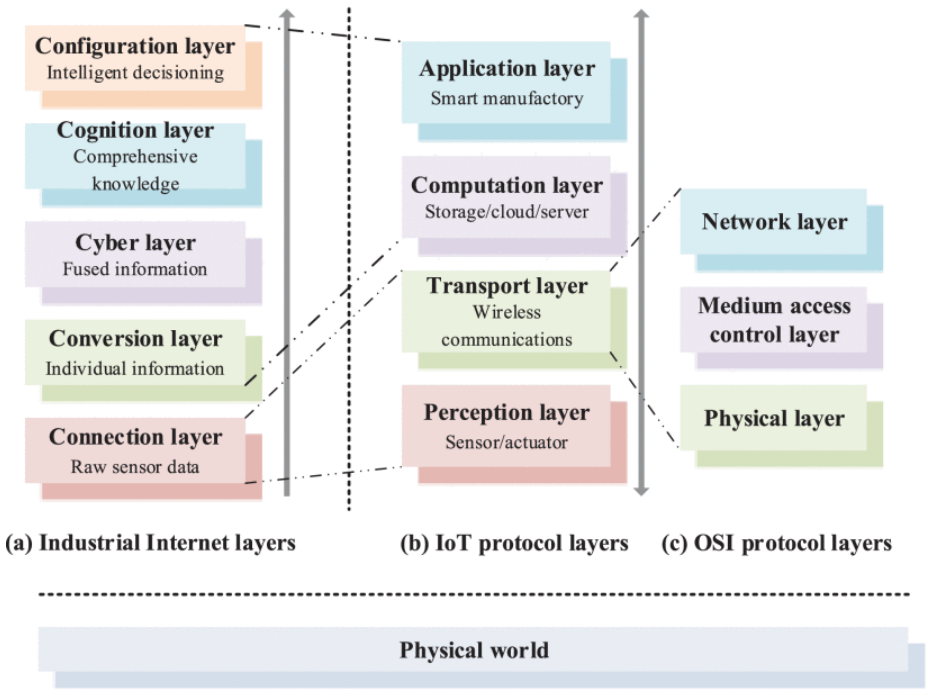


**Figure 6.2** Layered architecture of smart systems.
[Source: Zhou, Y., Yu, F. R., Chen, J., & Kuo, Y. (2020)]

Due to shared design concepts, there are architecture similarities between **Figure 6.2(a)** and **Figure 6.2(b)**. The connection layer in the industrial Internet protocol could correspond to the perception layer and transport layer in the IoT protocol. The layered architecture in **Figure 6.2(c)** provides an overview of wireless communications among various components, i.e., the transport layer, with this layer being equivalent to the physical layer, medium access control layer, and network layer in the

Open System Interconnect (OSI) protocol. The remaining four layers in the industrial Internet protocol could correspond to the computer layer and application layer in the IoT protocol, primarily focused on data processing and smart decision-making.

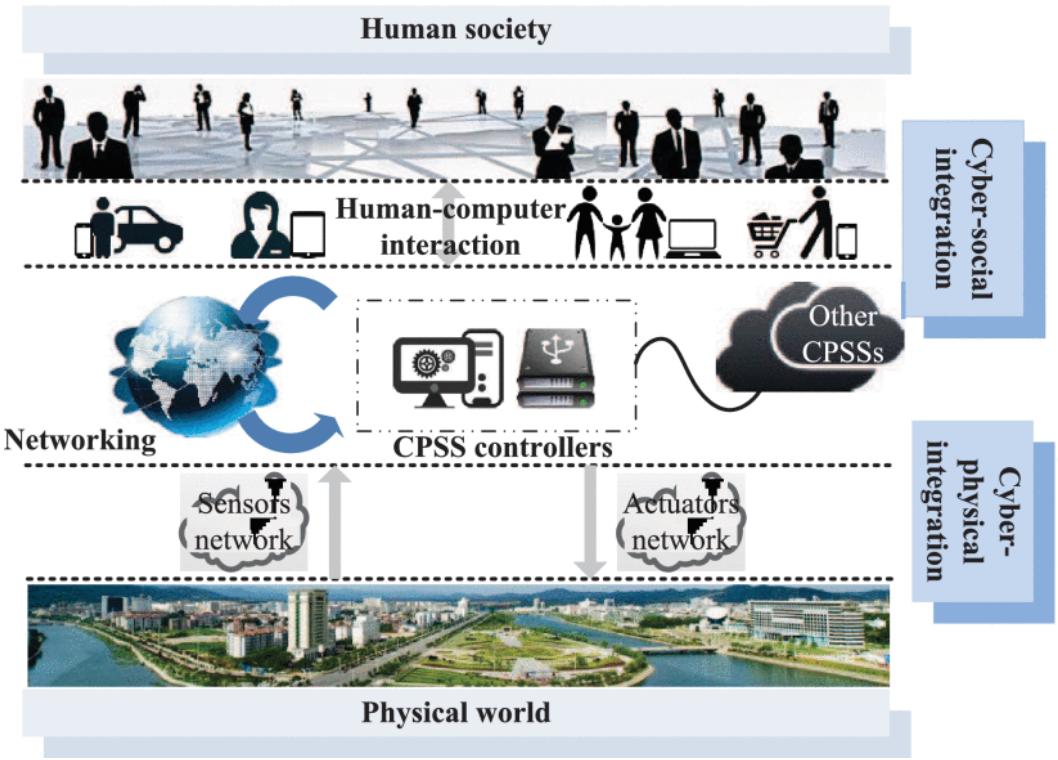


**Figure 6.3** Layered architecture of CPSS.
[Source: Zhou, Y., Yu, F. R., Chen, J., & Kuo, Y. (2020)]

The layered architecture of CPSS, as shown in **Figure 6.3**, could be realized based on existing CPS and IoT protocols. The cyber layer supports intelligent data processing for smart decision-making. Above this layer, there is a social layer representing human society, and below it, a physical layer containing every component in the physical world. The physical layer and the cyber layer are interconnected by sensor and actuator networks, with humans in the social layer participating in CPSS system operations through innovative social applications such as citizen sensing and citizen actuation. The specifics of CPSSs can be seen as an evolution of CPSs. While CPSSs, CPSs, and IoT all aim to achieve intelligent monitoring of the physical world, CPSSs place a greater emphasis on the human impact on the system compared to CPSs and IoT.

Certainly, the field of CPSS is in its early stages and is an interdisciplinary subject. However, examining existing research reveals that the layered architecture of CPSS, as illustrated in **Figure 6.3**, has gained approval within academic circles. This architecture is fundamentally grounded in established academia and industry standards of CPS. Notably, there is a foundational framework for implementing CPSS in practical applications. For instance, the roots of intelligent transportation can be traced back to the 2090s, with the initiation of the PATH project (Partners for Advanced Transportation Technology) by the University of California. The first CPS symposium took place in the United States in 2006. In 2013, Germany introduced the high-technology strategy Industrie 4.0, identifying research towards industrial CPS as its backbone. In 2015, China launched the "Made-in-China 2025" strategy, aiming to integrate industrialization and informatization. Importantly, among existing research, Industrie 4.0 is the only manageable protocol utilizing international standards, and reference architecture and requirement specifications for Industrie 4.0 are already available.

### 6.3.2 Innovative Architecture Design: Wireless Network Virtualization

**1. Motivation:** The IoT is seen as an effective means to achieve the interconnection of multiple distributed CPSSs. These systems communicate over wired or wireless networks, generating substantial data. Constructing an intelligent interconnection network requires careful consideration of design concerns during the deployment of existing CPSS protocols.

- **Construction Cost and Scalability:** CPSSs consist of diverse elements with complex structures supporting various functions across application fields. To achieve these systems with reduced construction and operation costs, the primary goals are to avoid redevelopment and redeployment of similar infrastructures, utilize existing resources fully, and ensure the system's scalability.

- **Business Service and Security:** Given the widespread use of CPSSs in various fields, the growing number of covered facilities raises concerns about data traffic and diversified business services. Managing this influx requires robust network resources to maintain security, particularly considering the direct interaction of CPSSs with the physical world.

**2. Architecture:** The advancements in wireless network virtualization (WNV) and software-defined networking (SDN) present effective means to realize CPSS interconnection networks, offering several benefits.

- **Lower Construction Cost:** WNV, supported by generic hardware and advanced software, reduces capital and operating expenditures for network operators. By decoupling infrastructures from services, devices with varying service requirements can access different virtual networks while sharing the same infrastructures, reducing construction costs for CPSS networks.

- **High Scalability:** SDN's abstraction and standardization of the control plane enable the evolution and updating of networks and applications without overhauling infrastructures, promoting the scalability of CPSSs.

- **Service Guarantee:** WNV utilizes existing facilities and limited network resources to provide services for different business types, improving resource utilization. Through virtualized multi-resource deployment, it satisfies wireless communication requirements like low power consumption, real-time performance, and transmission reliability.

- **Security Guarantee:** Devices requiring services with different secrecy levels can access various virtual networks, each implementing different confidentiality measures to satisfy diverse security requirements.

**Figure 6.4** illustrates the virtualization architecture for CPSSs, divided into three layers:

- **Physical Layer:** Encompassing widely distributed devices and infrastructures interconnected by IoT in various fields such as home, electricity, traffic, hospital, industry, and agriculture. Sensors and actuators in this layer enable intelligent monitoring of the surroundings.

- **Cyber Layer:** Serving as a bridge between the physical layer and the social layer, the cyber layer corresponds to computation modules and physical objects. Central controllers and

distributed controllers in this layer handle data archiving, processing, decision-making, and task assignment. It supports data collection, information collation, and provides services to users in the social layer. The cyber layer is further divided into a control platform and a data plane.

- **Control Platform:** SDN separates the control platform from the data platform, allowing virtual network operators to realize virtualization processes efficiently and at a low cost.

- **Data Plane:** The virtualization process in the data platform converts physical networks into various virtualized networks targeted to different industries, such as smart vehicle networks, smart medical networks, smart industrial networks, smart agriculture networks, smart home networks, and smart grids. Each smart virtualized network is independent for users in the social layer and sensors and actuators in the physical layer, despite sharing the same physical facilities and resources as shown in **Figure 6.5**.

- **Social Layer**: Users in the social layer play various roles like doctors, customs officers, servers, workers, or decision-makers. They act as service consumers by submitting experience information to the cyber layer and service providers by participating in decision-making, contributing to the system's development.

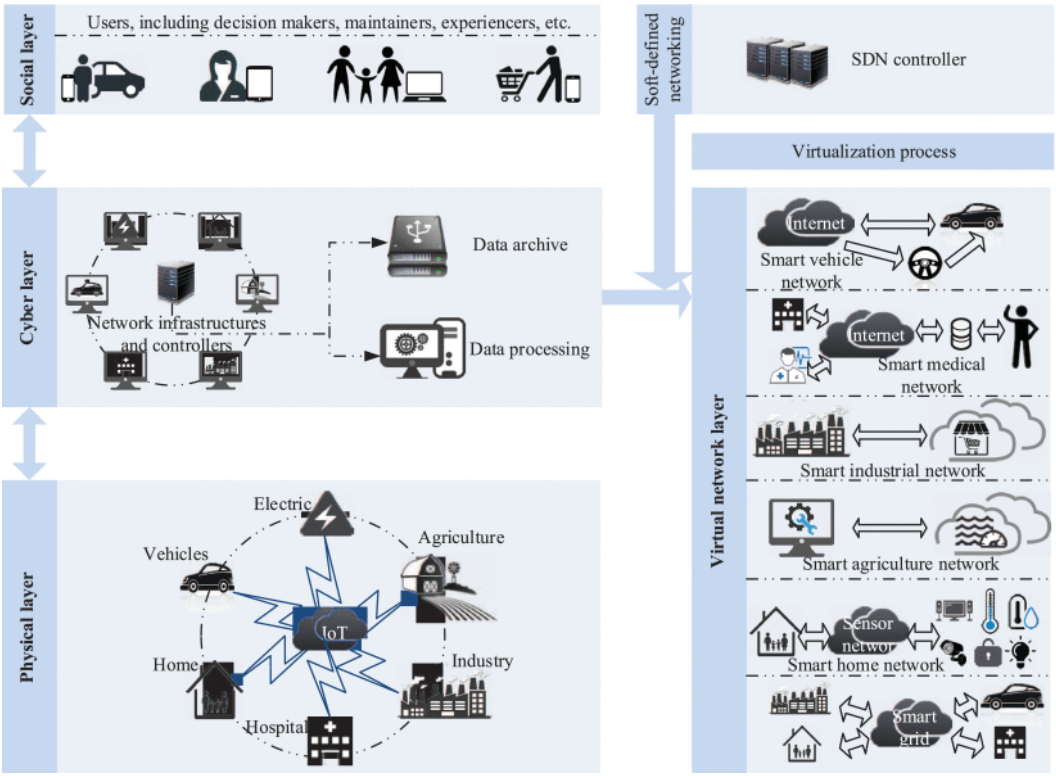


**Figure 6.4** A virtualized architecture for CPSSs.
[Source: Zhou, Y., Yu, F. R., Chen, J., & Kuo, Y. (2020)]

### 6.3.3 Innovative Architecture Design: Integration of Caching, Computing, and Networking

#### 1. Motivation

While virtualized CPSSs address certain scientific challenges, there are still operational and management challenges that need attention to further advance their development.

- **Information Retrieval:** Virtualized CPSSs house a wealth of information, and users or CPSS controllers need to quickly locate and extract relevant information.

- **Data Processing:** Real-time analysis is crucial, especially for edge data in virtualized CPSSs, demanding rapid processing response and low energy consumption.

- **Content Delivery**: Designing virtualized CPSSs to support frequent and reciprocating delivery of large-scale information, including service content and processing results, poses a challenge to limited bandwidth resources.

To tackle these challenges, it proposes an integrated framework of caching, computing, and networking for CPSSs, building upon the architecture presented in **Figures 6.4 and 6.5**.

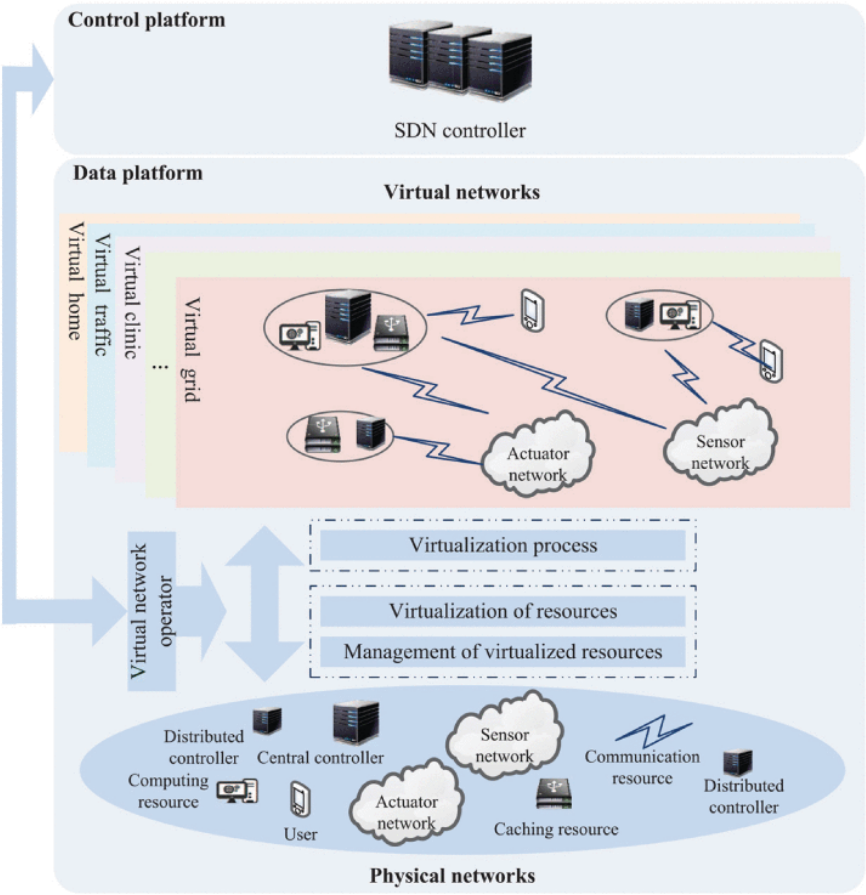


**Figure 6.5** Virtualization process for CPSSs.
[Source: Zhou, Y., Yu, F. R., Chen, J., & Kuo, Y. (2020)]

**2. Architecture**

Integrating caching (information-centric networking - ICN), computing (edge computing), and networking enhances CPSSs' efficiency and scalability in content retrieval and delivery, coupled with robust data processing capabilities.

- **Speedy Information Retrieval**: ICN supports in-network caching, allowing CPSS nodes to name and store contents within the network, facilitating rapid information retrieval.

- **Efficient Data Processing:** Deploying edge computing servers at CPSS nodes enhances processing capacity even at the edges. The joint design of caching and computing modules promotes mutual enhancement. For instance, edge computing servers can transform caching contents, reducing the number of stored content versions and improving cache space utilization.

- **Efficient Content Delivery:** ICN employs a receiver-driven information-level delivery principle, enabling receivers to set up communication links without prior knowledge of content holders' locations. Optimizing caching, computing, and communication resources enhances the efficient delivery of required contents and analysis results among sensors, actuators, controllers, and user devices.

**Figure 6.6** illustrates an integrated framework of caching, computing, and networking for CPSSs. By selectively installing edge computing servers or utilizing storage space at each CPSS controller, four virtual networks are created to handle different services according to CPSS device and user requirements.

- **Traditional CPSS Network:** Serving areas with identical communication service requirements, this network manages services such as decision feedback with security and confidentiality features.

- **CPSS Network with Caching Function**: Useful for delivering frequently accessed large files like photo collections, install packages, tool books, and applications with a certain degree of cache value.

- **CPSS Network with Computing Function**: Utilized for privacy-sensitive computation tasks like QR code recognition and face recognition, where storage is unnecessary.

- **CPSS Network with Caching and Computing Function**: Provides video acquisition services, transcoding collected video contents in real-time to suit network conditions, storing popular ones to alleviate backhaul bandwidth workloads. It is also capable of implementing real-time navigation for virtual smart traffic, with edge computing servers providing route guidance and global traffic maps stored at various network nodes.

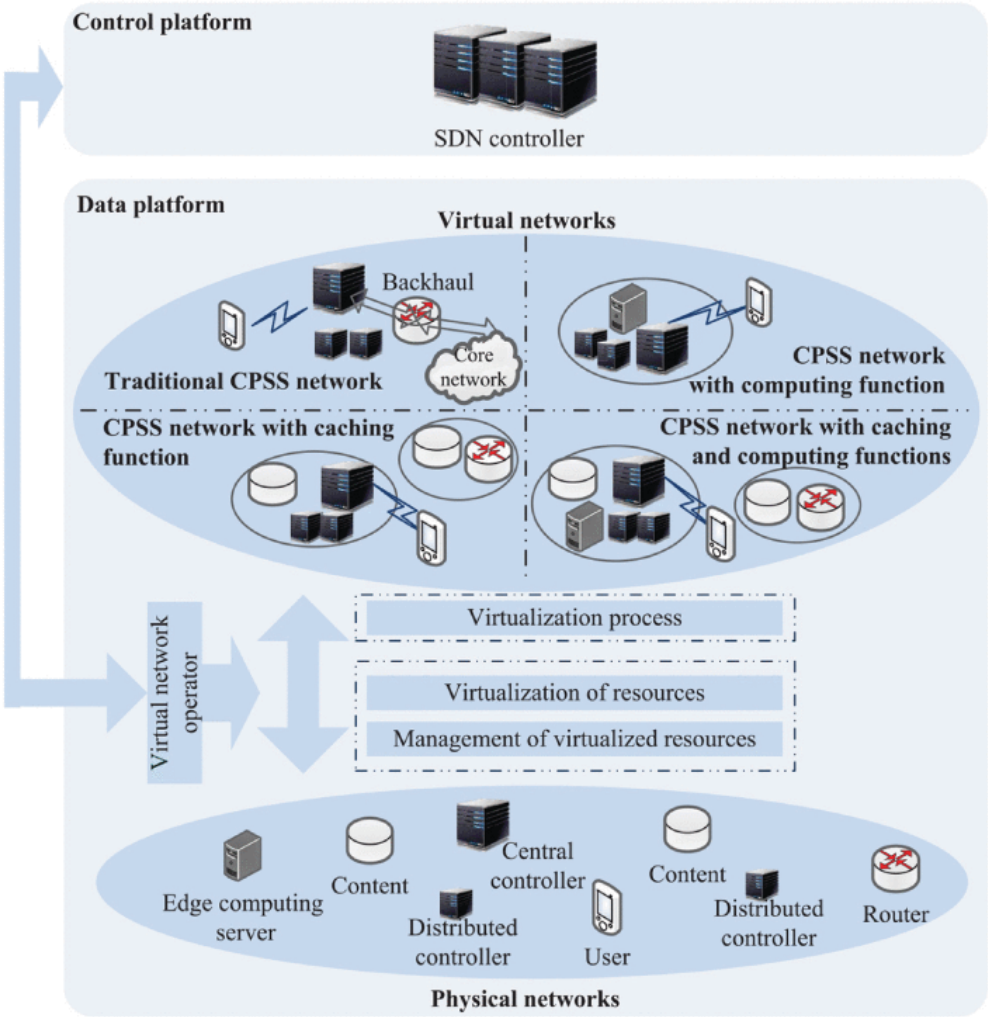


**Figure 6.6** The unified framework for caching, computing, and networking in CPSSs. [Source: Zhou, Y., Yu, F. R., Chen, J., & Kuo, Y. (2020)]

### 6.3.4 Insights of Architecture Design

This design contributes by presenting comprehensive CPSS architectures along with their optimization, substantiated by simulation results. The findings suggest potential strategies for CPSS design and enhancement. However, to operationalize these insights, several challenges need addressing, such as integrating the target architecture with existing protocols and standards and developing effective user evaluation and assessment methods.

Moreover, the optimizations are developed in a simplified manner, focusing primarily on elucidating the advantages of involving humans in the system and leveraging human resources. In real-world scenarios, the sheer proliferation of networks, devices, tasks, and users poses significant challenges in optimization. Determining optimal thresholds that consider both user evaluation values and fairness is a crucial but complex issue that warrants attention. Reasonably solving these challenges is essential for deploying CPSS architectures with human evaluation and incentive mechanisms, as well as the four-dimensional joint optimization scheme, in practical environments.

### 6.4. Applications and Standards

**Figure 6.7** provides a visualization of CPSSs. Traditionally, design concepts often omit the human factor from the system loop, deviating from the user-centered design principle. CPSSs, in contrast, aspire to integrate humans comprehensively into the loop, enriching the intelligence of the environment through innovative social applications like citizen sensing and citizen actuation. These applications have the potential to influence diverse aspects of our daily lives, spanning transportation, industry, agriculture, pro-environment initiatives, energy, healthcare, and more. This section will explore existing research on CPSS applications, common standards, and real-world case studies. Through a detailed examination of the current research landscape, the significant market potential of CPSSs to enhance intelligence across various domains becomes evident.

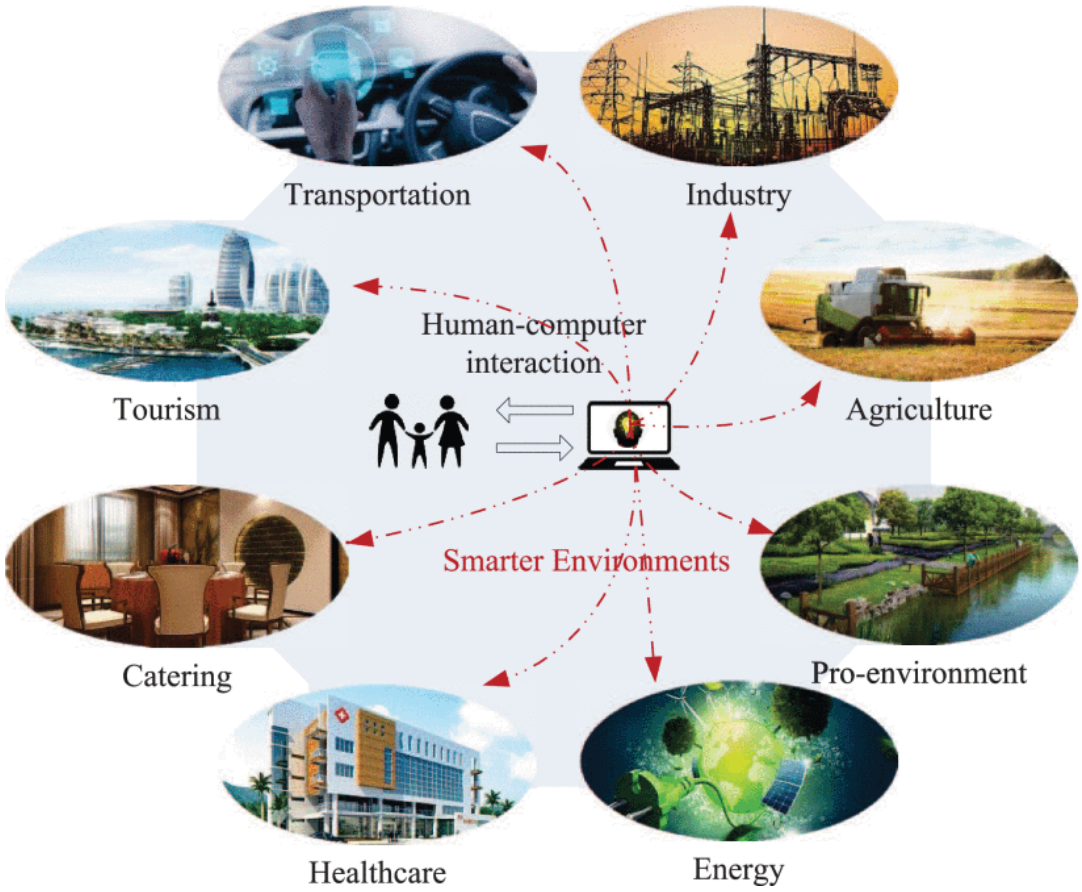


**Figure 6.7** Cyber physical social vision.
[Source: Zhou, Y., Yu, F. R., Chen, J., & Kuo, Y. (2020)]

#### 6.4.1 Applications

The existing work of CPSSs, the motivation of which relies on the exploration of CPSS applications in different research directions. The details will be discussed in the following.

**1. Transportation**

CPSSs can be designed effectively for intelligent traffic management. Vehicles connect to external elements like infrastructures, other vehicles, and pedestrians, aiding in the collection and analysis of surrounding information. This connectivity facilitates semi-autonomous or autonomous driving.

The notion of intelligent transportation spaces introduces the integration of traffic management centers, vehicles, roadside infrastructures, and pedestrians, enhancing the safety and efficiency of vehicles and traffic. CPSS-based intelligent transportation systems (ITS) enable features like smart parking and vehicular communication-based traffic control. Transportation 5.0 emphasizes the role of society as an active entity in ITS, engaging in sensing, computing, communications, control, and management processes.

Intelligent vehicles represent a significant implementation in transportation. Cloud-based CPSS frameworks, promote connected automated driving through interactions among vehicles, drivers, and information. Parallel techniques such as parallel testing and learning contribute to realizing connected automated driving in complex environments. CPSSs also play a role in optimizing road traffic signals. A framework allows for the self-configuration of traffic signals, considering social characteristics and conducting experiments to validate their feasibility.

**2. Social Manufacturing and Smart Factories**

For social manufacturing and smart factories, CPSSs gather data from underlying facilities, enabling dynamic configuration and production optimization to align with consumer behavior and business models. Social manufacturing emphasizes personalization and socialization, focusing on providing personalized products and services. The social manufacturing covers aspects like business models, architecture, case studies, and enabling techniques. Similarly, smart factories utilize CPSS architectures to integrate cyber control with physical factory infrastructure. In-line data deduplication file systems (LDFS) address manufacturing challenges by enhancing read and write performance. LDFS contributes to cyber-physical-social computing and networking systems (CPSCN) in social manufacturing and smart factories.

**3. Environment and Sustainability**

CPSSs contribute to environmental maintenance and sustainable development. For instance, the development of a smart hydroponic farming system is to monitor parameters and enable flexible hydroponic system monitoring. A CPSS-based agricultural production management system is to reduce labor and fertilizer waste. Smart water grids in river basins constitute a CPSS architecture, addressing water management challenges through dynamic analyses and decision-making. This approach serves as a tightly connected cyber-physical-social network for water management.

**4. Energy Distribution**

Smart grids powered by CPSSs enable intelligent energy distribution for homes, offices, and applications. The consumer-centered energy system (CCES) integrates the power grid, communications, computing, and consumer interconnections. The CCES architecture includes a request-and-schedule energy management protocol for efficient energy coordination. In fuel distribution, an inventory control system utilizes CPSS implementation architecture to enhance the sustainability of fuel supply. This system focuses on service requirements and customer satisfaction for public gas stations.

**5. Healthcare**

CPSSs facilitate smart personal healthcare by deploying sensors on the body or in homes and clinics to detect health conditions. Social network-based e-healthcare services is developed to control infectious diseases. Recommendations for selecting doctors based on performance and patient preferences are also taken into account. The application of CPSSs in healthcare involves service consumers (patients) and providers (nurses and doctors) that an efficient way to motivate healthcare providers to retrieve patient information, enhancing service quality even at a distance.

**6. Catering and Tourism**

Smart recommendation systems in CPSSs find applications in catering and tourism. Group-centric recommender systems provide a foundation for personalized smart computing. Smart culinary incorporates GPS, cloud computing, and social media for restaurant recommendations. The dynamic social structure of things (DSSoT) aids people in unfamiliar places during journeys by reducing contextual complexity.

A modeling and computing method is used for geological information services during journeys based on cyber-physical-social-thinking (CPST). Additionally, artificial evacuation systems is proposed in crowded areas during journeys, considering the complexity of human behavior during evacuations. The framework utilizes CPSS methodology and computational experiments for real-time evacuation guidance.

### 6.4.2 Standards

In this part, enumerate several prevalent standards is commonly employed in smart systems.

**1. Transportation**

Numerous standards facilitate vehicular networks, including European Committee for Standardization (CEN) TC278, Institute of Electrical and Electronics Engineers (IEEE) 1609, Internet Engineering Task Force (IETF), and International Organization for Standardization (ISO) TC204. The Intelligent Transportation Society of America (ITSA) is pivotal in dedicated short-range communications (DSRC) and follows the IEEE 802.11 standard for physical and media access control sublayers. IEEE 1609.x addresses protocols in other layers, collectively forming wireless access standards for vehicular environments. Given the diverse applications, Intelligent Transportation Systems (ITS) are expected to adopt multiple communication technologies and standards.

**2. Industry**

Manufacturing environments align with the reference architecture model for Industrie 4.0 (RAMI4.0), where machine-to-machine (M2M) standards are crucial for cost-effective manufacturing and smart factories. OneM2M standards integrate M2M activities to minimize fragmentation. Additionally, the IEC 61499 standard is introduced for machine controlling and functionality modeling, facilitating low-level control and functionality reconfiguration in manufacturing.

**3. Agriculture**

The IEC 61400-25 standard supports unified information exchange during monitoring and control in the wind power industry. It seamlessly integrates with communication network architecture for smart wind farms. The TLS protocol addresses communication security issues, incorporating an agent mechanism model in IEC 61400-25-3, and aligns with international safety standards IEC 62351.

**4. Smart Grid**

Communication standards for smart grids encompass Distributed Network Protocol (DNP3.0), IEEE Std. C37.118, IEC 61850, and MODBUS. Core protocols include IEEE Std. C37.118, focusing on synchrophasor measurements, and IEC 61850, a comprehensive international communication standard integrating substation functions like measurement, monitoring, control, and protection.

**5. Healthcare**

The ISO/IEEE 11073 standard defines communication protocols for exchanging healthcare information in medical and wellness devices. Although it doesn't support the Internet Protocol (IP), it can be extended using 6LoWPAN and BLE, making it versatile in various environments, including IoT environments.

**6. Deep Media**

In the realm of CPSSs, it is noteworthy that "video big data" constitutes a major portion of information flows across cyber, physical, and social spaces. The IEEE 1857 standard, known as the Standard for Advanced Audio and Video Coding, efficiently addresses surveillance video needs. Differentiating from other standards like High Efficiency Video Coding (HEVC)/H.265, IEEE 1857 focuses on coding efficiency by removing "scenic redundancy" in consecutive pictures, making it a valuable tool for various video applications in CPSSs.

### 6.4.3 Real-World Case Studies

This exploration into real-world case studies within the existing research on CPSSs has been presented. Two illustrative real-world instances is introduced, serving as foundational examples to advocate for the adoption of CPSSs in various practical applications.

**1. Intelligent Vehicles in Transportation 5.0**

In the realm of CPS-based applications, Transportation 5.0 or Intelligent Transportation Systems (ITS) 5.0 represents CPSS-based transportation applications. Urban transportation, intricately linked with environmental and social elements, particularly stands out as a real-world application. ITS, pivotal for urban transportation complexities, requires evolution to ITS 5.0 or Transportation 5.0.

The case study explores the intelligent vehicle as a typical case within the next generation ITS 5.0. It introduces three primary agents: driver agents in controlled vehicles, personal agents of pedestrians, and traffic manager agents at roadside locations. These agents engage in reserving space-time blocks, guided by the traffic manager agents' analysis in the cyber layer of CPSSs. This cloud-based system utilizes V2V/V2I protocols for real-time road information updates and travel guidance.

In ITS, humans, such as drivers and pedestrians, are seen as service consumers with a guaranteed service of collision avoidance through travel guidance. Given the dynamic nature of human behavior, human assistance is currently indispensable in automatic driving. ITS 5.0 is still in its nascent stage, and the provided case study is speculative, lacking actual tests. Comprehensive investigations, investments, and tests are imperative for its implementation and advancement.

**2. Chinese Solar Greenhouse**

The Chinese solar greenhouse, a prevalent horticultural facility, faces challenges influenced not only by environmental factors but also by social conditions such as price fluctuations and grower knowledge. Traditional solar greenhouses require an effective management system to avoid low production and unsalable products.

Drawing parallels to the layered architecture of CPSSs, real-world case studies delve into effective greenhouse management. Sensing information, comprising social and physical data, is gathered. For instance, the study utilizes historical price data of tomatoes from different markets and physical data including air temperature, humidity, and light intensity. Agricultural CPSSs leverage artificial systems and computational experiments to predict plant development, optimizing fertilization, spaying timing, and marketing.

Agriculture CPSSs analyze historical market prices with predictions of plant growth and environmental conditions. Service providers, including price makers and growers, collaborate to determine planting strategies and marketing plans. This collaborative approach ensures a win-win situation for both providers and consumers, maximizing planting profits and product quality.

### 6.4.4 Insights of Standard

To advance CPSSs and streamline their implementation, a compartmentalized design approach is suggested, allowing individual parts of the system to be designed separately, aligning with existing standards. However, an integrated operation of these standards and proposals is crucial for the holistic functionality of CPSSs. Although real-world case studies exist, they are often confined to specific research areas and might face limitations in other applications due to diverse requirements.

At the present theoretical stage, CPSSs exhibit potential and value across various engineering sectors, including transportation, industry, agriculture, pro-environment, energy, healthcare, catering, and tourism. The market for CPSSs is anticipated to expand in line with the general trend of IoT. As technology matures, CPSSs are expected to sustain robust development, offering a new impetus for global economic growth. The trends involve designing comprehensive platforms and business models, integrating relevant technologies and human behavior patterns to foster multi-win scenarios for manufacturers, operators, integrators, and service providers.

This CPSSs is envisioned, emphasizing the enormous market potential across diverse fields. Common standards laid out earlier provide a solid foundation for CPSS applications. The ongoing evolution of CPSSs promises adaptability, capability, resiliency, scalability, safety, security, and usability, surpassing the simplicity of current embedded systems. Leveraging the mature foundation of CPSs, CPSS applications stand out by incorporating humans into the system, forming a closed loop and enabling smarter environments.

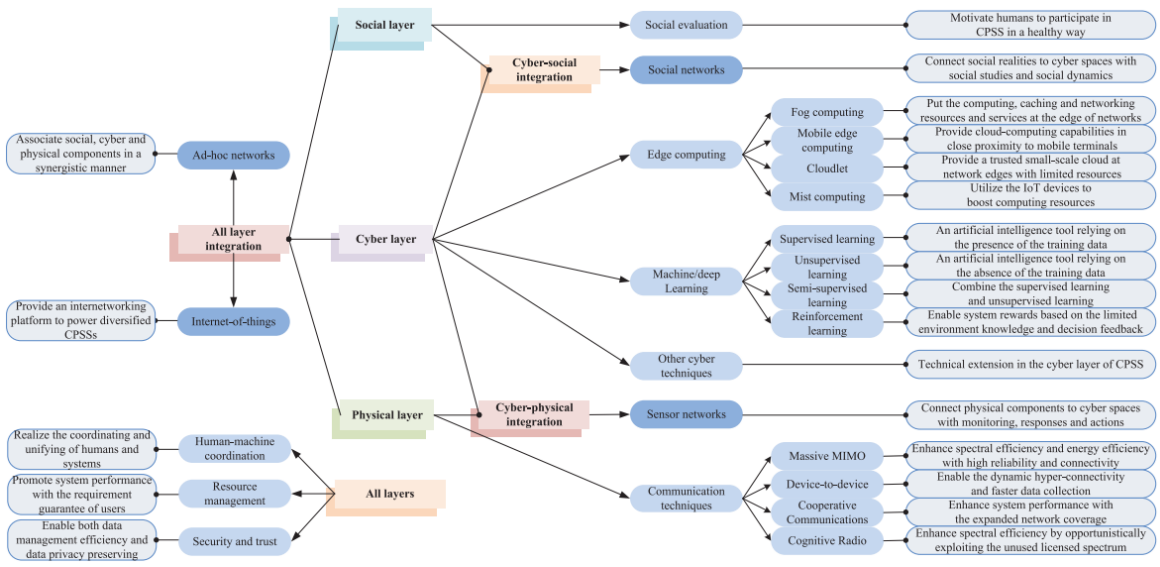


**Figure 6.8** An Overview of Enabling Techniques and Networks in CPSSs.
[Source: Zhou, Y., Yu, F. R., Chen, J., & Kuo, Y. (2020)]

## 6.5 Enabling Techniques and Networks

The implementation of CPSSs heavily depends on various facilitating technologies and pre-existing networks. Understanding these components is pivotal for comprehending the functionalities of CPSSs. In this segment, it explores the technologies and network applications that empower CPSSs, categorized based on the hierarchical structure of CPSSs. **Figure 6.8** provides an overview of these enabling techniques across each layer of CPSSs and the networks facilitating their integration. The elements marked in mazarine in **Figure 6.8** signify potential network applications and architectures.

Organizing the enabling techniques and networks according to the categories illustrated in **Figure 6.8**, grasping the roles of each type of technique and network within CPSSs. It also facilitates an understanding of how these techniques and networks support various facets of CPSSs. This categorization reveals interrelationships among different techniques and networks.

### 6.5.1 Physical Layer: Communication Techniques

Communication techniques form the fundamental basis for interconnecting various components within the physical layer of CPSS, ensuring the characteristic of hyper-connectivity. Before delving into potential communication techniques, it is imperative to address the challenges associated with integrating CPSSs into existing communication networks.

CPSSs primarily involve two distinct types of communication—human-type and machine-type. Human-type communications align with conventional communication services in existing networks, whereas machine-type communications emerge as a service supporting the connection between CPSS and IoT devices in the upcoming 5G era. Machine-type communications involve the transmission of sensing and actuation data among machines, facilitating data processing and decision-making without human intervention during communications. This aligns with CPSS design principles, enabling diverse smart systems like ITS, smart grids, and healthcare.

For human-type communications, using cellular networks as an example highlights challenges. Human-type devices in cellular networks follow the control of eNodeB in Long-Term Evolution for spectrum access. However, CPSS human-type devices may generate substantial traffic with high data rate requirements, presenting challenges due to the limited spectrum in cellular networks. Anticipated massive human-type devices pose packet scheduling problems, leading to degraded network capacity and spectral efficiency.

Machine-type communications present different challenges. Although the number of machine-type devices is typically large, they generate small amounts of data and exhibit little to no mobility. Existing contention-based transmission protocols, suitable for human-type communications, may lead to frequent network congestion in machine-type communications due to massive access requests with low latency requirements. Moreover, machine-type communications require design considerations for specific attributes such as high connection density and extra-long battery life.

The optimization of machine-type communications or the joint optimization of machine-type and human-type communications within CPSSs remains largely unexplored. However, existing CPSs cover network congestion and system overload, delays in radio access processes, and physical layer security, forming foundational work for machine-type communications in CPSSs. To integrate CPSSs into existing networks like cellular, four wireless communication technologies can be applied in CPSSs. The following details these communication technologies and their respective advantages:

#### 1. Massive MIMO

Massive Multiple Input Multiple Output (MIMO) is crucial for connecting both stationary (machine-type) and moving (human-type) devices to data centers in CPSSs. Unlike traditional MIMO, massive MIMO supports unequal numbers of antennas at different terminals. This allows data centers to install multiple antennas to serve multiple human-type devices simultaneously. Massive MIMO enhances spectral efficiency, and network capacity, and is a core technique supporting human-type communications in CPSSs. While challenges include accurate channel estimation under high mobility scenarios, massive MIMO can efficiently enhance energy efficiency for machine-type devices with little or no mobility.

**2. D2D Communications**

Device-to-device (D2D) communications facilitate both machine-type and human-type communications among CPSS devices over existing network infrastructures. In D2D communications, nearby CPSS devices can directly interconnect without relying on base stations or central points, enabling dynamic hyper-connectivity and faster data collection in CPSSs. Although current works lack the utilization of D2D in CPSSs, existing work in CPSs and IoT provides a foundation for extending its application to CPSSs.

**3. Cooperative Communications**

Cooperative communications enhance CPSS performance by retransmitting signals from one transmitter to one destination with the help of intermediate nodes. This reduces error transmission rates, lowers transmission power, improves system capacity, and extends network coverage. While cooperative communications may reduce spectrum efficiency, combining cooperative communications with D2D communications, known as relay-assisted D2D communications, further extends the communication range among different CPSS components.

**4. Cognitive Radio**

Cognitive radio technology efficiently addresses spectrum utilization issues in human-type communications. In cognitive radio networks, secondary users (unlicensed users) can opportunistically exploit the unused spectrum of primary users (licensed users). Cognitive radio facilitates improved spectrum utilization and robustness in CPSSs, with a blind rendezvous algorithm, such as the Sender-Jump Receiver-Wait algorithm, contributing to enhanced spectrum utilization and robustness in existing networks.

### 6.5.2 Cyber-Physical Integration: Sensor Networks

The deployment of wireless sensor networks (WSNs), incorporating energy-sensitive and wireless-communication sensors, has found applications in various practical fields, including industrial IoT, to achieve pervasive monitoring. It serves as an effective means to establish a close connection between cyberspace and the physical world. The core responsibilities of WSNs include data collection in the physical layer through sensing nodes and delivering information to the cyber layer with the operation and scheduling. In comparison with traditional monitoring and control systems, WSNs offer advantages such as flexibility, inherent intelligent processing capability, rapid deployment, and self-organization. Thus, WSNs are indispensable for CPSSs, supporting highly reliable cyber-physical integration with swift responses and appropriate actions.

Sensor scheduling emerges as a pivotal technology in WSNs, facilitating sensing resource allocation with the optimization objective of maximizing scheduler performance over a future time horizon. Sensor resource management involves determining which sensors should be activated at each time epoch. This problem is formulated as a constrained discrete optimization problem and can be solved using enumerative methods, greedy methods, or approximate dynamic programming techniques. While few CPSS studies focus on sensor resource management, existing work on WSNs can be effectively applied to CPSSs. The main challenge lies in the joint optimization of sensing resources with other resources and the associated performance trade-offs.

Parameter estimation is critical for comprehending the physical situation based on the distributed information captured in WSNs. Recognizing that most existing WSN work assumes homogeneous nodes, a relay-assisted WSN is explored to enable distributed estimation in industrial automation. This network mainly consists of sensing nodes and relay nodes. The tree-based broadcasting strategy, based on a Kalman filtering approach for distributed sensor fusion, and consensus-based estimation algorithms for sensing and relay nodes, demonstrates efficiency and accuracy in a hot rolling process monitoring system, a typical smart industrial system.

Given the detection and regulation functionalities of CPSSs, WSNs can extend to wireless sensor-actuator networks (WSANs) for processing control applications. Wireless control systems in WSANs, compared to traditional control systems, face challenges such as meeting stringent latency requirements for feedback control and dealing with dynamic channel conditions caused by external interference.

**6.5.3 Cyber Layer: Computing Techniques**

Edge computing and machine and deep learning are pivotal techniques enabling hyper-intelligence in the cyber layer of CPSSs, facilitating efficient data processing and intelligent decision-making.

**1. Edge Computing:**

Whether for CPSSs or IoT, an increasing volume of data is produced even at the network edge. Although this data can be efficiently processed at the cloud center with fast processor speeds, concerns about data transportation delays, transmission reliability, and scarce bandwidth need attention. In response, edge computing emerges as a novel computational paradigm positioned at the network edge to replace cloud computing. The benefits of edge computing include faster response times, bandwidth relief, a safer approach to processing user data, and lower-energy radio access for terminals, especially at the cell edge.

Representative paradigms of edge computing include:

- **Fog Computing:** An alternative to cloud computing, fog computing places computing, caching, and networking resources and services at the edge of networks, offering decentralized computing infrastructures or fog computing nodes. This reduces communication latency and enables location awareness for CPSS services and applications. Fog computing can be applied to mobile cloud computing (MCC), introducing mobile edge computing (MEC) to address high transportation latency issues.

- **MEC:** Announced by the European Telecommunications Standards Institute (ETSI), MEC provides cloud-computing capabilities and information technology close to mobile terminals within the radio access network. This allows CPSS devices to access low-latency, high-rate services. MEC expanded to Multi-Access Edge Computing.

- **Cloudlet:** Associated with fog computing, a cloudlet can be viewed as a trusted, small-scale cloud at network edges with limited resources and private services. It consists of a cluster of internet-connected computers offering resources and services for nearby devices. The architecture can be extended to a three-layer structure, including devices, cloudlets, and the cloud.

- **Mist Computing:** Addressing the limited computational resources at fog computing nodes (APs, routers, switches, and gateways) amid increasing data traffic, mist computing utilizes IoT devices (sensors, controllers, small servers, cell phones, home appliances, and probes) to enhance computing resources. Mist computing acts as a lightweight and rudimentary form of fog computing, employing microcontrollers and microcomputers to feed into fog computing nodes at the extreme edge of networks.

  It provides a comparison of different edge computing techniques:

  - **Locations of Computing Nodes:** Fog computing nodes can be located anywhere between the cloud and the edge, extending to network infrastructures. In mist

computing, these nodes are extended to include IoT devices. MEC servers and cloudlets integrate computing modules in servers or data centers.

- **Use of Dedicated Devices:** MEC and cloudlets use specialized computing modules in servers and data centers. In contrast, fog computing and mist computing do not require dedicated devices.

- **Computing and Caching Capacities**: Fog computing has lower computing and caching capacities compared to MEC and cloudlets. Mist computing, leveraging more devices as computing nodes, generally has higher capacities, although they may still be less than MEC and cloudlets.

- **Proximity to Devices:** Fog computing and mist computing may require multiple hops to reach edge devices, as the first hop might not be resourceful enough. MEC servers and cloudlets, with abundant resources, can provide services within one hop for nearby users.

- **Range of Service Objects:** Fog computing and mist computing support multiple hops to edge devices and utilize things (routers and gateways) as computing nodes supporting non-IP-based protocols. They have a wider range of service objects compared to MEC and cloudlets.

- **Context Awareness:** MEC possesses detailed information regarding the locations of edge devices and network load to enhance content awareness. In mist computing, computing nodes can analyze and comprehend the dynamic behavior of IoT devices. They operate in fuzzy environments, collaborate with neighboring nodes, and achieve advanced autonomous behavior through self- and context-awareness.

- **Whether or Not to Connect to Central Clouds**: Fog computing and cloudlets are designed with the central cloud in their architecture, whereas mist computing typically connects to the fog computing level.

- **Privacy and Security**: Fog computing, cloudlets, and mist computing place a stronger emphasis on privacy and security compared to MEC. Consequently, it is essential to delve into privacy and security issues specifically while formulating resource management strategies based on MEC.

- **Architecture:** Fog computing exhibits a more intricate hierarchy with storage and deep packet networking in comparison to MEC. The MEC structure features a computation-oriented single layer of nodes or base stations. Cloudlets follow a three-layer architecture, comprising the component layer, node layer, and cloudlet layer.

The computing techniques available are still lacking in CPSS systems enabled by edge/cloud computing, and further developments in this are deemed necessary. To address the growing and diverse needs of CPSSs, an integrated cloud framework is introduced for CPSS big data, encompassing five functional processes: data representation, dimensionality reduction, relation establishment, rank, and retrieval. The framework offers significant advantages in integrating CPSS big data into the cloud.

Proposing that fog computing features are desirable for most IoT applications, especially those requiring low latency and intense services, the definition and architecture of fog computing are focused. It delves into issues like latency reduction, fault tolerance, security, and privacy concerns in fog computing. Additionally, MEC is considered as an advanced computing model supporting the computing ability of mobile users in CPSs. It introduces a joint optimization model aiming to minimize system energy and packet congestion, demonstrating notable advantages in energy consumption and execution delay during packet transmission to MEC.

The ways begin exploring edge computing in CPSSs, designing a novel data processing pattern based on stream processing technology, focusing on distributing workload to edge devices, sharing personal computational resources, and supporting cluster computing at the network edge. An application platform for CPSCN with fog-based characteristics is presented, using a distributed dataflow programming model. It establishes an exogenous coordination model supporting the separation of computation and communication activities and addresses challenges posed by the large-scale distribution of computing resources and dynamic characteristics of mobile hosts in CPSCN systems.

Moreover, the cloud-edge computing CPSS framework concentrates on presenting the CPSS services. A framework consists of cloud and edge planes, where the former processes long-term, large-scale, global data, and the latter handles real-time situations with short-term, small-scale, local data. A tensor-based service model is developed based on this framework, and an application case is evaluated to verify its features. An edge cloud-assisted CPSS framework is introduced for smart cities, aiming to shift computation tasks from the central cloud to network edge devices, enabling lower latency and proactive services for residents and policymakers.

**2. Machine and Deep Learning:**

Despite the efficient processing of mass data at the network edge with edge computing support, advanced techniques are necessary on computing servers for hyper-intelligent data processing or hyper-automatic decisions.

In the smart manufacturing era of IoT, cloud computing, and edge computing, artificial intelligence techniques are essential for analyzing and processing big data. Factors promoting research interest in artificial intelligence include the sources of big data, machine learning methodologies, and powerful computing servers for big data computation services. The evolution of artificial intelligence is highlighted, comparing its relationship with smart manufacturing, and proposing a smart manufacturing concept for Industrie 4.0. The next generation of artificial intelligence supports decentralized control, unstructured content, machine learning, and deep learning, distinguishing it from traditional symbolic artificial intelligence.

Machine learning considered the core of artificial intelligence, allows computing servers to learn from experience without explicit programming. It can be classified into four categories: reinforcement learning, supervised learning, unsupervised learning, and semi-supervised learning.

- Supervised learning relies on training data with given input data and corresponding labels, enabling the machine to find the relation between labels and data features.

- Unsupervised learning operates without training data labels, aiming to discover hidden patterns in data and categorize input data based on intrinsic relations and similarities.

- Semi-supervised learning utilizes a small amount of labeled data along with a large amount of unlabeled data to reduce learning costs and improve accuracy.

- Reinforcement learning enables the system to receive rewards based on limited environmental knowledge and decision feedback, taking actions in response to a dynamic environment.

Deep learning, a branch of machine learning, achieves artificial intelligence through hierarchical artificial neural networks. The hierarchical structure allows deep learning to extract and screen input information layer by layer, enabling representation learning and end-to-end supervised and unsupervised learning. As artificial intelligence develops, deep learning is incorporated into reinforcement learning systems, creating deep reinforcement learning, which integrates deep learning perception and reinforcement learning decision-making. The key factors of various learning techniques in the context of IoT are considered. This situation now shifts focus to the application of these learning techniques in current CPSS works. The work on learning techniques in CPSSs primarily encompasses neural networks, classification, clustering, and reinforcement learning.

Neural networks, a form of supervised machine learning, facilitate detection, annotation, and prediction through extensive data analysis. Deep learning serves as an extension of neural networks. Intelligent algorithms based on neural networks find application in optimization scenarios. For instance, a neural network model is utilized, incorporating glowworm swarm optimization back-propagation, for optimizing vibrations in elliptical treadmills.

Beyond optimization, neural networks are employed in various applications. A novel data-driven method using deep convolutional neural networks is proposed for accurately predicting the remaining useful life (RUL) in CPSSs for industrial IoT. To enhance blind communication signal detection in CPSSs, a method based on back-propagation neural networks is introduced, improving signal detection precision. Additionally, for image annotation in CPSSs, internal relevance and imbalanced distribution of image classes are addressed, proposing a novel learning model for deep feature extraction using convolutional neural networks.

Data classification, another form of supervised machine learning, includes techniques like support vector machines, binary decision trees, and Naive Bayesian classifiers. Focusing on the majority of internet traffic being video content, it performs multivariate analysis of video call data using learning-based prediction in CPSSs. Classifiers trained by four learning algorithms, including support vector machines and decision trees, report enhanced accuracy for destination and bandwidth prediction during video conference connections.

Large data mining is crucial in CPSS development to enhance the quality of service for CPSS devices. Clustering, an unsupervised machine learning technique, is employed for discerning underlying patterns in data. Development related to clustering-based models and algorithms in CPSSs, proposing a high-order k-means heterogeneous-data clustering algorithm based on deep learning models. This aims to improve clustering accuracy for CPSSs with heterogeneous data.

Most existing clustering algorithms deal with static data, posing challenges in processing dynamic multi-modal data in CPSS environments. A parameter-free incremental co-clustering method is presented to address dynamic multi-modal data. Furthermore, an incremental clustering method is used for large-scale dynamic data, incorporating ideas from the fast search and find of density peaks approach, demonstrating improved effectiveness and efficiency.

Focusing on CPSS big data's heterogeneity, diversity, and high dimensionality construct a flexible clustering framework. An analytic and service framework is presented for flexible multiple clustering, with a tensor-based method aiming to enhance clustering quality. This framework

contributes to hyper-automation in CPSS industries. It also introduces multiple clustering methods based on tensor decomposition and multi-relational attribute ranking, efficiently handling high-dimensional data and supporting enhanced information extraction and services.

Some techniques concentrate on specific data processing problems. For instance, a multi-step clustering algorithm is presented for studying human fishing behaviors, monitoring illegal fishing, and protecting fishing resources at sea. Another focuses on sentiment classification of online reviews, proposing a word embedding clustering-based deep hypergraph model to improve classification accuracy.

In addition, they are exploring reinforcement learning in CPSSs. For example, concise techniques like parallel testing, learning, and reinforcement learning are presented to enable parallel driving in a cloud-based CPSS system framework with connected automated driving functionality. Reinforcement learning, deep learning, and deep reinforcement learning are representative learning techniques in artificial intelligence 2.0, which introduces the concepts and current status of these techniques and provides an overview of their applications in smart grids.

**3. Other Computing Techniques**

To implement extensive services, also known as service computing, geared toward providing predictive services, a multi-order distributed high-order singular value decomposition (HOSVD) method is introduced with an incremental computational algorithm. This method efficiently analyzes large-scale heterogeneous data, enhancing data diversity extensibility and adaptability, and transforming low-level data into actionable knowledge. To prevent redundant computations on historical data while handling incoming periodic data, a columnwise HOSVD algorithm and a similar columnwise incremental method is improved. This aims to scale existing big data processing methods, reducing dimensionality and noise for tensor-based big data and supporting online computation for incremental data streaming.

The mainstream technology in CPSSs is three-dimensional scanning, based on reconstruction algorithms and shape extraction algorithms with regularized points. Treating data as point clouds is an effective data processing approach. A slicing-based regularization method is suitable for scenarios with extensive raw point clouds, generating well-organized point clouds.

### 6.5.4 Cyber-Social Integration: Social Networks

Social networks are integral to CPSSs, comprising social realities like individuals, organizations, and corporations. In the cyber layer of CPSSs, social realities are interconnected nodes with specific types of interdependencies, like friendship, beliefs, financial exchanges, and common interests.

With the growing popularity of social networking sites, the total number of users in social networks has increased. Analyzing and improving social networks, given this volume, poses challenges. Social entities' dynamic characteristics further complicate analysis and processing. In response, social computing emerges, focusing on promoting social studies and dynamics through large-scale social context handling with information techniques.

Improving information propagation in social networks is crucial for efficient data dissemination. Enhancing information propagation is explored by adding new linkages to social networks while decreasing the total number of communication hubs. This improves communication effectiveness, contributing to practical social network communications and cyber-physical-social interaction and computing development.

Humans were viewed as individuals with varying levels of credibility, influence, or professional quality. Social networks view human society as a whole, arbitrarily divided. Different divisions reveal relationships among people in terms of friendship, beliefs, financial exchanges, and common interests, emphasizing human dependency. Utilizing collective wisdom instead of individual wisdom produces outstanding results.

**6.5.5 Social Layer: Social Evaluation**

Humans in CPSSs can be both service consumers and providers. An efficient social evaluation mechanism is beneficial for placing humans in both roles. However, CPSSs have been currently limited in social evaluation. Potential evaluation directions for CPSSs are considered.

When users act as service consumers, social evaluation could include satisfaction evaluation to estimate users' satisfaction after acquiring services. This common evaluation can guide service improvement and predict satisfaction before business supply, enhancing service quality. In CPSSs, the satisfaction evaluation mechanism can be employed for smart recommendation systems in real target environments, ensuring not only accuracy and helpfulness but also user enjoyment.

When users are service providers, the social evaluation mechanism encompasses influence, capability, and reputation evaluation. Influence evaluation measures a person's social influence. In CPSSs, this could determine a person's influence in an industry, leveraging high-value human resources effectively. Capability and reputation also need evaluation when users work as service providers. Capability denotes a user's completion quality in fulfilling assigned tasks, while reputation indicates whether a user honestly completes assigned tasks within the task's time-to-live (TTL).

A mechanism can inspect every aspect of each user, optimizing human resources utilization and service provision. Social evaluation can be incorporated with the human incentive mechanism motivating users with higher ability and credit to participate in CPSSs' operation and management.

**6.5.6 All Layers: Human-Machine Coordination, Resource Management, and Security and Trust**

The predominant focus of current research across all layers in CPSSs centers around human-machine coordination, resource management, and security and trust. Furthermore, with the integration of humans into the CPSS loop, certain aspects possess unique characteristics or necessitate additional considerations when compared to techniques applied to CPSs. This provides details related to human-machine coordination, resource management, and security and trust in CPSSs, with detailed information outlined in the following.

**1. Human-Machine Coordination:**

As humans are considered integral components of CPSSs rather than existing outside the system boundary, system design must facilitate the coordination and unification of humans and systems. Given the distributed environments where humans and systems coexist in CPSSs, coordination theory is viewed as an effective means to model CPSSs and overcome challenges related to complex structures and dynamic processes. In this context, a multi-dimensional meta-model based on coordination theory is introduced, encompassing coordination, human, and system views. The coordination view defines the interdependencies and actions of CPSS components, the human view explains human integration and interaction with CPSS components, and the system view presents co-organizing and structural relationships among components.

CPSSs employ both machines and humans as active computing units, allowing humans to participate as both service consumers and providers. Several coordination patterns for human-based and machine-based computing units are considered, investigating reliability among different patterns

through a reliability analysis framework. Addressing monitoring issues in coordinated CPSSs, the metric models with associated data quality are presented to support elastic monitoring of execution metrics. The monitoring framework is implemented, capturing, and analyzing runtime metrics from various compute units, including sensors, actuators, human-based compute units, software services, and gateways.

Self-organization is a primary self-control function in CPSSs, contributing to achieving the hyper-automation characteristic. An upper-level ontology for CPSSs with multi-level self-organization of CPSS resources is proposed, aiming to support human decisions, activities, and task solutions in daily life. This self-organization mechanism merges physical resources into human resources, viewing humans as participants in the resource self-organization process.

According to coordination theory, self-synchronization in CPSSs is also a self-organization and self-adapting process. The self-synchronization mechanisms are used for the command-and-control organizations in CPSSs, facing challenges from combining different domains, such as social, cognitive, information, and physical domains. The self-synchronization mechanisms include vertical self-synchronization across domains and horizontal self-synchronization within each domain. A CPSS framework is proposed, supporting the dynamic operational mechanism of self-synchronization for the entire command and control organization. This framework couple humans and physical systems in the loop, emphasizing human-system interaction during command and control. Humans' observation, orientation, decision, and action are supported by physical systems, while physical systems make supplementary decisions or implement routine work based on human organizational intelligence.

**2. Resource Management:**

To enhance system performance, the focus shifts to resource management in CPSSs, encompassing computing, communication, and power resources.

- **Computation Resources:** CPSSs house abundant computation resources crucial for real-time analytics and business intelligence. A general model for tensor computation is designed, optimizing economic cost, energy consumption, execution time, reliability, and security through a tree-based distributed HOSVD method. Social users in CPSSs can be considered computation resources. A bargaining game theoretic approach was introduced for task allocation in high-confidence CPSSs. A trust evaluation mechanism assesses user reputation, and a virtual currency-based incentive mechanism encourages users to handle computation tasks. A user reputation-based incentive scheme is designed, to classify social users into malicious, speculative, and honest types, promoting crowdsourcing services. The optimal social users are selected through an auction game model, enhancing the accuracy of sourcing data.

- **Communication Resources:** Effective deployment of communication resources is crucial for the rational functioning of CPSSs. A social interaction model is designed for self-managed smart CPSS devices in WiFi scenarios. An active interference measurement methodology detects in-range and hidden terminal interference, and a Nash bargaining-based coordinated power control method reduces interference. Spectrum management ensures communication requirements of social components. A joint resource optimization and access control scheme based on the parallel network architecture is designed, classifying social users based on priorities and bandwidth requirements. Q-Learning is applied for automated network configuration, management, and optimization. A resource allocation problem is formulated to maximize the communication energy efficiency of cyber-physical IoT systems. The scheme decomposes the optimization problem into power and channel allocation, demonstrating

efficiency in energy efficiency and quality of services. An energy-efficient resource allocation scheme is proposed under imperfect channel state information, significantly promoting system energy efficiency and meeting transmission outage requirements of CPSS controllers and actuators.

- **Power Resources:** Optimization of power is not confined to communication and computation fields. For instance, addressing the increased variability in renewable power generation, such as wind and solar power, suggests that managing the electric power loads of consumers is a promising approach. A centralized demand-side management approach for the cyber-physical-social electric grid is proposed, incorporating sensing, communication, and computation technologies. Flexible power loads of consumers are modeled to maximize total utility while minimizing overall power consumption, subject to operational constraints. Power loads can also be controlled through a decentralized approach based on a non-cooperative game. Results demonstrate the validity of a monotone utility game in the proposed decentralized approach, providing robust lower bounds on the anarchy price. Human interactions in managing CPSS power loads are emphasized, assuming that system input is induced by human behavior. A convex optimization problem is formulated to minimize power loads and price compensations for user participants, stimulating human decision-making to construct a system-wide optimization model. The accurate prediction of reducible power is verified through experiments.

  In CPSSs, both energy suppliers and demanders can be humans in the social space, cooperating and making decisions with different preference behaviors. Designing a distributed energy management scheme is focused on a microgrid based on CPSSs with parallel learning. The scheme minimizes total operating energy cost while guaranteeing energy balance, capacity limits, operating regions, and minimum demand constraints. It is verified to be effective in improving the quality optimum of distributed energy management.

Moreover, job splitting and allocation are critical factors for processing CPSS big data. A job allocation mechanism is proposed to minimize battery consumption, continuously reflecting the battery consumption rate of mobile devices to handle jobs. It minimizes the job reallocation problem based on periodic measurement results of battery consumption and surplus resources. This mechanism avoids job reallocation due to battery rundown, demonstrating increased job processing speed. To extend the service life of CPSS devices, especially human-type devices, the emerging technique of wireless power charging is studied based on radio frequency with mobile chargers. An optimization problem is formulated to minimize energy consumption during IoT device charging by planning the motion trail of the mobile charger and determining efficient charging points. It reveals near-optimal performance in terms of charging efficiency.

**3. Security and Trust**

Security and trust issues are common concerns for both human society and systems in CPSSs. Security threats, including information leakage, inference attacks, and associated risks, pose significant challenges in CPSSs. The attackers may seek opportunities pointed out that to acquire sensitive information and data in the system. The different leakage models with inference methods are identified, indicating that some information leakage models can tolerate powerful attacks with little prior knowledge. Additionally, novel inference attacks are proposed based on partial knowledge of target documents, shown to be more scalable and effective without optimization overheads. The CPSS-associated risks are investigated by using a hybrid Bayesian risk graph model to estimate and evaluate risk propagation in a layered risk architecture. It analyzes temporal attack activity patterns in dynamic CPSS environments.

Secure deduplication and secure verification are advanced techniques for data management efficiency and data privacy preservation in CPSSs. A convergent key management scheme is proposed based on the session key, ensuring the security of dynamic updates for data deduplication. A convergent key-sharing scheme is presented to support group combination and remove the gateway aid, achieving computation and communication efficiency for key management. A secure certificateless public integrity verification scheme is proposed, supporting certificateless public verification and resistance against malicious auditors, providing stronger security guarantees. Moreover, a privacy preservation framework is proposed based on real-world knowledge of CPSSs, constructed with user expectations and privacy concerns. A data publishing mechanism is designed to conceal sensitive user profiles while guaranteeing comprehensive social profiles. It indicates that the scheme achieves locally maximized performance on the published data size.

Trust, realized by analyzing expectations of social interactions and dependencies among humans and other components, is a key subject for the development, operation, and management of CPSSs. Structured assurance cases are used to analyze trust in CPSSs, demonstrating the utility and feasibility of the proposed trust analyzing method with a telemedicine domain example. The smart and connected senior caring systems are explored, discussing the necessity of trust in CPSS design and trust formalism approaches. Additionally, trust problems among artificial agents of humanoid robots and virtual humans are addressed in a CPSS. A robot-virtual human bilateral trust model is proposed to support the system with a trust guarantee, featuring real-time trust measurement to facilitate collaboration between virtual humans and robots and assist in various human tasks.

### 6.5.7 All Layer Integration: Ad-Hoc and IoT

#### 1. Ad-Hoc Networks

Efficient connectivity among the social, cyber, and physical components in CPSSs is crucial for their synergistic promotion through ad-hoc connections among devices in CPSS networks. Establishing an ad-hoc CPSS network poses challenges, such as:

- Simultaneously associating all relevant nodes due to limited network resources like power consumption and spectrum.
- Maintaining a fixed network state amidst device mobility, which can lead to network performance degradation.

To address these challenges, a novel mobility-aware method with a reliable local tree-based topology is presented for constructing an ad-hoc mobile smart system. This method aims at achieving adequate network connectivity while minimizing power consumption. Additionally, a specific scenario of dynamic transportation systems, namely, vehicular ad-hoc networks (VANET) is focused and proposed an analytical approach to evaluate network performance by dynamically adjusting the transmit power and contention window of vehicular communications. Monte Carlo simulations indicate that the proposal achieves dynamic adaptation effectively compared to existing works.

#### 2. IoT

The concept of the IoT represents an ambitious plan and ultimate goal. It shares several similarities with CPSSs, including:

- Interaction among the social world, physical world, and cyber world.
- Detection of physical components in the real world through information-sensing equipment.
- Transmission and sharing of measured data information over the communication network.
- Computing of measured data through central and distributed controllers to achieve safe, effective, and intelligent monitoring.
- Wide-ranging application fields such as smart traffic, smart homes, smart hospitals, smart grid, smart industry, and smart agriculture.

IoT differs from CPSSs in its emphasis on architecture design:

- CPSSs focus on a system with a vertical system architecture for realizing various intelligent applications.
- IoT emphasizes a network with a horizontal system architecture, aiming to interconnect all physical components in the network through the transport layer. The outcome of IoT can be seen as the integration of information technologies and physical objects or systems.

In contrast to CPSSs, IoT emphasizes the internetworking of every element, possessing a horizontal architecture. Along these lines, IoT is considered an efficient approach to achieving the interconnection of all CPSS devices through the transport layers, extending almost everything. The resource optimization and trust problems for CPSSs are explored and powered by IoT.

### 6.5.8 Insights of Techniques and Networks

CPSSs strive for the real-time and comprehensive fusion of the cyber world, physical world, and social world, embodying hyper-connectivity, hyper-intelligence, and hyper-automation, as illustrated in **Figure 6.9**. The techniques and networks detailed above play a crucial role in ensuring these fundamental hyper-characteristics within CPSSs.

- **Hyper-Connectivity:** Communication techniques in the physical layer serve as potent means to facilitate ultra-high-speed connections among various components in the physical world. These techniques can also be applied to sensor networks and social networks, fostering integrations between the physical-cyber and cyber-social realms. Additionally, ad-hoc and IoT networks contribute to efficient and effective connectivity among social, cyber, and physical components in CPSSs.

- **Hyper-Intelligence:** This hyper-characteristic is upheld by numerous techniques in cyberspace, including edge computing and machine/deep learning. These techniques ensure that the system can generate valuable decisions, ultimately enhancing the quality of human life.

- **Hyper-Automation:** Learning techniques not only provide intelligent services to service consumers but also serve as a means for high-level automatic regulation based on intelligent analyses and decisions. Consequently, they contribute to achieving hyper-automatic control in CPSSs. Furthermore, the self-control functions and coordination mechanisms also play a role in realizing hyper-automatic management in CPSSs.

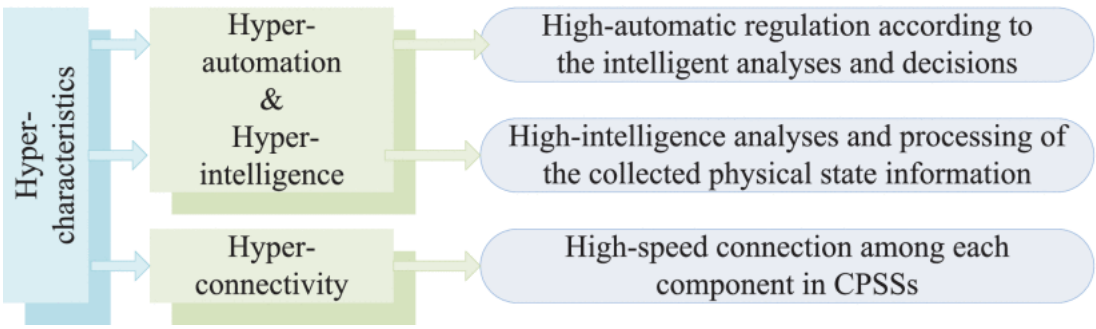


**Figure 6.9** The hyper-characteristics of CPSSs.
[Source: Zhou, Y., Yu, F. R., Chen, J., & Kuo, Y. (2020)]

Automation and intelligence can accomplish specific human objectives with little or no human intervention, creating a potential contradiction to the core principle of CPSSs, which emphasizes human involvement. It is important to note that CPSSs capitalize on the notion that humans can generate innovative solutions and possess collective wisdom, implying that decisions made collectively by a group of individuals often yield exceptional results. While these technologies can achieve highly intelligent and automated control or management, they might not consistently foster innovation. Furthermore, both automation and intelligence do not inherently prioritize serving humans, and involving humans in the decision-making process can enhance service effectiveness. However, in the context of CPSSs, there is still a need for further exploration of intelligent automatic control and management, especially regarding the harmonious coexistence of automated smart systems and human participation.

Additionally, this state in various technical domains reveals uncertainty about effectively integrating social networks and social evaluation into CPSSs. The benefits of incorporating social networks and social evaluation are highlighted, but significant challenges persist. These challenges include determining how to select social groups based on evaluation values and evaluating each individual within a social group after task completion. Moreover, when leveraging collective wisdom to serve the system, the situation becomes more intricate. For instance, how does the system reconcile conflicting opinions within a social group? Determining the dominance of each person in the group adds complexity to system design and optimization.

### 6.6 Issues and Challenges

The directions by considering challenges and potential solutions.

#### 6.6.1 Energy Management

CPSSs with their broad applications connecting nearly everything in our daily lives face a significant challenge of energy consumption. Many connected devices, such as sensors, actuators, and user devices, have limited energy resources. Addressing the energy consumption problem is crucial for achieving the overall system optimization goal, ensuring sustainability.

The challenge in energy management for CPSSs lies in balancing energy consumption with other performance indicators. For instance, reducing transmission rates can attenuate communication power, and lower computational efficiency can save computation power. Thus, tackling energy consumption needs to consider other index requirements.

Here are potential solutions for energy management in CPSSs, addressing the challenge:

- **Energy-efficient design**: Designing novel energy optimization protocols to balance energy performance with other indicators, a common strategy in various network applications.
- **Utilization of renewable energy:** Designing CPSSs to leverage renewable energy sources like wind, hydropower, and solar, though this requires special conversion equipment, increasing construction costs and floor space.
- **Harvesting radio energy:** Harvesting energy from radio frequency sources, such as interference signals, which does not require excessive equipment space but faces random variations in radio frequency energy.

#### 6.6.2 Intelligent Caching and Computing

The caching, and computing are areas deserving further exploration to enhance content delivery and data processing in CPSSs.

- **Intelligent Caching:** Optimizing caching in CPSSs involves cache decision and content delivery. Intelligent caching, through the analysis of system data with machine learning support, can learn and predict dynamic user behaviors and preferences. This enables intelligent cache decisions based on predicted future content popularity and user mobility.

- **Intelligent Computing:** CPSSs need real-time data analysis and processing of massive data. Separating useful data from noise is crucial. Intelligent computing, with machine learning support, can remove data impurities and support process analysis and future trend prediction. Collaborative computing, designed jointly with intelligent computing, focuses on utilizing nearby computing servers as a collaboration unit for computation tasks, promoting big data analyses in CPSSs.

### 6.6.3 Resource Coordination and Management

The multi-resource deployment offers technical advantages but requires further progress.

- **Distributed Multi-Resource Deployment**: CPSSs, with their ubiquitous interconnections, face challenges in optimizing computation complexity due to their large scale. Distributed algorithms, such as the Alternating Direction Method of Multipliers (ADMM), decouple optimization problems into subproblems executed on different virtual CPSS controllers, reducing signaling overhead and computation complexity.

- **Context-Aware Reliable Crowdsourcing**: Efficiently leveraging human resources in CPSSs is an area that needs more attention. Context-aware techniques, utilizing user information like locations, times, environments, adjacent members, equipment, and activities, can infer events and enhance crowdsourcing applications. Context-aware reliable crowdsourcing is a potential solution for efficient task assignment and execution among social groups. The reliability of results depends not only on the leader's reputation but also on contextual work, emphasizing the importance of user evaluation and incentive mechanisms.

### 6.6.4 Security and Privacy

CPSSs interconnect physical and computer systems, creating a larger attack surface compared to pure computer systems. Side channels in the physical system, such as power consumption, timing, electromagnetic emissions, and even disk drive sound, allow observation and manipulation of the computer system. The robust security measures are crucial in CPSSs.

Additionally, the proliferation of CPSSs, especially those enabled by IoT, connects various aspects of daily life. Ensuring privacy among interconnected devices becomes paramount. CPSSs also link social worlds with CPSs, requiring secure communication channels to admit new participants while protecting user information, including data and locations.

**1. Security**

Current security measures are typically applied at upper layers, assuming reliable physical links. To address this, physical layer security emerges, focusing on the physical layer and adopting information-theoretic principles. Security is ensured and enhanced by analyzing mutual information among senders, receivers, and eavesdroppers, preventing side-channel attacks under different channel conditions. However, real scenarios pose challenges, and information-theoretic principles may not guarantee absolute security. Jointly designing physical layer security with upper-layer protection strategies can strengthen CPSS security.

**2. Privacy**

Traditional privacy methods like anonymity and fuzzification may be inadequate for data and location privacy in CPSSs due to multiple data fusion requirements. Traditional cryptography has a limited impact on Privacy: timely big data analyses. The differential privacy model is advanced, protecting user location privacy while retaining useful information for data analyses. It is independent of the attacker's background knowledge and computing ability, offering advantages like assumed maximum background knowledge and a solid mathematical foundation.

### 6.6.5 Cross-Layer and System Design

The term "system" in CPSSs refers to different intelligent systems, like smart factories and grids, or different functional systems such as communications, caching, and computing. The heterogeneous nature of connected infrastructures and wireless resources requires CPSSs to be compatible with different intelligent and functional systems, each with unique requirements. Designing a standardized protocol and strategy is challenging, as different standards for different systems consume a significant part of the design space.

CPSSs do not strictly follow the OSI model; they directly interact with the physical worlds, comprising the physical layer, cyber layer (control platform and data platform), and social layer. Existing protocols and strategies need updating to adapt to CPSS system architecture with virtualization. CPSSs require applications coexisting in each layer with different design and optimization objectives, leading to potential conflicts. Traditional works might not be applicable, and a cross-layer and system design is necessary. Existing works have yet to explore this adequately. Extending multi-resource deployment schemes and security measures to different layers and systems is essential, balancing various indicators from both system and user perspectives.

## 6.7. Chapter Summary

This chapter delved into the domain of CPSSs, which integrates CPSs with the social world, emerging as a crucial factor for shaping the smart world. The exploration commenced by tracing the evolution of techniques from CPSs to CPSSs. Subsequently, the existing CPSS architecture was utilized. Motivations and requirements for infusing CPSSs with Wireless Network Virtualization (WNV) were studied, leading to the dialogue of a virtualized CPSS architecture. To enhance ubiquitous CPSS computation services and scalable content retrieval and delivery, an integrated framework encompassing caching, computing, and networking for CPSSs was illustrated. A four-dimensional joint optimization was introduced to validate the performance enhancements via simulation. The chapter then synthesized the recent works on CPSS applications, including discussions on common standards and real-world case studies, providing insights into how different components, standards, frameworks, or protocols harmonize CPSS functions. Furthermore, enabling techniques and networks for CPSSs were scrutinized to advance hyper-connectivity, hyper-intelligence, and hyper-automation. This encompassed potential techniques across layers and network applications for layer integration. Although CPSSs present a broad research landscape with numerous challenges, it is imperative for the wireless community to promptly address these challenges and forge ahead.

**Problems**

1. Explain the development of the cyber-physical-social system.
2. Describe the key architectural of the cyber-physical-social system.
3. Characterize a virtualization process for the cyber-physical-social system.
4. Give a concept of the application of CPSS in transportation.
5. Provide a detail of the application of CPSS in energy distribution.
6. Describe the standards of CPSS in the industry.
7. Specify the standards of CPSS in the smart grid.

8. Describe the standards of CPSS in healthcare.
9. Distinguish the enabling techniques and network in CPSS.
10. Define the issues and challenges in CPSS.

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# Chapter 7

# Modeling Cyber-Physical Systems

**Chapter Objectives**

- Learners can explain the modeling of cyber-physical systems.
- Learners understand the modeling of cyber-physical systems.
- Learners become familiar with cyber- physical modeling.

A wide array of cyber-physical system (CPS) applications, encompassing design, control, diagnosis, prognostics, and various other tasks, rely on the availability of models. Typically, there are two primary approaches to modeling: Physics-based or Equation-based modeling (referred to as Model-Based, MB) and Machine Learning (ML). There has been an increasing recognition that ML techniques, which rely heavily on data, should be combined with existing scientific knowledge (or physics-based approaches, MB) to model CPS effectively. This integration of MB with ML is often referred to as a hybrid learning method. Hybrid modeling (HB) methods represent a burgeoning area within both the ML and scientific communities, recognized for their potential but still in the early stages of development. Several studies have endeavored to merge MB and ML models to fully exploit their combined strengths. However, existing development is scattered and lacks organization. Therefore, it undertakes a systematic and thorough effort to categorize and standardize methods for combining ML and MB models. Additionally, five metrics are proposed for the comprehensive evaluation of hybrid models. The challenges associated with hybrid models emphasize areas where the modeling should concentrate to realize the full potential of these approaches. Notably, this chapter focuses specifically on hybrid modeling within the context of cyber-physical systems.

## 7.1 Introduction

Significant efforts have been dedicated by control system engineers to enhance the monitoring and control performance of the physical system. Concurrently, computer science and electronics engineers have been focusing on advancing the cyber system to improve the capabilities of computing and communication systems, leading to the widespread integration of low-cost computing and communication networks into everyday gadgets and electronic devices. This integration is anticipated to have a substantial impact on the energy system. The convergence of the physical and cyber systems has given rise to a novel digital technology known as Cyber-Physical System (CPS), gaining attention across various sectors, including agriculture, energy, medical, oil & gas industries, and transportation.

CPS is characterized as a heterogeneous multi-dimensional system with an integrated cyber component (control, computing, communication) aimed at achieving stability, robustness, efficiency, and reliability in physical systems applications. Within CPS, the cyber system acquires data from the physical system through sensors and provides control signals back to the physical system to achieve common goals.

A CPS is a system that harmonizes the internet and physical system elements, functioning as distributed networks in unpredictable environments. It employs control systems and embedded systems to monitor and regulate the physical power system in real-time, creating a structure of interacting elements with physical input and output. Unlike simply adding computing and communication techniques to conventional inventions, CPS involves the integration of computing and networking with physical systems to generate innovations. Cyber, in this context, refers to the integration of communication, computation, and control systems, while physical pertains to natural and human-made power systems governed by the laws of physics, as shown in **Figure 7.1**.

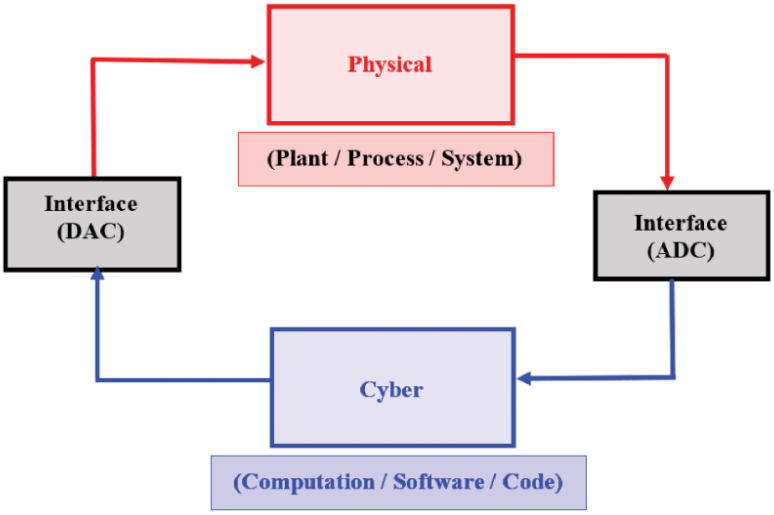


**Figure 7.1** Structure of the cyber-physical system.
[Source: Yohanandhan, R. V., et al. (2020)]

In this model, CPPS is represented as the interconnection of a physical system, a cyber system, and the components that link them. The physical system encompasses the system's physical components that require monitoring and control, while the cyber system involves computational algorithms, including control or communication algorithms. Components linking the physical and cyber systems include Analog-to-Digital Converters (ADC), Digital-to-Analog Converters (DAC), and Digital Networks. The hybrid dynamical system theory is employed for CPPS modeling, utilizing differential equations to portray the continuous-time behavior of the physical system and difference equations to represent the discrete behavior of cyber systems, converters, and digital networks. This approach captures the mixed behavior of continuous and discrete systems, along with their interconnections in CPPS.

1) **Physical Components Modeling:** The physical system, as a continuous-time system, is modeled using a differential equation with a time parameter that parameterizes the system's variables.

2) **Modeling of Cyber Components:** Cyber components play a role in executing algorithms, carrying out computations, and transmitting data across digital networks. The state variables of these cyber components are discrete values, updated during discrete events drawn from specific sets rather than from a continuous range.

   - **Finite State Machines with Pure States**

   The Finite State Machine (FSM) is a computational model depicting the relationship between input and system state. It is utilized for representing control execution flow or simulating sequential logic in various applications. The FSM's state and output are updated with every

input value. The FSM's states, inputs, and outputs derive values from discrete sets and undergo updates during discrete transitions triggered by inputs.

- **FSM Incorporating Conditional Structures**

In specific applications, FSM transitions hinge on conditional structures; for example, a transition might be prompted when the input. This conditional structure involves a Boolean expression. If the evaluation yields a true condition, the transition is activated; otherwise, it is aborted.

- **Modeling of Computer Computations and Discrete-Time Algorithms**

Two types of computations exist: one-shot computation and iterative computation. The computation model is depicted in a discrete-time system as the input and the output. Difference equations find application in modeling discrete-time algorithms. The discrete-time feedback controller can be formulated either by discretizing a continuous-time controller, designed through continuous-time system design tools, or by directly designing the discrete-time feedback controller.

3) **Modeling the Interface System Between Cyber and Physical Components**

The model illustrates the distinct dynamics of cyber and physical systems: discrete dynamics for the cyber system and continuous dynamics for the physical system. Interfaces play a crucial role in connecting cyber and physical systems and appropriately converting signals. The mathematical model of these interfaces, connecting the cyber and physical systems, integrates the cyber system, physical system, and interfaces, forming the comprehensive model of CPS.

- **Analog-to-Digital Converter (ADC)**

The ADC serves as a sampling device or sensor, transmitting measured information from the physical system to the cyber system. Its primary function is to sample the physical system's output at a rate, sending the samples to the embedded computer in the cyber system. The ADC model involves two states: the sample state and the timer state. When the timer reaches the sampling time, it resets to zero, updating the sampler state with the most recent output from the physical system.

- **Digital-to-Analog Converter (DAC)**

The DAC transforms digital signals into analog signals for use in the physical system. The Zero-Order Hold (ZOH) model, commonly used for DAC, updates its output at discrete instants periodically and maintains a constant output between updates until new information is available at the next sampling time as a mathematical modeling of the DAC.

- **Digital Networks**

Information transfer between the cyber and physical systems, or between cyber system subsystems, occurs via a digital network. This network bridges all subsystems and components, transmitting sampled information at discrete-time intervals. If the triggering condition is met, the information at its input is transmitted over the digital network and stored until new information arrives. Let's assume the information was transmitted over the digital communication network at specific time instants.

4) **Combining Models of Cyber and Physical Components**

The comprehensive mathematical model of CPS is achieved by interconnecting individual models of cyber and physical components with interfaces of the feedback interconnection modeling of CPS. The individual CPS models are interconnected to derive the complete

mathematical model of CPS, incorporating continuous and discrete dynamics through combinations of differential and difference equations or hybrid inclusion forms.

The impetus behind the integration of various sensors, computational intelligence, communication, and control mechanisms to imbue a wide range of CPSs with smart capabilities represents the forefront of ComputingScopes. CPSs, being intricate systems capable of Cognition, Communication, Computation, and Control (4C), are comprised of four primary components each serving distinct functions. These components include a physical infrastructure equipped with sensors for detecting stimuli and collecting raw data, actuators for responding to stimuli, a computational intelligence platform for processing responses based on stimuli, and a network facilitating interconnectivity among these elements. The architecture and operation of a CPS are illustrated in **Figure 7.2**. This review centers on the advancement of intelligent computational techniques (part of the CPS's computation component) capable of utilizing raw data acquired by CPS sensors to generate actionable insights, often concealed within the data.

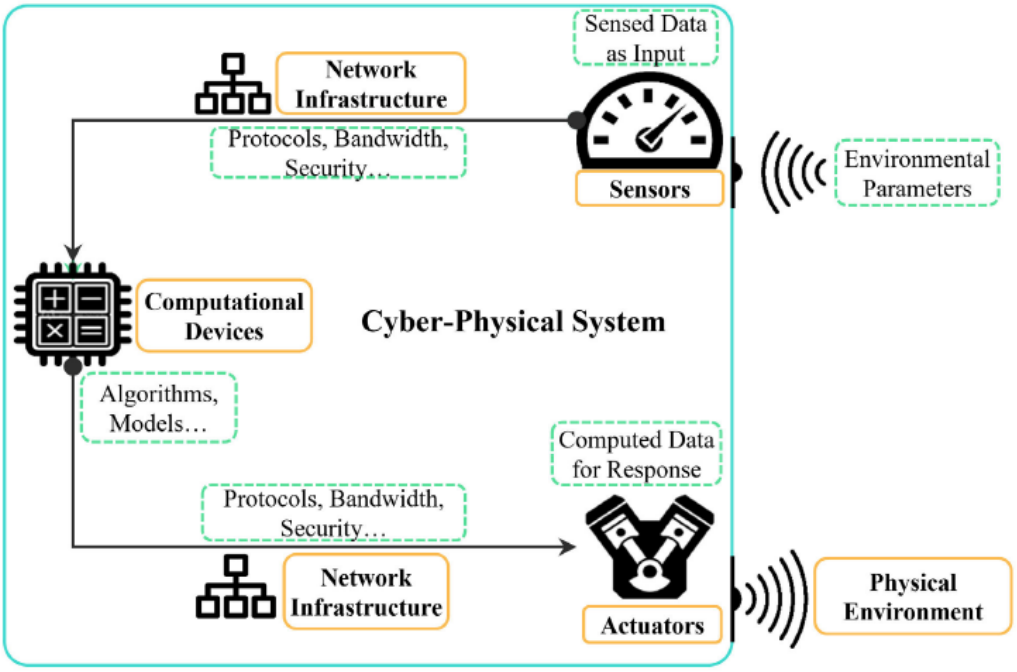


**Figure 7.2** Diagram of a Cyber-Physical Systems depicting the physical and cyber components. [Source: Rai, R., & Sahu, C. K. (2020)]

A variety of applications in Cyber-Physical Systems (CPS), such as design, control, diagnosis, and prognostics, rely on the availability of models. Two main modeling approaches exist: Physics/Equation-based modeling (Model-Based, MB) and Machine Learning (ML). Model-based methods presume the existence of precise system models, while data-driven methods are rooted in machine learning. Purely data-driven ML methods disregard any understanding of the physical or abstract systems. Furthermore, ML approaches necessitate ample labeled training data, which is often unavailable. MB approaches demand robust physics models and accurate parameter specifications. However, when constructing models for complex CPSs, limitations arise due to inaccessible system component parameters, incomplete technical specifications, obscured physical interactions, or interactions too intricate to model from fundamental principles. Consequently, simplifying assumptions (e.g., linear approximations) are often made, leading to coarse models that inadequately depict real system behavior. A prudent strategy involves hybrid methods that leverage system physics and prior domain knowledge to guide the development of machine learning techniques like

Deep Neural Networks (DNNs). This primary objective is to explore challenges associated with developing hybrid methods that integrate multi-physics equation-based models with data-driven machine learning models to enable predictive modeling of CPSs in the presence of imperfect models and sparse, noisy data.

### 7.2 Modelling

A cyber-physical system integrates physical entities and processes with computational capabilities to bridge the gap between the physical world of sensors and actuators and the virtual world of information processing. The CPS has garnered significant attention and is envisioned to revolutionize various domains by the federal Networking and Information Technology Research and Development (NITRD). These domains include agriculture, building control, security, energy management, hazard response, healthcare, society, transportation, environment, and manufacturing industries. Despite burgeoning interests and investments, the field of CPS is still in its early stages.

The progress in CPS automation can be categorized into three eras. Initially, the automation focused on labor-intensive and hazardous tasks, followed by the automation of routine activities such as clerical tasks and service transactions. Currently, in the third era, CPS is evolving to make autonomous decisions. Artificial intelligence (AI), particularly machine learning, plays a crucial role in enabling CPS to make automated decisions for physical tasks. While traditional automation addresses manual tasks with low cognitive demand, AI-powered automation has the potential to handle more cognitively challenging tasks. However, several research challenges remain open. CPS must ensure precision, accuracy, and low latency, bridging the gap between the computing and physical worlds. Addressing issues of time and space asynchrony, privacy, security, heterogeneity, and complexity are also essential. Moreover, CPS must comprehend and model internal, external, and cross-functional dynamics while integrating discrete logical functions from the virtual computing world with the continuous physical dynamics of the real world.

Various approaches have been undertaken to model CPSs in order to leverage their transformative potential. Depending on the specific objectives of the CPS and its inherent characteristics, modeling techniques have diversified into four main categories:

- Physics-based equations
- State machine-based models
- Rule and agent-based models
- Data-driven models

These modeling paradigms are visually depicted in **Figure 7.3**. These techniques encompass white-box models, grey-box models, and black-box models. Physics-based equations and state machines are employed to represent the continuous and discrete dynamics of a system, respectively, relying solely on the system's physical dynamics. While robust, they lack intelligence. Rule and agent-based models utilize both system-generated data and domain knowledge, rendering them more capable. Data-driven methods exploit available data. The following provides a critical evaluation of these modeling paradigms.

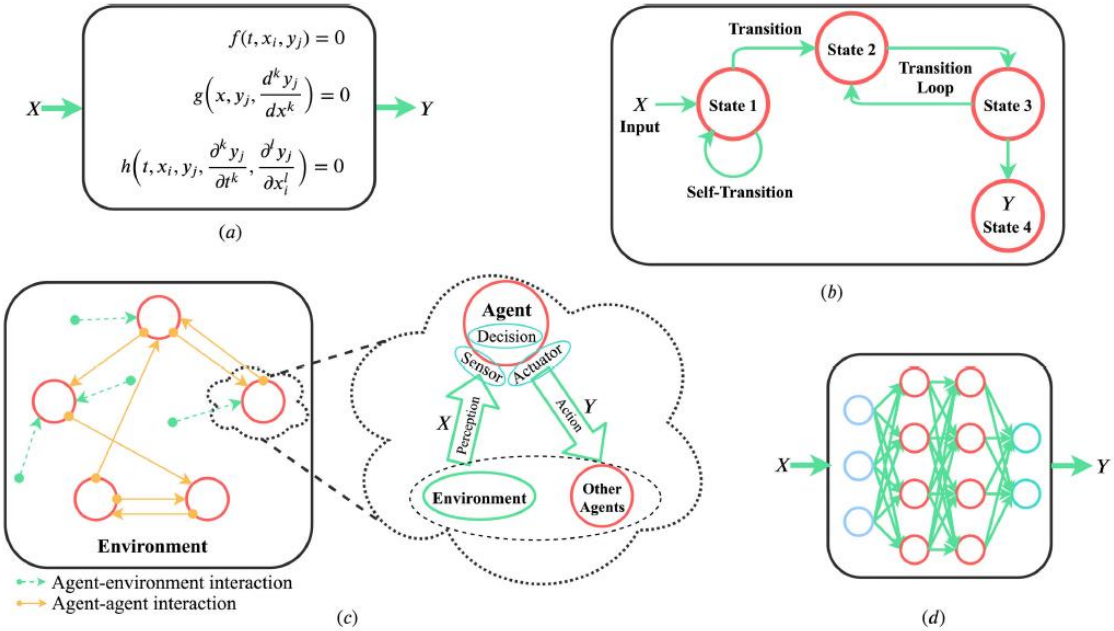


**Figure 7.3** CPS modeling paradigms: (a) Physics-based equations; (b) State machines; (c) Rule and agent-based models; (d) Data-driven (DNN) models.
[Source: Rai, R., & Sahu, C. K. (2020)]

### 7.2.1 Physics Equation-Based CPS Modeling

The continuous nature of the physical dynamics inherent in all systems, including CPSs, is effectively represented by physics-based equations in **Figure 7.3(a)**. These models typically manifest in the form of equations, which can range from simple dependency equations to ordinary or partial differential equations, or a combination. In the case of complex systems, it is difficult to identify the individual impact of a parameter accurately. In such cases, the dynamics take the form of partial differential equations. The equation-based models are limited to modeling continuous dynamics. Causality, conservation laws, objectivity, and composability are the main attributes of physics-based equations.

### 7.2.2 State Machines-Based CPS Modeling

State machines are utilized for modeling discrete dynamics, which involve a series of distinct sequential steps, such as the number of times a ball bounces under the influence of gravity. Unlike continuous dynamics, which exhibit smooth transitions, discrete dynamics are characterized by abrupt changes. These changes occur instantaneously, resulting in a zero derivative before and after the event, but tending towards infinity at the moment of change. Discrete dynamics can be represented using finite-state machines or extended-state machines, depending on the complexity of the system. These machines can operate on either event-triggered or time-triggered principles. Mathematically, a finite state machine is defined by a tuple comprising five variables: States, Inputs, Outputs, Update, and Initial State. State machines can be broadly categorized into Mealy machines and Moore machines. In Mealy machines, the output is generated during a transition, whereas in Moore machines, the output is produced when the machine is in a specific state. These two types of machines can be converted into each other. An illustrative example of a simple finite state machine model is provided in **Figure 7.3(b).**

State machines offer an efficient approach to modeling discrete dynamics, sharing properties such as causality, time invariance, linearity, stability, and memorylessness with physics-based equations.

### 7.2.3 Rule and Agent-Based CPS Modeling

CPS can also be depicted using a group of agents and semantically defined rules, offering a method that surpasses the limitations of state machines in capturing interdependencies among different states. Rule and agent-based models are designed to address the intra- and inter-dependencies among cyber and physical components, along with the inherent heterogeneity and complexity of CPS. These systems are also known as multi-agent systems (MAS) and agent-based models (ABM). MAS or ABM describes the system by delineating its constituent parts, making them particularly effective for modeling systems where the whole is greater than the sum of its parts due to their interactions. MAS relies on a set of sensors to perceive the environment and generate data, which is then processed by intelligent agents using decision-making algorithms as shown in **Figure 7.3(c)**. These agents base their decisions on semantically defined rules, enabling MAS to derive valuable insights from the available data. Key attributes of intelligent MAS include temporal continuity, social skills, and autonomy. Unlike physics-based or state machine-based models, which may face challenges related to adaptability and interoperability in CPS, rule and agent-based systems are inherently smart and adaptable. This accounts for the significant growth in research focused on rule and agent-based models of CPS in recent years. However, the complexity of some systems presents a notable challenge to MAS, similar to the challenges encountered in physics-based or state-machine-based models.

### 7.2.4 Data-Driven CPS Modeling

Data-driven models rely solely on data and do not require knowledge of system dynamics. These models must be capable of capturing the inherent characteristics of CPS, including both continuous (regression) and discrete (classification) dynamics.

Various approaches have been attempted to develop data-driven models for capturing hybrid dynamics in CPS. These approaches have drawn upon concepts from Bayesian learning, algebraic geometry, bounded error, compressive sensing, inference of state transition logics, regression techniques with recursive clustering and linear multi-class classification, symbolic regression, and hybrid stable spline algorithms, among others. Earlier methods typically focused on simple piecewise affine systems with linear transition rules, while more recent methods aim to capture nonlinear dynamics from relatively complex systems. Deep Neural Networks (DNNs) have gained widespread recognition for their ability to learn complex nonlinear functions and have started to be used in modeling CPS. There is a growing consensus that models powered by artificial intelligence, such as DNNs, are best suited for achieving acceptable levels of autonomy in CPS by addressing the uncertainties of the real world.

However, deep learning techniques have their limitations, including their inability to generalize beyond their initial training data, sparse training data sets, agnosticism to underlying physics resulting in predictions inconsistent with physical laws, and challenges in anomaly detection, particularly when anomalies lie in the tail end of the data distribution. To address these limitations, the focus is on combining conventional physics knowledge with neural networks to enhance the performance of data-driven CPS modeling for state assessment.

## 7.3 Obstacles in Modeling Cyber-Physical Systems

The models of CPS must encompass every element of the system, including physical components, processes, computational algorithms, software, and networks. The interpretability and composability of physics-based models are key factors driving their widespread adoption. Interpretability helps

prevent failures, while composability facilitates the construction of complex CPS. Together, they make physics-based models indispensable in the field. However, these model-based systems face various challenges, including solver dependency, Zeno behavior, non-determinacy, system heterogeneity, maintaining consistency among model components, distributed behavior, and misconnected components.

Different numerical solvers used in CPS models may exhibit varying numerical precision, resulting in different behaviors of the models. As simple components evolve into complex systems, understanding and modeling the interactions among components becomes more challenging. Ensuring consistent evolution among all components is also difficult. Moreover, factors such as computation and communication delays, uneven time measurements across components, loss in communication, and network delays must be incorporated into the models. While our aim is not to address all these challenges, it primarily focuses on specific CPS modeling challenges that can be mitigated or minimized by combining model-based and data-driven methods.

### 7.3.1 Discretization of the Continuum

In cyber-physical systems, discrete dynamics are exhibited by cyber components such as microprocessors and digital communication networks, while continuous behaviors are portrayed by physical elements like electro-mechanical, human, and chemical components. Therefore, modeling a CPS involves addressing both continuous and discrete behaviors and their interactions. To model a CPS effectively, continuous behavior must be integrated with discrete behavior. Computational models, which inherently represent discrete dynamics, need to capture continuous behavior through methods like numerical approximation or integration. The time precision of computational models should be finer than that of the discrete system dynamics to adequately capture discrete events.

However, computational models have a fixed time precision limit, posing challenges when continuous events become extremely fine. As physical events become finer, occurring in increasingly shorter time intervals, countless events may happen within a small timeframe. For instance, consider a ball bouncing under gravity with wind resistance and energy loss during collisions, resulting in diminishing bounce amplitudes. Eventually, the amplitude becomes so small that differentiating between successive free falls becomes difficult, and the time intervals between events shorten considerably. This phenomenon, known as Zeno behavior, entails infinite events occurring within a finite time interval, posing significant challenges for system modeling. The point beyond which events cannot be accurately modeled by the computational model is termed the Zeno point. Although determining the Zeno point is challenging, prior research has made attempts to address it in CPS modeling, yet there remains a lack of comprehensive work on modeling Zeno behavior.

### 7.3.2 Environmental Chaos and Limits of Determinism of Models

In addition to the challenge of discretizing the continuum, two additional challenges hinder the robustness of CPS models: chaotic environmental behavior and the limitations of model determinism. Deterministic systems are predictable, where accurate predictions can be made if inputs, system parameters, and initial conditions are precisely known. However, many nonlinear feedback systems encounter uncertainties, even seemingly robust real-time systems like standard scheduling algorithms can exhibit chaotic behavior in the presence of uncertainty. Chaotic behavior undermines determinism, an essential property facilitating definitive CPS analysis and enabling complex, reliable designs. Nonetheless, deterministic models are inherently incomplete. For instance, a single-threaded imperative program is deterministic when only considering the output but becomes non-deterministic when factoring in computation time. Therefore, inherent indeterminacy exists, leading to cases where deterministic models fail, rendering them invalid. In such scenarios, non-deterministic models become essential, reminiscent of Heisenberg's uncertainty principle, although originally

limited to quantum mechanics. However, even for practical cases, Newtonian mechanics alone is insufficient and requires supplementation with Mertonian laws to enhance practicability.

### 7.3.3 Evolution from Newtonian Systems to Mertonian Systems

With the rise of data-driven modeling, there has been a significant increase in the prevalence of Merton's systems compared to Newton's systems. This shift is attributed to the close interaction between real and artificial life, leading to the emergence of cyber-physical social systems (CPSS). While there are some initial low-fidelity model-based (MB) approaches for CPS, adapting them for processes lacking well-understood first principles, such as mobility behavior or advertisement click rates, is impractical. Modeling such systems has become feasible with the support of technologies like big data, cloud computing, the Internet of Things (IoT), neural networks (NNs), and reinforcement learning. This transition can be characterized as a shift from traditional systems, characterized by small data and big Newtonian laws, to modern systems with big data but smaller Mertonian laws. Deterministic systems have receded to the background, making way for statistical systems governed by probabilistic laws. Newton's laws alone are insufficient for modeling CPSs; Merton's laws must also be introduced. Merton's systems operate based on the principle of self-fulfilling prophecy, where a prediction directly influences its outcome due to the feedback between belief and action. Such systems operate under free will, making them difficult to control but possible to influence toward desired objectives in a probabilistic manner. The uncertainty inherent in the complex spatio-temporal dynamics of the environment creates a gap between deterministic models and actual physical systems. While causality prevails in Newtonian systems, it is challenging to achieve in Merton's systems due to their complexity, diversity, and uncertainty. Bridging this gap requires integrating model-based approaches based on Newtonian laws with data-driven approaches rooted in Merton's philosophy.

### 7.3.4 Advent of Big Data

It is essential to recognize that physics-based models for system modeling do not inherently rely on data; rather, they require a deep understanding of the causal relationships among the system's parameters and variables. The results are effective in modeling systems ranging from simple to moderate complexity, particularly those with small to medium-scale data. However, recent years have witnessed a significant increase in the volume of collected data, leading to improved insights into complex systems where inferring causal relationships can be challenging. The proliferation of data collection is fueled by pervasive sensing, rapid computational capabilities, and the widespread use of the internet, giving rise to what is known as big data.

Big data necessitates more extensive and efficient processing technologies, which have transitioned from model-based algorithms to data-driven techniques. While model-based approaches benefit from larger datasets covering the state space more comprehensively, they face challenges in handling the volume and variety of big data. The variety of data increases its complexity, potentially introducing unforeseen influences on models and contributing to their complexity. Moreover, the sheer volume of data ensures that nearly all exceptional cases are captured, each potentially revealing new phenomena that may require entirely new models.

In contrast, data-driven methods, although less explainable, are better suited to model the state space comprehensively, making them a preferable solution in scenarios involving big data.

## 7.4 Collaboration Between Machine Learning and Physics-Based Models

Both machine learning (ML) models and physics-based models serve as valuable tools for system modeling. Physics-based models, as mentioned earlier, do not rely on data but rather require an

understanding of the system's dynamics for modeling. They may incorporate data to refine their accuracy. Conversely, ML models depend on data to model the system, enabling them to adapt to various system types without prior knowledge of their dynamics. However, data collection is limited by the discrete nature of system parameters and output variables, resulting in incomplete datasets. Consequently, ML models may struggle beyond the scope of their training data, lacking extrapolatability. This limitation is evident in the evolution of convolutional neural networks (CNNs), which significantly improved with the development of the ImageNet database but encountered challenges with older databases. ML models, particularly deep neural networks (DNNs), operate monolithically, hindering modularity, hierarchy, and composability, as the entire network learns simultaneously without consideration for intermediate variables. Moreover, ML models lack interpretability because they disregard the causal relationships among system variables. As ML models learn, they are prone to capturing spurious yet accurate mappings from input to output data, rendering ML a double-edged sword.

In contrast, physics-based models (MBs) have the potential to achieve completeness by considering all system dynamics, ranging from intrinsic to extrinsic and micro to mega-scale. However, capturing such dynamics is immensely challenging, often requiring intricate simulations and meticulous observations, which can be costly in terms of resources, computation, and time. Consequently, certain dynamics are frequently overlooked, and simplifying assumptions are made to streamline the model, leading to inaccuracies and incompleteness. For instance, phenomena like wind drag, energy loss from non-elastic collisions, material elasticity, and medium buoyancy are commonly disregarded, as seen in the modeling of a bouncing ball. Despite these inaccuracies, physics-based models tend to extrapolate system behavior. However, if simulations are conducted meticulously to accurately capture dynamics, the resulting models can become complex, compromising their tractability, particularly crucial in control applications. At times, certain dynamics are deliberately overlooked to enhance model amenability, further contributing to extrapolation beyond validated operating conditions, albeit with reduced accuracy.

On the other hand, acquiring data from simulations is often easier than comprehending system dynamics. ML models readily fit sparse data, effectively discovering continuous functions to fill the state space, even though data inherently cannot cover the entire state space. Therefore, while data may not fully span the state space, the model can. Given the same data, validating an MB is relatively straightforward, provided it exists. However, if the data lacks anomalies, neither ML nor MB can be validated against them. For instance, consider the acceleration magnitude of a bouncing ball under gravity, which deviates from gravitational acceleration upon impact with the ground, presenting an anomaly. If this moment is absent from the data, neither ML nor MB can ensure consistent behavior. Thus, comprehensive data capturing of all events is essential. Similarly, when a bouncing ball exhibits Zeno behavior, ML models cannot effectively model it due to limitations in data recording beyond the Zeno point imposed by simulation constraints.

However, the underlying causes of Zeno behavior can be identified, allowing MB to effectively model them. In the case of a bouncing ball, inhibiting forces from the environment—such as air drag, medium viscosity, non-elastic collisions, and the deformable nature of the ball's material—contribute to Zeno behavior, while factors like the ball's initial height and medium buoyancy act as driving forces. These nuances can only be captured using MB, highlighting the importance of complementing ML with MB. By integrating them, a comprehensive model of the CPS can be constructed. MB incorporates existing knowledge, while ML discovers unknown knowledge. Nonetheless, all models are imperfect, but some are beneficial. Hybrid models are notably more beneficial and efficient as they leverage the strengths of both approaches. The effectiveness of hybrid models compared to pure MB and ML models is illustrated in **Figure 7.4**, depicting the prediction of a quadrotor's trajectory in an autonomously operating swarm of UAVs, a typical CPS application.

Furthermore, hybrid models offer convenient recalibration. While recalibrating MB with new data may involve solving highly complex optimization problems, ML recalibration occurs incrementally, easing the process of hybrid model recalibration.

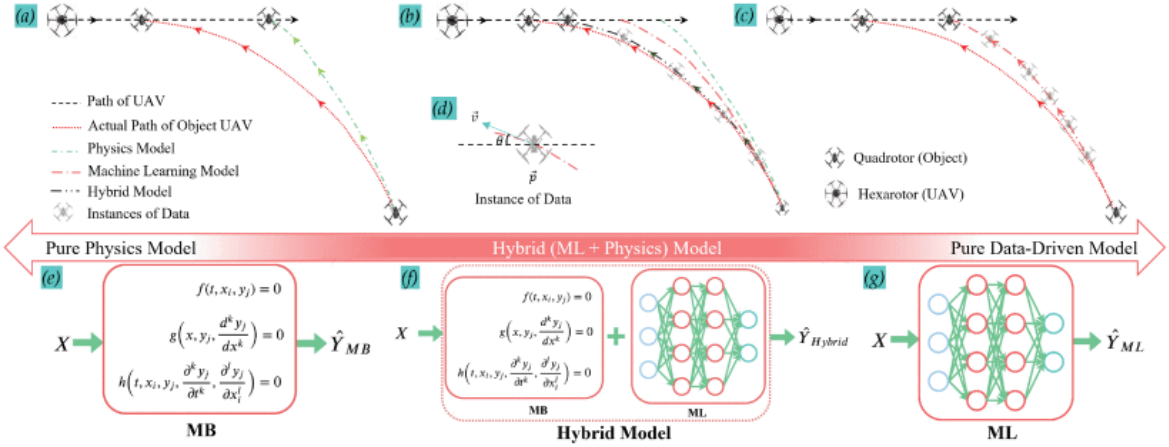


**Figure 7.4** The spectrum of a quadrotor: (a), (c) and (b) the predicted path, pure data-driven, and hybrid models in (e), (g), and (f). (d) the position, orientation, and velocity.

[Source: Rai, R., & Sahu, C. K. (2020)]

### 7.5 Hybrid Modeling: Infusing Physics into Data-Driven Models.

Consider a predictive modeling task within a CPS context, such as predicting the trajectory of an approaching quadrotor from a hexarotor within an autonomously navigating UAV swarm (refer to **Figure 7.4**). In this scenario, it has input state variables X (in **Figure 4(d)**), model parameters PMB, and the target variable Y (which represents the state variables of the quadrotor at a future time). In physics-based models, input state variables and parameter values are mapped to the target variable Y. In a purely model-based predictive modeling approach, the primary focus is on calibrating model parameters PMB using observational data. Typically, in such approaches, simplifications are made, and simple physics-based models of essential system components are developed. For instance, the response of a mechanical CPS system may be modeled as that of a linear mass-spring-damper component, despite its typically nonlinear behavior. Consequently, the output (resulting from the calibrated model) often offers an incomplete representation of the target variable due to abstraction, simplification, and missing physics, leading to discrepancies between the model output and observations Y, as depicted in **Figure 7.4(a)**. On the other hand, the data-driven machine learning approach focuses on training a model over a set of training data to generate estimates of outputs given inputs X. However, ML models also face limitations in predicting the trajectory accurately (as shown in **Figure 7.4(c)**) due to their limited ability to capture system dynamics.

In a hybrid modeling approach, the goal is to create a synergistic combination of both MB and ML methodologies, harnessing the strengths of each (as illustrated in **Figure 7.4(b)** and **7.4(f)**. One strategy to integrate them involves using the output of the physics-based model as an input to the ML model, resulting in a hybrid model denoted. Here, the ML component captures the residual complexity of the system not captured by the physics-based model, providing complementary insights for accurate model predictions. In this scenario, if the physics-based models are precise, the hybrid model will ensure that the predicted output matches the estimated output. However, if the ML model improves modeling accuracy but lacks the mechanistic coherence of the underlying system (such as violating the physical laws of the system), it cannot be utilized in the CPS modeling domain.

Hence, it is crucial to ensure that the ML model learns in a manner consistent with the physics of the system. Moreover, synthetic labeled data generated from physics-based models can be employed alongside experimental training data to mitigate the issue of data sparsity and enhance the training of ML models. Additionally, the output of a tuned hybrid model can be leveraged to generate supplementary data for fine-tuning the parameters PMB of the physics equations intelligently, especially if they were initially calibrated coarsely using sparse observations.

The hybrid modeling approach offers two key innovations: firstly, the synergistic combination of MB and ML models enhances predictive accuracy while respecting the underlying system's physics, and secondly, it leverages both physics-based models and sensor-acquired data to train the ML model and estimate MB model parameters in a mutually beneficial manner. Numerous works across diverse applications have explored the integration of ML and MB models, albeit under varying terminologies. Some common descriptors used for such architectures include using prior information, physics-guided, residual physics, physics-based, physics fusion, physics-infused, theory-guided, hybrid, physics-informed, and physics-constrained, among others. Despite differences in nomenclature, these hybrid models share many commonalities.

Existing work in the hybrid modeling domain can be broadly categorized into three main types based on the interaction between MB and ML parameters within the model, including:

1) Approaches utilizing MB parameters as preprocessing or inputs to ML models (such as deep learning

2) Innovative network architectures embedding the physics of the problem into ML parameters

3) Loss functions enforcing physics integration in the learned deep learning model.

These categories are driven by the control mechanisms of a deep neural network (DNN) for learning optimal functions to achieve accurate mappings. Other works in the hybrid modeling domain that do not neatly fit into these categories are grouped under a Miscellaneous category.

While the focus is primarily on hybrid modeling using deep learning (neural networks), similar concepts can be applied with other ML approaches such as Support Vector Machines (SVM) and Random Forest (RF). Additionally, given the limited prior research on hybrid modeling in the cyber-physical domain, the scope of hybrid models is broadened to encompass all existing applications to ensure comprehensive coverage.

### 7.5.1 Physics-Based Preprocessing (PBP)

Most data processing methods typically involve three fundamental steps: data preprocessing, feature extraction, and feature processing. The primary objective of preprocessing is to prepare the data for subsequent steps, making it easier to work with. Preprocessing techniques encompass tasks such as noise removal, data transformation, data reduction, instance selection, dimension reduction, and more. Unlike feature extraction techniques, which can be highly specific to certain applications, preprocessing techniques are generally applicable across a wide range of scenarios. Preprocessing plays a crucial role in preparing data for ML models, with normalization being one of the simplest preprocessing methods. Other examples of preprocessing techniques include band-pass filtering, downsampling, channel selection, time window setting, data cleaning, and encoding.

In the first category of hybrid architectures, physics-based models (MB) are utilized to preprocess the data before feeding them into the ML model. The MB processes the input data x and transforms it into $\hat{x}$, which is then used as input for the ML model. The ML model learns a mapping between the

preprocessed data $\hat{x}$, and the actual outputs y, ultimately predicting the actual output $\hat{y}$, with an associated error $\epsilon i$, calculated as $\epsilon i = y - \hat{y}$. Such hybrid models, employing physics-based preprocessing, are depicted in **Figure 7.5**.

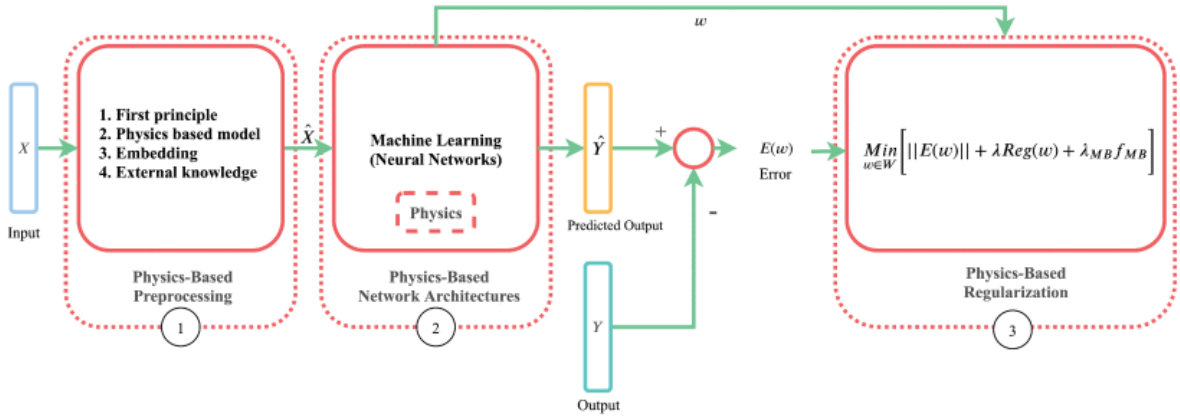


**Figure 7.5** Hybrid modeling: 1) physics-based approaches 2) ML model 3) regularization functions.

[Source: Rai, R., & Sahu, C. K. (2020)]

DNNs have largely diminished the necessity for data preprocessing since they excel at learning from raw data. However, this reduction in preprocessing requirements often corresponds with the utilization of deeper and more complex networks. Moreover, dealing with inadequate or noisy data further complicates ML models, underscoring the potential benefits of preprocessing. Raw data typically manifests as time-series signals, which can transform the frequency domain via techniques like fast Fourier transform (FFT). This conversion results in a transformation of the associated features. Frequency domain representations are commonly employed for stationary signals, given their heightened sensitivity, making them prevalent in anomaly detection tasks. Conversely, for non-stationary signals, time-frequency representations are favored. Both time domain and frequency domain representations are one-dimensional. To convert these 1D representations into 2D time-frequency domain representations, techniques such as wavelet transform, empirical mode decomposition, and short-time Fourier transform can be applied.

Preprocessing techniques for data analysis can be broadly categorized into three domains: time-domain analysis, frequency-domain analysis, and time-frequency analysis. Time-domain analysis encompasses methods like mean-variance estimation, empirical mode decomposition, and kurtosis estimation. Frequency domain analysis involves techniques such as fast Fourier transform and bispectrum analysis. On the other hand, time-frequency-based preprocessing techniques encompass methods like short-time Fourier transform (STFT), wavelet transform, Hibert-Huang transform, sparse decomposition, and wavelet packet transform.

Hybrid architectures incorporating physics-based preprocessing have been widely applied across various industries, including manufacturing, healthcare, energy, hydrology, and meteorology, among others. Techniques such as compressed sensing have been utilized to extract low-dimensional features from raw temporal data, which are then inputted into stacked denoising autoencoder DNNs. Spectral kurtosis and envelope analysis have been employed for extracting frequency bands containing the most pertinent information, with the output further processed using a fast Fourier transform before being fed into CNNs. Ensemble empirical mode decomposition (EEMD) has been employed to decompose input data into intrinsic mode functions (IMFs) and a residual series, with each IMF subsequently processed by ANNs. Other preprocessing techniques like empirical mode

decomposition (EMD) have been applied before supplying data to various models including radial basis function networks, Elman NNs, autoencoders, LSTM networks, and DBNs.

The frequency spectrum of raw data has been fed into DNN-based stacked autoencoders, while time-frequency domain data and energy spectrum features have been used for preprocessing before inputting into deep Boltzmann machines, stacked autoencoders, and deep belief networks. Non-linear soft threshold and digital wavelet frames have been utilized for denoising data before feeding into stacked autoencoders. Wavelet analysis has been employed to convert raw data into 2D time-frequency images, which are then inputted into deep CNNs. Data transformed into wavelet packet energy images has been supplied to CNNs, while Morlet wavelet decomposition has been used to obtain multiscale spectrogram images, which are then processed by CNNs. Deep Boltzmann machines have typically been fed data preprocessed by wavelet transform or the Teager-Kaiser energy operator.

Furthermore, computationally inexpensive methods such as delayed error normalized least mean square (DENLMS) filters have been used for preprocessing, and discrete wavelet transform has been employed for noise removal before feeding data to recurrent neural networks (RNNs). The impact of various preprocessing techniques on the performance of autoencoders, including PCA, scaling, and normalization, has been studied. Additionally, envelope metrics, statistical metrics, frequency domain metrics, and discrete domain metrics have been extensively reviewed for feature extraction. For a comprehensive overview of preprocessing techniques, provides a valuable resource.

While preprocessing techniques serve diverse objectives such as noise elimination, data transformation, and feature extraction, many of them primarily focus on shallow features. These techniques typically lack the incorporation of system-specific information into the ML model.

**7.5.2 Physics-Based Network Architectures (PBNA)**

The PBNA aims to investigate the optimal fusion of NN architecture and data derived from the MB component. A multitude of such architectures has emerged recently, driven by the absence of definitive answers to questions such as how NNs truly learn system features and what the most effective architecture for integrating MB into an ML model. This quest has given rise to a new research domain known as neural architecture search. These architectures can encompass various types of NNs, including DNNs, CNNs, RNNs, and others, integrated with physics. These innovative architectures may incorporate the output of the MB into a specific node of a particular layer of the ML, or embed the MB output into the NN. Moreover, besides the MB output, they may also take raw input data as an additional input.

Physics-based architectures have been applied in various fields including environmental data analysis, dynamical systems, biological systems, and image processing. For instance, in the context of modeling the temperature of a lake, the output of a physics model was integrated as an additional input feature into a multilayered perceptron. In other applications such as modeling an inverted pendulum and the growth of cancer cells, the output of the physics-based model was incorporated into the last layer of a Long Short-Term Memory (LSTM) network along with unprocessed inputs. In predicting the nonlinear dynamics of aerial vehicles, a physics-based motion model was positioned between two Recurrent Neural Network (RNN) modules to facilitate multistep prediction, resulting in improved training speeds, convergence, and prediction accuracy. Moreover, novel architectures like the deep Lagrangian network (DeLAN) have been developed to learn the motion of mechanical systems by integrating Lagrangian mechanics into hybrid architecture. Fusion methods in these architectures are classified into series and parallel models based on the connection between the MB and ML components. A combination of series and parallel connections, for example, was employed in predicting turbine blade failures. Another study aimed to recover the shape of an object by

combining a CNN-based autoencoder with a physical solution and polarized images of the object. Additionally, various fusion techniques have been proposed, such as feeding rotational invariance to the last hidden layer of a Multilayer Perceptron (MLP) in the form of a tensor to model Reynolds stress anisotropy and infusing an adaptive neuro-fuzzy inference system with predicted tool wear for predicting remaining useful life.

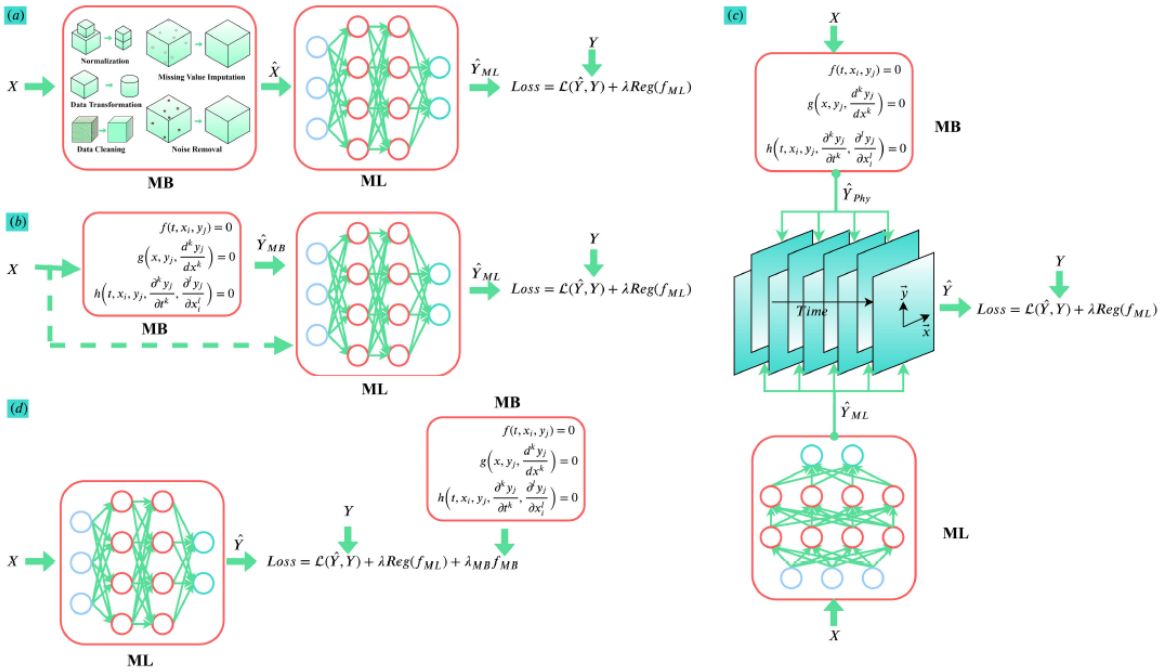


**Figure 7.6** Types of hybrid physics-based ML models: (a) preprocessing; (b) Physics-based network architectures; (c) network architectures for spatiotemporal data; (d) regularization.

[Source: Rai, R., & Sahu, C. K. (2020)]

The previously discussed architectures directly integrate the output of the physics-based model (MB) into the machine learning (ML) model. However, in scenarios involving spatio-temporal data and accompanying spatio-temporal physics models, such direct fusion is impractical. These situations often arise in applications such as videos, fluid dynamics, and thermal processes. In such cases, a deep embedding of the MB output into the ML model is necessary, involving the integration of the MB output at every time and space step as shown in **Figure 7.6(c).** This approach has been applied in fluid flow scenarios, where the output of the MB is fed into a neural network (NN) as a set of collocation points. Increasing the number of collocation points enhances the influence of physics in a hybrid architecture. This architecture accommodates both continuous and discrete-time models and has been employed for both solving and discovering nonlinear partial differential equations (PDEs).

Moreover, efforts have been made to encode the MB as a neural network and fuse it with an ML model. Transforming the MB into a NN facilitates better integration with a neural network framework. For instance, a cellular neural network was utilized to solve PDEs in the Hybrid-Net framework before linking it with a Convolutional Long Short-Term Memory (ConvLSTM) network for fluid and thermal applications. Symbolic multilayered neural networks inspired by equation learners were also employed to incorporate prior knowledge into learning accurate PDEs from data. Furthermore, the LEarned Alternating Direction Method of Multipliers (Le-ADMM) technique was unrolled into a neural network for solving inverse problems, and this method was appended to

another pure neural network or U-Net for reconstructing mask-based lensless images into traditional images captured by lensed cameras. This physics-based unrolled network approach has been applied to tasks such as image reconstruction and optimizing coded illumination in LED array microscopes.

As determining the optimal architecture for a specific problem remains a challenging task, a physics-based neural architecture search model has been developed for predicting the trajectory of projectiles and estimating the velocities of rigid objects after collisions.

In this category of hybrid models, the physics-based equations serve as an additional regularization term within the loss function of the NN. This incorporation ensures that the NN adheres to the principles of physics. The fundamental idea behind such hybrid architectures involves penalizing or minimizing the deviation from physics-based constraints or governing equations. The physics equations, typically denoted as $y = f(x)$, are reformulated as $y - f(x) = 0$ to utilize them as a constrained loss term. Consequently, minimizing the loss $y-f(x)$ becomes an additional objective within the loss function referred to in **Figure 7.6(d)**. Unlike physics-based preprocessing and fusion architectures that necessitate the evaluation of the physics-based model or the solution of partial differential equations (PDEs), regularization-based approaches directly integrate the equation as a constraint, thereby impacting the computational cost.

These hybrid models have been applied across diverse domains such as environmental data analysis, machine vision, and fluid dynamics. For instance, constraints based on temperature-density and density-depth relations were utilized to model lake temperature at varying depths. In another scenario, a weighted constraint function was employed to penalize data that deviated from prior knowledge, as observed in the case of projectile video analysis. In the context of urban land use prediction, the loss function of the pix2pix architecture within a conditional generative adversarial network (GAN) was subjected to penalties via a constraint-enforcing module for spatial sensitivity analysis. Similarly, in hemodynamics, the loss function of a fully connected NN was expanded to incorporate boundary conditions and residuals of governing equations for surrogate modeling.

Reinforcement learning techniques have also been harnessed to train non-parametric models within constrained state spaces, particularly in dynamic applications like quadcopter navigation and the cart-pole problem. Additionally, physics priors have been integrated into reinforcement learning frameworks.

To address scenarios where labeled data is scarce or absent, various regularization-based hybrid approaches have been devised. For example, a constrained convolutional autoencoder was utilized for surrogate modeling and uncertainty quantification in steady-state flow scenarios. In multiphase flows, an architecture incorporating both fusion and constrained regularization, alongside an additional loss term to measure the deviation between the output of the physics-based model and the actual output, was demonstrated to perform effectively under conditions of data scarcity. Moreover, in scenarios involving video datasets lacking labels, a neural network was trained in a supervised manner using purely physics-based constraints.

### 7.5.3 Miscellaneous Architectures

Precisely inferring the physical dynamics of a system through conventional means can be extremely challenging, even with abundant data available. Machine learning models, including neural network-based ones and the hybrid architectures discussed earlier, are limited in their ability to learn new, interpretable physics. This limitation arises from two primary factors.

Firstly, data alone lacks inherent meaning without being grounded in physical dynamics. For instance, consider the scenario of a ball bouncing on Earth compared to the same ball bouncing in a

viscous medium on the moon. The energy dissipated during bouncing on Earth is solely attributable to Earth's gravity. Conversely, on the moon, this energy dissipation involves both the moon's gravity and the viscosity of the medium. If data from both scenarios are fed into machine learning models to model the dynamics, the models can learn the same mapping for both cases because they overlook the underlying physics. In the case of the moon, the machine learning model may disregard the viscosity effect, which explains the difference in gravitational accelerations between the moon and Earth. Thus, the data lacks an intrinsic understanding of what it represents.

Secondly, the activation functions utilized in neural networks lack significant physical interpretation, leading to skepticism regarding their ability to uncover unknown physics. To address this challenge, several data-driven machine-learning methods with physical significance have been developed to discover physics from data. These methods utilize mathematically meaningful operations or interpretable activation functions, or they employ classical neural networks to reveal the physics-based equations governing system dynamics. In such approaches, data is used to extract underlying physics, which can then complement the machine learning models.

The Sparse Identification of Nonlinear Dynamics (SINDy) utilized a thresholded least square-based method to establish connections between the target function and a library of potential functions, including both algebraic and transcendental functions. Dynamic Mode Decomposition (DMD), which builds upon proper orthogonal decomposition (POD), is capable of extracting spatio-temporal correlations. DMD aims to infer a linear operator, particularly for short time intervals, to approximate spatial data, even when dealing with datasets containing millions of degrees of freedom. To address the limitations of linear operators in modeling nonlinear dynamics, the Koopman operator, an infinite-dimensional linear operator, was introduced to extend DMD for nonlinear dynamics. However, due to the inefficiencies of linear operators in capturing nonlinear dynamics, the extended dynamic mode decomposition (eDMD) was developed.

SINDy, DMD, and Koopman theory have also been extended for control applications. Moreover, symbolic regression has been utilized to uncover the conservation laws governing dynamic systems.

Additionally, the equation learner utilized interpretable activation functions such as sine, cosine, and identity within a Deep Neural Network (DNN) to comprehend the governing equations of system dynamics. PDE-Nets exploited the relationship between convolutional filters and differential operators to learn Partial Differential Equations (PDEs) governing thermal dynamics. In an attribute grammar framework, an n-gram model and a recursive neural network were employed to uncover efficient mathematical identities. For spatio-temporal data, two DNNs were employed to uncover nonlinear dynamics represented by nonlinear PDEs. These methodologies have been applied to model dynamic and fluid systems effectively.

Variational Autoencoders are recognized for encoding features like physical properties. The discriminator within a GAN can learn a similarity metric at the feature level. Therefore, in 3D-PhysNet, a deep variational encoder, along with a discriminator, was trained using data from a finite element simulator to reveal the behavior of deformable objects under external forces.

In systems where the dynamics of certain components remain unknown, an NN can be employed to understand the dynamics of these components. The NN can function as a module alongside modules corresponding to other components. For instance, in Neural Lander, the dynamics of a UAV were learned using NN, while the physics-based model was utilized for its control. Similarly, a physics-infused DNN was employed to learn each feature and then concatenated to predict the properties of organic compounds.

### 7.6 Directions in Hybrid Modeling Domain

In CPS, multiple elementary components collaborate toward a larger common objective. Their amalgamation amplifies their interactions and effects. Consequently, the limitations of individual components diminish, while new challenges emerge. These challenges may stem from their interactions or any individual component undermining others. Similarly, in a hybrid model, ML mitigates several limitations of the MB approach. As a result, there has been considerable interest in the hybrid modeling domain. However, despite significant recent advancements in hybrid modeling, various challenges hinder the comprehensive development of hybrid models. Addressing these challenges is crucial to fully harness the potential of hybrid models.

#### 7.6.1 Hybrid Models: Model Selection

Selecting the appropriate model is pivotal within the realm of hybrid modeling. While model selection in physics-based and machine-learning domains is typically straightforward, it becomes more nuanced in the case of hybrid models. The choice of suitable MB approaches hinges on factors such as the system under consideration, its dynamics, and associated parameters. Data generated by a system can generally be categorized into spatial data, sequential data, or a combination thereof. Various MBs are available to model these data types individually or in conjunction. Among the deep learning techniques for data processing, CNNs excel at handling spatial data, while Long Short-Term Memory (LSTM) networks are adept at processing sequential data. Their fusion is often employed for handling a combination of spatial and sequential data. Additionally, autoencoders are utilized to extract abstract features from datasets in an unsupervised manner. While there exists a clear intuition for model selection in both the physics and deep learning domains, the same cannot be said for hybrid modeling. A well-defined set of guidelines for selecting hybrid models would enhance their performance across various metrics and expand their applicability.

#### 7.6.2 Benchmark Problems in Hybrid Domain

A standardized set of benchmark problems plays a crucial role in facilitating the evaluation and comparison of different algorithms, thereby fostering growth within every domain. Currently, benchmark problems such as the ImageNet database and the inverted pendulum are widely recognized for object detection and reinforcement learning tasks, respectively. However, there is currently a lack of benchmark problems or datasets specifically tailored for evaluating and comparing hybrid models in the CPS domain. Furthermore, it is important to note that benchmark problems are typically specific to each application and evolve with the advancement of state-of-the-art algorithms. For instance, benchmark problems in object detection and recognition have progressed from CalTech 101 to CIFAR-10 and eventually to ImageNet. Generally, the complexity of benchmark problems reflects the advancement of state-of-the-art techniques in a particular domain. Therefore, the benchmark problems for hybrid modeling in CPS should also evolve in tandem with advancements in expertise. Additionally, given the diverse applications within CPS, it may be necessary to develop unique benchmark problems tailored to each specific domain within CPS.

#### 7.6.3 Regression Problems with Low Amount of Data

Supervised learning algorithms aim to develop accurate models capable of predicting the value of the dependent attribute (output) based on the attribute variables (inputs). Regression represents one of the two primary categories of supervised learning problems, with classification being the other. In regression problems, the output variable typically represents a real or continuous value. Regression tasks are prevalent across various domains within CPS. However, adapting, training, and fine-tuning hybrid models for regression problems pose distinct challenges compared to classification tasks.

Moreover, within the spectrum spanning from full incorporation of physics to complete absence of physics, and from minimal data to big data, there exists a domain in hybrid modeling characterized by limited data and limited physics. Many CPS modeling scenarios fall within this category of limited data and physics. Developing accurate hybrid models for regression problems with limited data presents a promising area for future research. Previous studies have demonstrated that hybrid models, as evidenced by works such as consistently outperform both pure physics-based (MB) and machine learning (ML) approaches in terms of their ability to interpolate and extrapolate, particularly in scenarios with limited data. However, these studies have primarily focused on relatively simple systems and have not been extensively tested in CPS applications. Therefore, a dedicated and comprehensive assessment of hybrid models in the context of CPS with limited data is necessary.

### 7.6.4 Learning with Less Labels

With enough data, it is feasible to construct accurate hybrid or data-driven models. However, creating accurate hybrid models currently necessitates extensive labeled data. Industries such as image, video, and text analytics in the commercial sector have assembled large, labeled datasets for training models, employing cost-effective crowdsourcing methods. Unfortunately, crowdsourcing techniques are not conducive to generating datasets for the CPS domain. Alternative methods of data labeling can result in significantly higher costs and longer labeling times. Therefore, developing innovative hybrid models that can learn with fewer labels presents a new area of research and practical application. Specifically, exploring semi-supervised hybrid learning approaches that utilize a reduced amount of labeled data alongside a vast quantity of unlabeled data represents an intriguing avenue of research within the CPS hybrid modeling domain.

Furthermore, given that CPS encompasses a wide array of domains, labeling data may necessitate domain-specific expertise. Hence, leveraging techniques such as active learning and semi-supervised learning for hybrid modeling, particularly within the CPS context, holds promise. Hybrid learning methods have yet to fully incorporate principles from active and semi-supervised learning. Additionally, it is imperative to establish a set of metrics for evaluating unsupervised learning in CPS. The successful integration of unsupervised learning techniques into CPS hybrid modeling has the potential to significantly advance the ubiquity of CPS applications.

### 7.6.5 Intelligent Collection of Datasets for Hybrid Models

Data collection is a resource-intensive process, and data is inherently sparse and incapable of fully representing the entire state space. Therefore, it is essential to collect data intelligently to capture the global behavior of the system. While the model improves its ability to interpolate as it trains on the acquired data, there is no guarantee that it will perform well on new data, known as extrapolation. The model's extrapolation performance will match its interpolation performance only if the new test data is within the vicinity of the training data space, and vice versa. Hybrid models can learn the complete system model. Therefore, to develop a comprehensive system model, new data must be collected from regions of the system space that are distant from the training set, where the model is likely to falter. Simulation of the system should encompass exceptional cases such as system failure and abrupt behavior. This data acquisition approach is particularly critical for systems where failure consequences can be catastrophic. The model should be trained on such data to reduce bias until its accuracy reaches saturation. Subsequently, new regions should be explored, and the process iterated. In conclusion, data acquisition and model training should be approached as a non-cooperative game-theoretic process to influence the mean square error. Additional data collection techniques can also be employed. Improvement in model accuracy can be expected incrementally, with each step corresponding to a new region of data not proximate to the trained data.

### 7.6.6 Geometric Machine Learning in Cyber-Physical Systems

CPS has ushered in an era of extensive big data across various domains. With big data comes the challenge of high-dimensional input data. When data dimensionality is exceptionally high, the valuable data is typically embedded within a low-dimensional manifold. Understanding and learning such manifolds fall within the realm of geometric deep learning. Recent developments in CPS have delved into geometric deep learning, especially when dealing with non-Euclidean data. In a non-Euclidean context, properties like translation invariance and stability against local deformations, which are fundamental to Euclidean geometry, do not hold globally; they only hold locally. Consequently, conventional CNNs, which rely on these properties for spatial data processing, become ineffective. This necessitates the integration of novel concepts from geometric deep learning into the cyber-physical domain. Notably, structured graph CNNs and spectral clustering techniques have already found applications in CPS. Further exploration of techniques such as spectral CNNs graph CNNs geodesic CNNs, and manifold learning holds promise for CPS applications. Geometric deep learning techniques have the potential to revolutionize the processing of big data in the cyber-physical domain.

### 7.6.7 Imbalanced Data and Data at Tail

Data imbalance, where certain classes are underrepresented compared to others, is a common occurrence in various applications such as security, disease classification, and fraud detection. This imbalance can have significant consequences, particularly in scenarios like disease prediction or security, where misclassifying the minority class (detecting a disease or identifying a perpetrator) due to limited data can be potentially catastrophic. Strategies to address class imbalance typically involve manipulating either the data, the learning algorithm, or both. However, the effectiveness of these techniques in mitigating the impact of class imbalance is still subject to debate. Additionally, dealing with data at the tail end, such as anomalies in CPS system behaviors, poses additional challenges. Anomalies, which represent deviations from normal behavior, are difficult to capture as they are rare and often require significant resources to record. Consequently, anomalies are not commonly observed in real CPS systems. Addressing imbalanced data and tail-end data remains a significant challenge in the context of CPS hybrid modeling, requiring further research and innovation.

## 7.7 Chapter Summary

This chapter represents a systematic effort to consolidate the collective knowledge surrounding hybrid models in a structured manner. It has been categorized hybrid models into distinct groups, including physics-based preprocessing, physics-based network architectures, physics-based regularization, and miscellaneous categories, based on how the Model-Based (MB) component is integrated into the hybrid architecture. It has also been highlighted how the synergy between these models can address challenges posed by big data, the probabilistic nature of CPS, environmental uncertainties, and the limitations of determinism inherent in existing CPS modeling techniques. Furthermore, it has been demonstrated how the MB can alleviate limitations encountered by Machine Learning (ML) models stemming from the time resolution of data acquisition systems. This combination presents a mutually beneficial scenario. Additionally, it introduces five metrics for comprehensive performance evaluation of hybrid CPS models, surpassing traditional accuracy metrics confined to the training dataset. Finally, it outlines the challenges confronting hybrid models that hinder their advancement in the CPS domain. The aspiration serves as a foundational resource for the organized dissemination and advancement of CPS hybrid models.

**Problems**

1. Describe the modeling of the structure of the cyber-physical system.
2. Explain the modeling techniques of the cyber-physical system.
3. Identify obstacles in modeling the cyber-physical system.
4. Analyze the collaboration between machine learning and the physical-based model.
5. Describe the hybrid modeling of the cyber-physical system.
6. Explain physical-based preprocessing (PBP).
7. Specify physical-based network architecture (PBNA).
8. Detail the hybrid modeling directions of the cyber-physical system.

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# Chapter 8

# Codesign Methodology

**Chapter Objectives**

- Learners can describe the codesign methodology of the cyber-physical systems.
- Learners know the codesign methodology of the cyber-physical systems.
- Learners familiarize the codesign methodology of the cyber-physical systems.

Analyzing and designing Cyber-Physical Systems (CPS) presents inherent challenges due to their intrinsic heterogeneity. CPS design often involves integrating cyber components into existing physical systems, which essentially separates the design process into two distinct phases. The co-designing the cyber and physical components simultaneously can yield solutions that excel in various aspects such as safety, efficiency, security, performance, reliability, fault tolerance, and extensibility. Achieving this requires automated co-design tools due to the complexity of the involved problems. The essential requirements and challenges associated with developing tools for modeling, simulation, synthesis, validation, and verification in CPS co-design. It highlights promising co-design approaches.

This chapter also addresses the complexities involved in modeling CPSs stemming from their inherent heterogeneity, concurrency, and sensitivity to timing. The fuel management subsystem of an aircraft vehicle management system (VMS) serves as an example to highlight these issues. Additionally, the detail provides various technologies that offer partial solutions to these issues. These technologies encompass hybrid system modeling and simulation, models of computation that cater to concurrency and heterogeneity, the application of domain-specific ontologies to improve modularity, and the integrated modeling of functionality alongside implementation architectures.

## 8.1 Introduction

A cyber-physical system (CPS) is the integration of computation and physical processes, where embedded computers and networks monitor and control these processes, creating intricate feedback loops. Designing such systems requires a profound understanding of the collective dynamics involving computers, software, networks, and physical processes. In the realm of CPS, distinct challenges arise that are uncommon in general-purpose computing. Unlike general-purpose software, where task duration primarily concerns performance, in CPS, task timing is often crucial for correct system functioning.

CPS involves concurrent events, where physical processes comprise numerous simultaneous occurrences, in contrast to software processes deeply rooted in sequential steps. Concurrency is inherent in CPS, leading to technical challenges in bridging inherently sequential semantics with the intrinsically concurrent physical world. The aim is to spotlight advancements, to be widely adopted, in the complex field of CPS design. The primary focus is on models and their correlation with CPS realizations, particularly dynamic models depicting the system state's evolution over time. Structural models represent static information about system construction.

Working with models offers a crucial advantage, providing formal properties and enabling definitive statements. For example, a model's determinism ensures consistent outputs for given inputs, offering confidence in the physical realization of the model as a good abstraction. This confidence is particularly valuable in embedded systems, where malfunctions pose threats to human lives. Studying system models provides insights into their behavior in the physical world.

CPSs, encompassing autonomous vehicles, industrial robots, medical devices, smart buildings, and infrastructure, hold significant economic and societal potential. However, designing these systems presents formidable challenges due to their escalating scale and complexity, intricate interactions with dynamic physical processes, adoption of advanced distributed embedded platforms, and stringent requirements across multiple design metrics such as performance, safety, security, fault tolerance, extensibility, energy consumption, and cost.

A fundamental approach to address these challenges involves co-designing the various cyber and physical components of the system. This entails modeling, simulating, synthesizing, and validating sensing, control, computation, and communication algorithms, as well as software and hardware implementation platforms, mechanical components and processes, and the surrounding physical environment and human activities, within a unified environment. The CPS underscores this unified perspective on heterogeneous cyber and physical components, emphasizing the criticality of analyzing their interactions for optimal system design.

Despite this, CPS design practices often involve isolated stages focusing on individual elements. For instance, control design typically considers physical process modeling but overlooks the cyber platform. Given the significant impact of computation and communication reliability and timing on control performance and stability, such compartmentalized design approaches may lead to prolonged production cycles, subpar systems, or even infeasible designs.

To facilitate CPS co-design, novel methodologies and tools are imperative. These tools must capture the essential interactions among diverse cyber and physical components and enable the exploration of the entire design space in a holistic, quantitative, and automated manner. It explores a vehicle management system (VMS) challenge problem, specifically focusing on the fuel management subsystem. This illustration reveals modeling challenges arising from the intrinsic heterogeneity, concurrency, and sensitivity to timing in CPS.

**8.2 Modeling and Simulation**

Modeling and simulation tools play a pivotal role in laying the groundwork for co-designing CPSs. They empower designers to comprehend the behavior of diverse cyber and physical components, define design requirements and objectives, assess, and validate design alternatives through simulations, and pinpoint critical design factors essential for synthesis and verification.

To streamline co-design in CPSs, these tools must offer the following functionalities:

- **Modeling heterogeneous components within a unified environment:** Unlike conventional embedded systems, CPSs often feature components with diverse behaviors, possibly captured using different models of computation (MoCs). For instance, discrete cyber components and continuous physical processes exhibit intrinsic distinctions. The initial step in codesign entails enabling the modeling of such heterogeneity within a shared environment. Although the component models need not be represented in the same language, their interfaces must be clearly defined, with well-understood syntax and semantics.

- **Co-simulating heterogeneous components:** Simulation plays a vital role in understanding CPS behavior. It necessitates the co-simulation of components with varying semantics, abstraction levels, and time scales. To facilitate such co-simulation, precise execution semantics must be established at both the component interfaces and the system level. Monitors and rollback mechanisms may be introduced to aid the simulation process.

- **Segregating design considerations**: Effectively and efficiently codesigning multiple design components, such as a control algorithm and its embedded implementation, requires a clear separation of their models and the formalization of interfaces. This modeling segregation offers the advantage of 1) exploring design alternatives for one component while reusing the designs of others, and 2) identifying the pivotal factors influencing component interactions and leveraging them in the co-design process.

### 8.2.1 Metropolis and Metro II

The concepts of heterogeneous modeling, co-simulation, and separation of concerns have long been established within the framework of platform-based design and implemented in the design environment known as Metropolis. Metropolis notably accommodates various modeling of computations (MoCs), such as dataflow, state machine, discrete event, and discrete time, within a unified language called the Metropolis meta-model (MMM). This unified framework allows heterogeneous components to be represented using MMM and co-simulated using a SystemC-based engine.

A fundamental tenet of Metropolis is the clear division between the modeling of system functionality (what the system accomplishes) and the modeling of the architectural platform (how the system is constructed). These distinct functional and architectural models, both described within the MMM framework along with design constraints, are subsequently merged through a mapping process. During this mapping process, various platform implementations of the functionality are explored. This segregation of concerns also facilitates function-architecture codesign, wherein different functional designs or platform options can be investigated independently without necessitating changes to the other component's model (while taking into account the implications on the other component through mapping).

In the second generation of Metropolis, known as Metro II, the foundational principles supporting codesign are further reinforced. Firstly, Metro II introduces wrappers that facilitate the integration and co-simulation of components described in different languages, rather than mandating that all components be captured in the same MMM language. This flexibility is particularly valuable for CPSs, where components from diverse domains often utilize distinct modeling languages and simulation tools.

Secondly, in addition to the existing separation of functionality and architecture, Metro II introduces a finer distinction between the modeling of logical quantities (event sequencing) and physical quantities (time and energy consumption) through the concepts of schedulers and annotators. While Metropolis manages all quantities through quantity managers, Metro II's clearer delineation of logical and physical aspects aids in analyzing intricate component interactions and identifying crucial factors for codesign.

Several case studies have showcased the efficacy of Metropolis and Metro II in system codesign, spanning a range of applications from traditional embedded systems in multimedia, telecommunications, and automotive domains, to CPSs in building and aircraft contexts. For

example, in the realm of building design automation, Metro II integrates a controller model described in Simulink and a building plant model described in Modelica, enabling their co-simulation with an architectural model for performance analysis and communication network synthesis.

### 8.2.2 Ptolemy

The Ptolemy II framework offers a modeling and simulation environment designed to facilitate CPS co-design by accommodating heterogeneity and separation of concerns. This framework supports various MoCs, including process networks, discrete events, dataflow, synchronous reactivity, and continuous time, facilitated by the concept and implementation of directors. Within a hierarchical model featuring multiple directors, heterogeneous components described with different MoCs can be integrated and co-simulated. For example, a controller component governed by a synchronous dataflow (SDF) director can be combined with a plant model governed by a continuous-time (CT) director and co-simulated at the system level under a discrete event (DE) director. Additionally, the framework employs domain-specific ontologies to detect misconnected components, such as those arising from unit, semantic, or transposition errors, ensuring the correct integration of heterogeneous elements.

In Ptolemy II, various system aspects are orthogonalized using aspect-oriented programming, a concept similar to quantity managers in Metropolis. Although the framework primarily focuses on functional modeling, it does offer the capability to integrate and co-simulate architectural models. Notably, the PTIDES programming model facilitates the clear separation of logical time in functional models and physical time in architectural platforms, ensuring timing consistency during the mapping of functionality and architecture. Additionally, a lightweight microkernel, PtidyOS, has been introduced to streamline this mapping process. Architectural models can be constructed within Ptolemy II itself or imported from other tools, as demonstrated in the Metronomy project.

### 8.2.3 Metronomy

Combining the capabilities of Metro II and Ptolemy, the integrated Metronomy framework offers heterogeneous modeling and co-simulation functionalities to facilitate CPS co-design, particularly for assessing system timing behavior during design space exploration.

In the Metronomy framework, the functional model is represented in Ptolemy, while the architectural model is articulated in Metro II, as depicted in **Figure 8.1**. At the system level, these two models are merged and co-simulated using a CoSimDirector, which implements Metro II's execution semantics within a Ptolemy director. The functional model may incorporate heterogeneous components—illustrated in the diagram by the co-simulation of a discrete controller model and a continuous physical plant model utilizing a custom discrete event director, CoSimDEDirector. Conversely, the Metro II architectural model can undergo simulation utilizing a SystemC simulation engine. During the integration of models, it is compiled alongside SystemC and Metro II libraries into an executable format, subsequently co-simulated with the functional model via interprocess communication, overseen by the CoSimDirector.

Through Metronomy, control engineers, and other domain specialists can utilize the diverse array of MoCs available in Ptolemy to capture the functional design of the system. Meanwhile, software and hardware engineers can capitalize on the flexibility and richness, alongside the libraries of schedulers and annotators, offered by Metro II to devise the architectural platform. System engineers can adeptly merge these two aspects within a co-simulation environment to codesign various components and validate the correctness and efficiency of their designs.

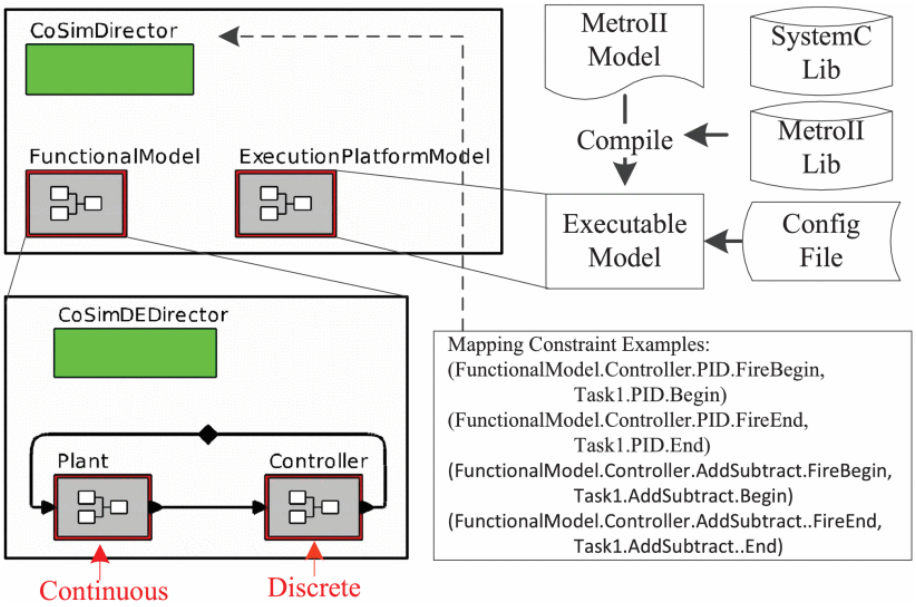


**Figure 8.1** Metronomy framework.
[Source: Zhu, Q., & Sangiovanni-Vincentelli, A. (2018)]

Specifically, Metronomy leverages contract-based design theory to establish an interface of timing contracts between the functional and architectural models. These contracts serve as a collection of timing assumptions and assurances mutually agreed upon by the domain experts responsible for designing the system functionality and the software/hardware engineers tasked with implementing such functionality on the architectural platform. During design space exploration via co-simulation, Metronomy can employ timing monitors to assess whether these timing contracts are upheld, thus eliminating infeasible design options.

Metronomy is employed in the design of two CPSs. In an instance involving an aircraft electric power system, a timing contract is established concerning the end-to-end latency of a control loop within the system, spanning from sensing to actuation. By co-simulating the controller alongside the implementation platform, various limits of the timing contract are assessed to gauge their effects on system performance and stability. These findings then inform the codesign process for the controller and its implementation platform. For example, decisions may revolve around whether to incorporate a voltage protection mechanism into the controller design when the timing limit is lenient, or if a faster communication bus should be adopted in the architectural platform when the limit is stringent.

In another scenario, the sampling period of the paper feed controller and the operating frequency of the implementation processor are cosigned in consideration of system performance. This decision-making process is again guided by the co-simulation of models and the validation of timing contracts.

### 8.3 Modeling Issues

In the realm of model-based design and model-driven development, models are pivotal in the design process, serving as specifications for systems and reflecting the evolution of system design. These models enable simulation and analysis, facilitating the early detection of design defects compared to prototyping. In certain scenarios, automated or semi-automated processes can synthesize implementations from these models. However, the intrinsic heterogeneity and complexity of CPS pose challenges to existing modeling languages and frameworks.

A CPS model encompasses physical processes alongside models of software, computation platforms, and networks. The intricate feedback loop between physical processes and computations involves sensors, actuators, physical dynamics, computation, software scheduling, and networks with contention and communication delays. Modeling such systems with fidelity demands the inclusion of control engineering, software engineering, and sensor networks, among other aspects. Moreover, these models often entail a multitude of heterogeneous components, emphasizing the importance of composition semantics.

To exemplify modeling challenges in CPS, it considers a segment of an aircraft Vehicle Management System (VMS), specifically the fuel management subsystem. Illustrative models, crafted in Ptolemy II, a modeling and simulation environment for heterogeneous systems, are presented. Ptolemy employs an actor-oriented design approach, where components communicate via ports, and actors can execute and communicate with others. The rules of interaction between actors are defined by the MoC.

In Ptolemy, an MoC is implemented by a director, a component in a model or sub-model. Multiple directors, realizing distinct MoCs, can be combined in a hierarchical model, and a region governed by a single director is termed a domain. The open-source Ptolemy software includes directors implementing various MoCs like discrete events (DEs), continuous time (CT), finite state machines (FSMs), synchronous reactive (SR), process networks (PNs), and different dataflow variants. Hybrid systems can be modeled using hierarchical compositions that combine CT models with discrete domains like FSM or DE.

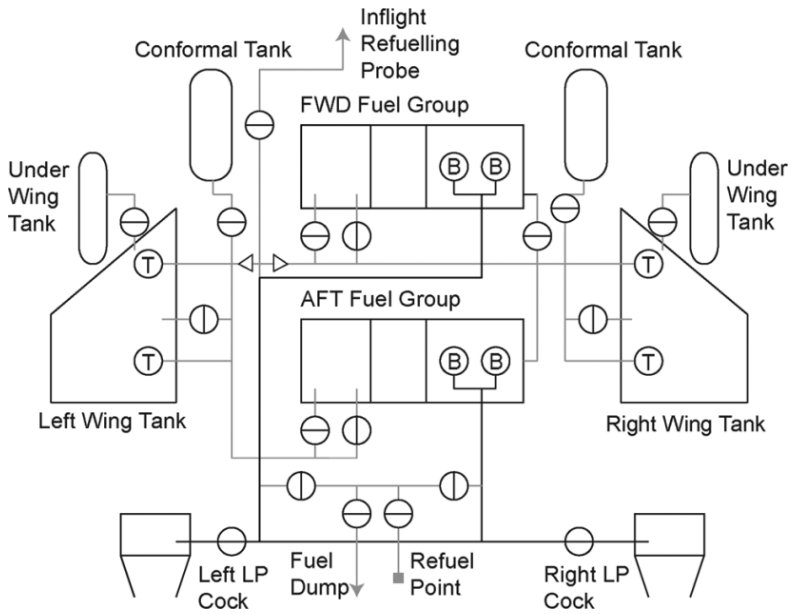


**Figure 8.2** Military aircraft system.
[Source: Derler, P., Lee, E. A., & Sangiovanni Vincentelli, A. (2012)]

The fuel system in modern aircraft is intricate, involving multiple fuel tanks, valves, pumps, probes, sensors, and switches. The primary goal is to reliably supply engines with fuel, while secondary functions include providing engine coolant and maintaining weight distribution for balance and optimal performance. The complex system involves fuel transfers, coolant functions, weight distribution, and heat management during flight. Several physical processes, influenced by factors like temperature and fuel type, impact the fuel control system. Measuring fuel level during flight involves considering tank shape, aircraft motion, temperature, and pressure, necessitating various sensors. The fuel control system monitors sensor values, computes, and displays fuel levels, and

operates pumps and valves. A schematic view of a typical aircraft fuel system for a military jet aircraft is shown in **Figure 8.2**

The significance of a fuel management system in aiding flight crew decisions is exemplified by the incident involving Air Transat Flight 236 on August 23–24, 2001, During this flight, a fuel leak was identified too late, leading to an emergency landing. The initial indication of an issue was a low oil temperature and high oil pressure reported by the flight control system. This resulted from an increased fuel flow caused by an engine leak, with fuel acting as a heat sink. The heightened fuel flow cooled the engine oil more than usual, altering its viscosity and subsequently increasing oil pressure. The flight control system reported a fuel imbalance between tanks. The flight crew addressed this imbalance by transferring fuel into the leaking tank. A more intelligent flight control system, integrating models, could have assisted the crew in detecting the leak earlier. For instance, model-integrated computing, where the behavior of a model is compared at runtime to the measured behavior of the deployed system, could have facilitated early detection. Using the fuel system as an example, this delves into specific modeling issues.

### 8.3.1 Issue 1—Models with Solver-Dependent, Nondeterminate, or Zeno Behavior

A CPS can be represented as a hybrid system, where physical processes are depicted as continuous-time models of dynamics, and computations are described using state machines, dataflow models, synchronous/reactive models, and/or DE models. CT models employ solvers to numerically approximate solutions to differential equations. While designing such solvers is a well-established art, integrating them with discrete models poses newer challenges, with persistent issues in various available tools.

One potential problem is that the behavior defined by a model might be nondeterminate, even if the underlying system is determinate. This implies that the model defines multiple behaviors rather than a singular one. This can occur, for instance, when DEs are simultaneous, and the semantics of the modeling language fail to specify a unique behavior, surprising system designers. Another issue is that numerical solvers dynamically adjust step sizes, impacting the model's behavior. Designers often lack insights into the rationale for step-size selection, causing surprises. A third challenge is that models might exhibit Zeno behavior, where infinitely many events occur in a finite time interval. Although this behavior may reflect physical phenomena, such as chattering, it can also arise as an artifact of modeling.

To illustrate these challenges, it considers a model of a fuel tank. Accurately specifying how the behavior changes when the tank becomes full or empty poses a challenging aspect of such a model. While it's reasonable to model “becoming full” and “becoming empty” as DEs, the physical world is not inherently discrete. To avoid forcing modelers to use overly detailed models of physical phenomena that are not central to their design problem, discrete models offer adequate abstractions.

**Figure 8.3** illustrates a potential Ptolemy II model of a single fuel tank, constructed using a continuous-time director with semantics akin to popular continuous-time simulation tools such as Simulink (from The MathWorks) and the LabVIEW Control Design and Simulation Module (from National Instruments). This MoC features components (actors) with input and output ports, contrasting with equational modeling tools like Modelica, where ports neither serve as inputs nor outputs. In Modelica, ports represent continuous-time signals, with actors and connections symbolizing declarative relationships among these signals.

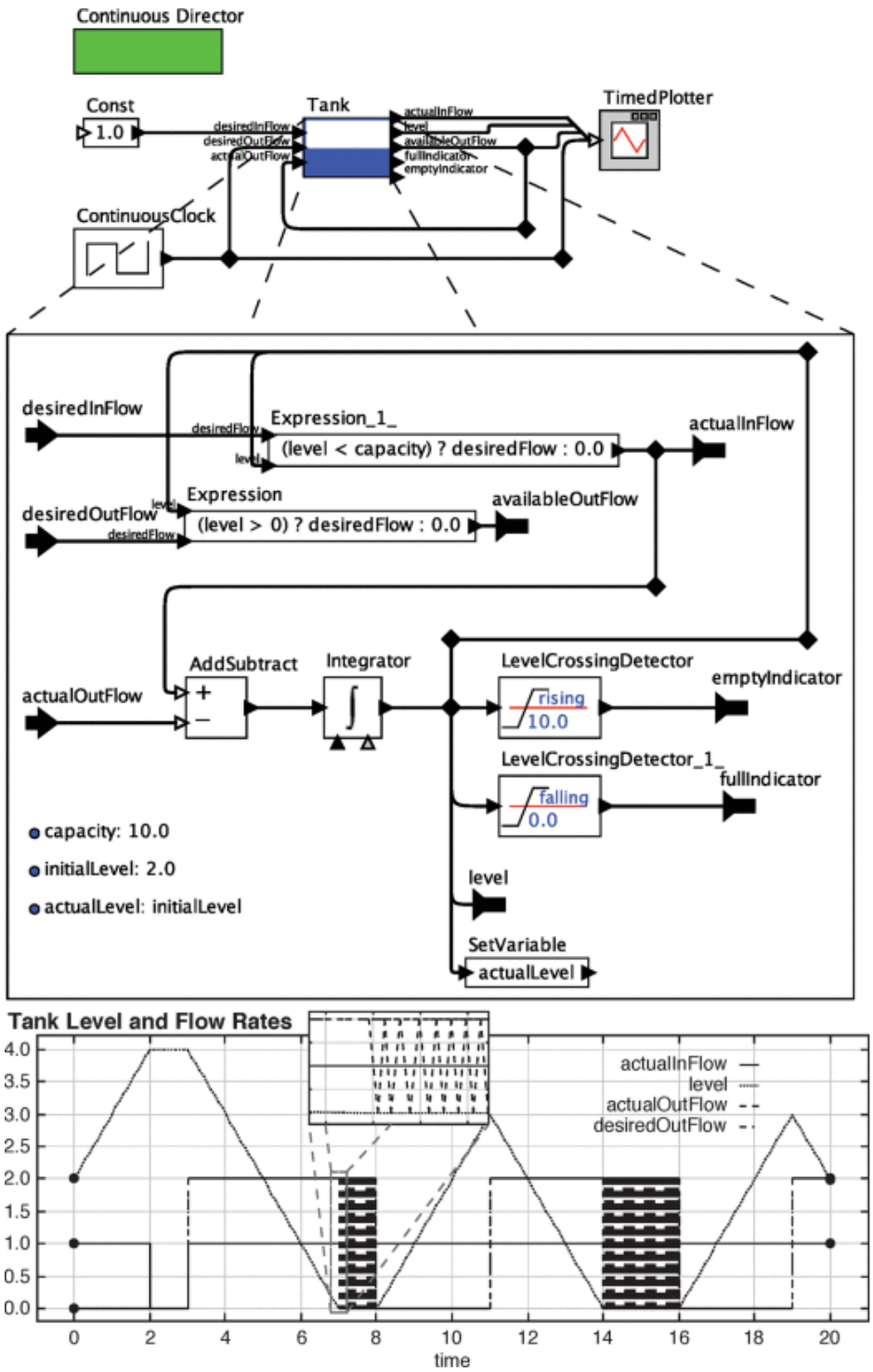


**Figure 8.3** Model of a single fuel tank in a simple test scenario.
[Source: Derler, P., Lee, E. A., & Sangiovanni Vincentelli, A. (2012)]

While it might be initially intuitive to model a fuel tank with inputs representing fuel inflow and outputs representing fuel outflow, this simplistic approach is not entirely accurate. In reality, an input cannot add fuel to a full tank, and an output cannot withdraw fuel from a full destination. Therefore, when modeling processes like fuel transfer between tanks, the amount of fuel transferred per unit of time needs collaborative determination by both tanks and a model of the intervening pumps and valves.

In addressing this complexity, **Figure 8.3** proposes a resolution. Two input ports of the tank represent desired input and output flows, which are not actual flows but intended flows. A third input port represents the actual output flow since the fuel cannot flow out without a designated destination. One output port represents available output flow, facilitating models where the destination may refuse some or all the output flow. At the top level, the available output flow is fed back to the actual output flow, reflecting situations where there is always a destination for the fuel.

Another output port denotes the actual input flow. Ideally, if the tank is not full, the actual input flow matches the desired input flow. However, if the tank is full, the actual input flow significantly deviates from the desired flow.

**Figure 8.3** also includes output ports providing fuel level and full and empty indicators, where the latter are DEs from LevelCrossingDetector actors.

This specific model utilizes two expression actors to depict a seemingly accurate representation of a fuel tank's behavior. In this model, when the tank is full, it disregards the desired input flow, setting the actual input flow to zero. It also halts the output flow when the tank is empty.

However, the model exhibits problematic behavior. Particularly, when subjected to a constant desired input flow of 1.0 and a desired output flow of 0.0 for three-time units followed by 2.0, the tank starts to chatter when empty. This behavior reveals flaws leading to solver-dependent outcomes or potential Zeno conditions. Specifically, when the tank becomes empty, the actual output flow goes to zero. Yet, infinitesimally later, the tank is not empty, allowing the output flow to resume. This cycle repeats, creating an appearance of time standing still in simulation, only visible through close examination of output signals.

This model presents challenges for simulation technology due to expression actors having discontinuous input-output relations. For instance, the lower expression actor in **Figure 8.3** features the expression "(level>0)?desiredFlow:0.0". The output of this actor equals the input when the level surpasses zero; otherwise, it is zero. When the level reaches zero, the actor's behavior depends on numerical precision and solver-determined step sizes. Assigning precise semantics to the moment when the level hits zero is nontrivial. Coordinating the behavior at this discontinuity requires intricate collaboration between the solver and the expression actor, a task not easily achieved in a modular framework.

Furthermore, the LevelCrossingDetector should generate a DE precisely when the tank achieves full or empty status. This necessitates careful cooperation with the solver to ensure that time step sizes include the event occurrence.

The chattering observed in the **Figure 8.3** model might accurately mirror the physical realization. A fuel tank controller designed to close an output valve when the tank empties could indeed exhibit chatter. A more effective design would restrict input and output flows when the tank reaches full or empty status. In this improved design, when the tank is full, the input flow is limited to be no greater than the output flow, and when the tank is empty, the output flow is constrained to be no greater than the input flow.

Subsequently, such a model illustrates how it can leverage rigorous hybrid-system semantics to offer a determinate and intuitive representation. Before it delves into developing this enhanced model, a second challenge is related to evolving and maintaining a multitude of models while ensuring consistency.

### 8.3.2 Issue 2—Ensuring Consistency Among Model Components

A basic tank model is constructed and subjected to a scenario that, while not representative of real-world situations, serves as a valuable regression test for the tank model. However, in practice, such test scenarios often become obsolete. They transform into more intricate and lifelike models, causing the simple regression test to fade away. If the model is retained as a regression test, there's minimal guarantee that the test model aligns with the final design. The final design typically evolves from a copy of the test model, and inevitably, the copy diverges from the test model. Moreover, during the development of embedded software, even if code generators are employed to synthesize software from models, the software and the model often undergo separate evolutionary paths, contributing to further divergence.

A similar issue arises when a straightforward model evolves into a complex one, wherein a singular component in the simple model transforms into multiple components in the complex version. This can ensure the synchronized evolution of these multiple components. Up until now, it has been examined models featuring a single fuel tank. However, contemporary aircraft typically incorporate numerous fuel tanks, with fuel being transferred between them.

The challenge of evolving multiple models that include various versions of components while ensuring a degree of consistency across these models.

In the model depicted in **Figure 8.4**, it introduces functionality for transferring fuel between tanks. Whenever the fuel level of Tank1 drops below one-fourth of its capacity, a FuelMover component facilitates the transfer of fuel from Tank2 to Tank1. This component employs a straightforward modal model to alter the desired output flow of Tank2 from zero in the initial idle mode to moveRate (a parameter) in the moving state. The FuelMover controller dictates the desired output flow of Tank2, subsequently providing an available output flow to the desired input flow port of Tank1. Tank1 responds with an actual input flow, which, in turn, becomes the actual output flow of Tank2. Therefore, if either tank reaches full or empty status, the flows are appropriately restricted.

In **Figure 8.4**, the FuelMover and the two tanks are integrated into a straightforward test scenario where Tank1 maintains a constant desired output flow of 1. This could represent, for instance, the fuel flow to an engine. The desired input flow of Tank1 is regulated by Tank2. Tank2, which does not receive any fuel (its desired input flow is 0), has its desired output flow regulated by the FuelMover. This component is a modal model that receives information about the fuel level of Tank1 and controls the desired output flow of Tank2. The fuel mover can be interpreted as the cyber component of this CPS, while the Tank models the physical processes.

In a modeling environment, the tank model can be duplicated and reused in various segments of the model. However, if a modification to the tank model is required later, the same modification must be applied to all other tank models that were duplicated. This process is error-prone, as there is no way to guarantee that all copies are updated consistently.

Below, it elaborates on how object-oriented design principles can be adapted to CPS models using the concept of actor-oriented classes, and how semantics-preserving transformation and code generation can mitigate divergence in evolving designs.

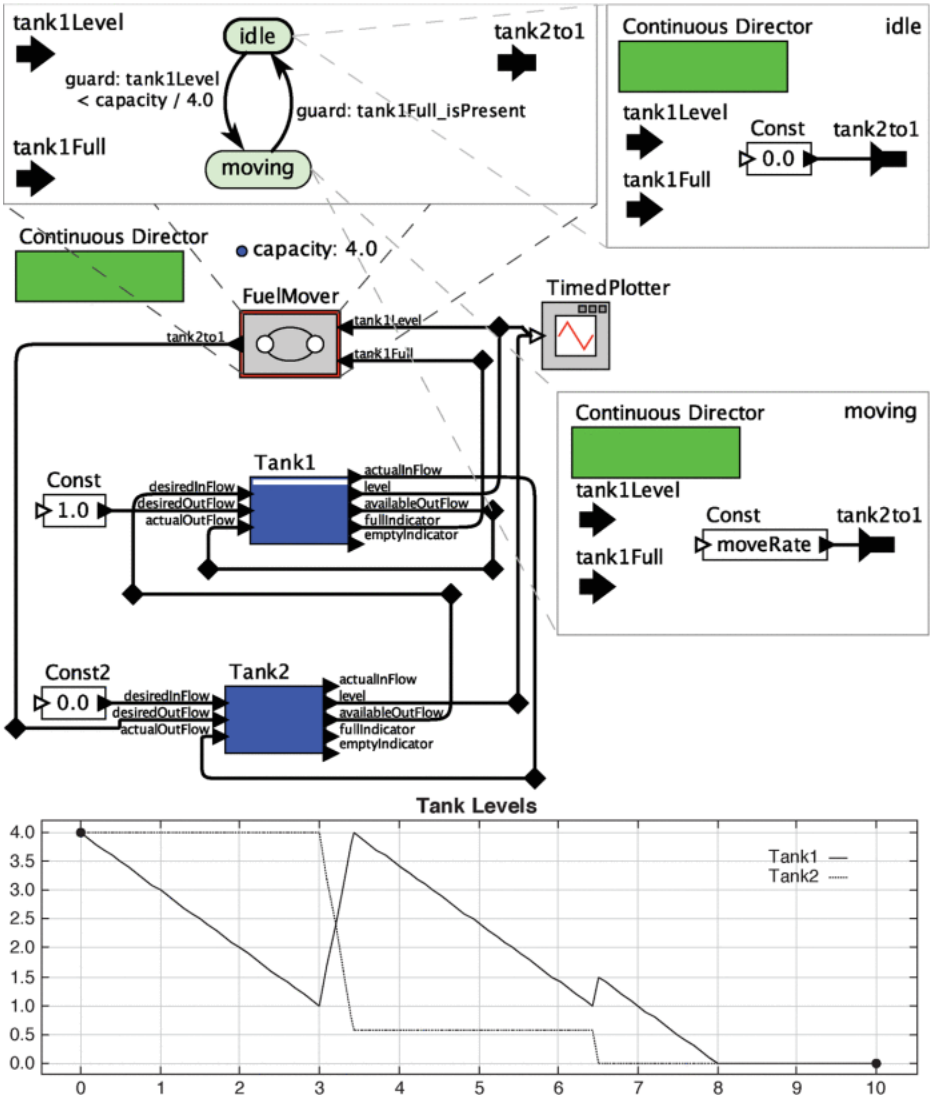


**Figure 8.4** Fuel system with two tanks.
[Source: Derler, P., Lee, E. A., & Sangiovanni Vincentelli, A. (2012)]

### 8.3.3 Issue 3—Preventing Misconnected Model Components

The bigger a model becomes, the harder it is to check for the correctness of connections between components. Typically, model components are highly interconnected, and the possibility of errors increases. It identifies three types of errors: 1) unit errors, 2) semantic errors, and 3) transposition errors, illustrated in **Figure 8.5**. Unit errors occur when a port provides data with different units than those expected at the receiving port. For example, in **Figure 8.5**, the output port of the left actor provides the fuel level in gallons, whereas the input port of the right actor expects a value in kilograms. An example of a semantic error 2) is shown, where a mid-tank level is provided to a port that expects an aft tank level. A transposition error 3) occurs when connections are reversed, as in the example where the engine input flow and a tank level are reversed. None of these errors would be detected by a type system. Below it explains how expressing knowledge formally in an ontology can encode domain knowledge and enable measures to automatically check for such errors.

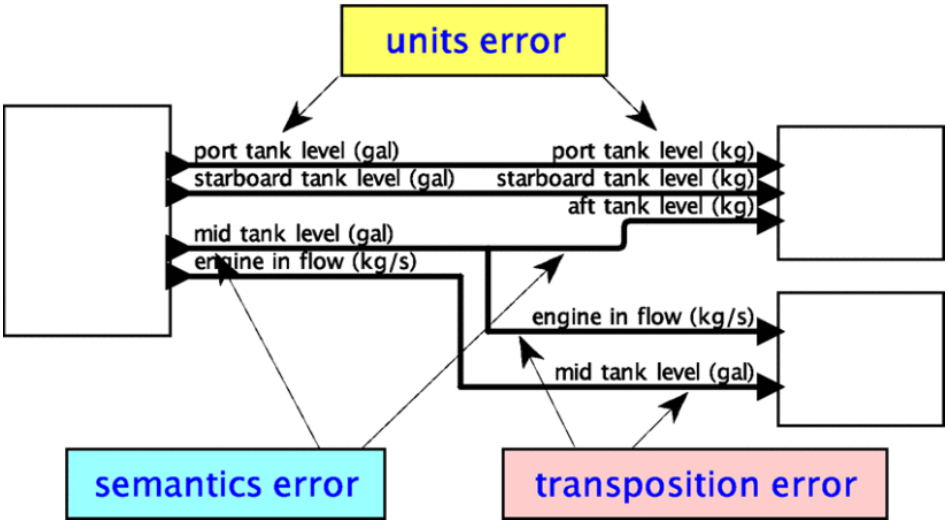


**Figure 8.5** Misconnected model components.
[Source: Derler, P., Lee, E. A., & Sangiovanni Vincentelli, A. (2012)]

### 8.3.4 Issue 4—Capturing Interactions Between Functionality and Implementation

The previously discussed models focus on describing the functionality of computations and physical processes, overlooking implementation details like the underlying platform and communication networks. These models implicitly assume instantaneous computation and transmission of data, neglecting the impact of software and network dynamics on system behavior. It contends that, to comprehensively assess a CPS model, it is essential to incorporate the dynamics of software and networks.

Implementation details are largely independent of functionality and should not be an intrinsic part of a functional model. Instead, it should be feasible to connect a functional model with an implementation model. The latter allows for exploring the design space, while the former supports the development of control strategies. The merged models facilitate the evaluation of interactions across these domains.

One approach to combining separate and independently maintained models involves the use of aspect-oriented programming (AOP). In AOP, disparate models can be "woven" together to merge their behaviors. While primarily developed as a software engineering technique, AOP has also been applied to merge models of functionality and implementation. Specifically, it elaborates on how the concept of quantity managers, introduced in Metropolis, can be used to associate functional models with implementation models.

### 8.3.5 Issue 5—Modeling Distributed Behaviors

The distributed nature of CPS necessitates strategies that simplify the composition of components situated in different locations. Modeling distributed systems increases the complexity of CPS modeling by introducing challenges such as variations in time measurements, network delays, imperfect communication, consistency of system state views, and distributed consensus. Below, a distributed programming model called PTIDES is outlined, addressing many of these challenges.

### 8.3.6 Issue 6—System Heterogeneity

An underlying theme in the aforementioned challenges arises from the intrinsic heterogeneity and complexity of CPSs. By definition, CPS integrates diverse subsystems, often employing domain-

specific and, at times, sophisticated modeling techniques. Integrating these diverse models to construct comprehensive views of the system becomes highly challenging.

### 8.4 Addressing the Issues

The University of California Berkeley has been engaged in researching model-based design techniques. These techniques are deemed to possess well-defined semantics, providing a robust foundation for platform-based design and engineering. Components designed to operate within a model exhibit predictable behavior when deployed in a system. The foundational rigor of these models facilitates integration across design domains, supports design adaptation and evolution, and enables analysis and verification. The outcomes have been demonstrated through open-source software frameworks such as Ptolemy Classic, Ptolemy II, Polis, Metropolis, and MetroII. The techniques developed have found application in various domain-specific areas, including hardware and FPGA synthesis, signal processing, automotive system design, computer architecture design and evaluation, instrumentation, wireless system design, mixed-signal circuit design, network simulation, and design, building system simulation and design, financial engineering, and scientific workflows.

#### 8.4.1 Models of Computation

Several challenges stem from the inherent complexity and heterogeneity of CPS applications. Model complexity is mitigated by employing more specialized, domain-specific models and utilizing modeling languages with clear, well-defined semantics. Addressing heterogeneity involves combining multiple models.

To tackle these issues, models should be constructed using well-defined MoCs. An MoC provides semantics to concurrency in the model, determining whether components execute simultaneously, share a notion of time, and how they share state. The MoC also defines communication semantics, specifying how data are exchanged, such as using publish-and-subscribe protocols, synchronous or asynchronous message transmission, or time-stamped events. It establishes a formal framework for understanding and comparing the semantics of various MoCs and defining heterogeneous interactions across MoCs. This foundation has been applied to multiclock (latency-insensitive) systems, globally asynchronous, locally synchronous (GALS) designs, and timed MoCs capable of reflecting real-time dynamics. The challenge is to define MoCs that are expressive enough with strong formal properties, allowing systematic validation of designs and correct-by-construction synthesis of implementations. Another issue is identifying the necessary MoCs and variants and educating the community on their use.

#### 8.4.2 Abstract Semantics

In many situations, using a single general MoC for an entire design limits property checking to extensive simulation. Less expressive MoCs are more amenable to analysis, enabling systematic exploration of design properties, often including formal verification. However, less expressive MoCs may not capture the richness and diversity of complex designs. The solution lies in heterogeneous mixtures of MoCs, a necessity given the heterogeneous nature of most CPS applications.

Furthermore, during the design process, the abstraction level, detail, and specificity in different parts of the design vary. Engineers employ different skill sets and design styles. Consequently, diverse specification and modeling techniques are used during the design process. The challenge is how to combine heterogeneous MoCs and determine the composition's behavior. Unfortunately, the semantics of different MoCs are typically not directly compatible.

A potential solution is to embed detailed models into a framework capable of comprehending the composed models. A theoretical approach to this view is abstract algebra defines interactions among incompatible models. In essence, this involves an abstraction of the MoC concept, refineable into any of the MoCs of interest. This abstraction is termed abstract semantics.

The inspiration for defining abstract semantics comes from recognizing that MoCs are constructed by combining three largely orthogonal aspects: sequential behavior, concurrency, and communication. Similar to the way an MoC abstracts a class of behavior, abstract semantics abstract the semantics. While termed "a semantics meta-model", the term "abstract semantics" here, as the term "meta-model" is more widely used in software engineering to refer to models of the structure of models. The concept of abstract semantics is leveraged in Ptolemy II, Metropolis, and Ptolemy Classic to achieve heterogeneous mixtures of MoCs with well-defined interactions.

### 8.4.3 Actor-Oriented Models

Model-integrated development for embedded systems often employs actor-oriented software component models. In these models, software components, termed actors, execute concurrently and communicate through message exchange via interconnected ports. Examples supporting such designs include Simulink (The MathWorks), LabVIEW (National Instruments), SystemC, component and activity diagrams in SysML and UML 2, and various research tools such as ModHel'X, TDL, HetSC, ForSyDe, Metropolis, and Ptolemy II. The previously presented fuel tank models adhere to an actor-oriented approach.

The primary challenge lies in establishing well-defined actor oriented MoCs with precise semantics. Frequently, semantics emerge incidentally from the software implementation rather than being inherently built-in. A key hurdle is integrating actor-oriented models with practical and realistic notions of time. Modeling distributed behaviors necessitates providing multiform models of time. Modeling frameworks incorporating a semantic understanding of time, like Simulink and Modelica, assume homogeneity, where time uniformly advances across the entire system. In practical distributed systems, even at the scale of a single chip, no such homogeneous time notion is observable. In a distributed system, despite using network time synchronization protocols, local time notions will differ. Failing to model such differences could introduce artifacts in the design.

The PTIDES project directly addresses the multiform nature of time in distributed systems. PTIDES, a programming model for distributed systems relying on time synchronization, acknowledges imperfections. PTIDES simulations can concurrently have multiple timelines, with events logically or physically placed on these timelines. Despite the diversity of timelines, there exists well-defined and deterministic semantics for interactions between events.

### 8.4.4 Hybrid Systems

CPSs integrate computation, networking, and physical dynamics. Modeling techniques addressing solely software concerns are insufficient. Integrating continuous physical dynamics expressed through ordinary differential equations with discrete behaviors expressed using finite automata leads to hybrid systems. Defining robust hybrid system modeling languages presents several challenges. These challenges include ensuring the determinacy of models of deterministic systems, preventing behavior that relies on arbitrary decisions made by numerical differential equation solvers, and accurately representing causally related events occurring simultaneously.

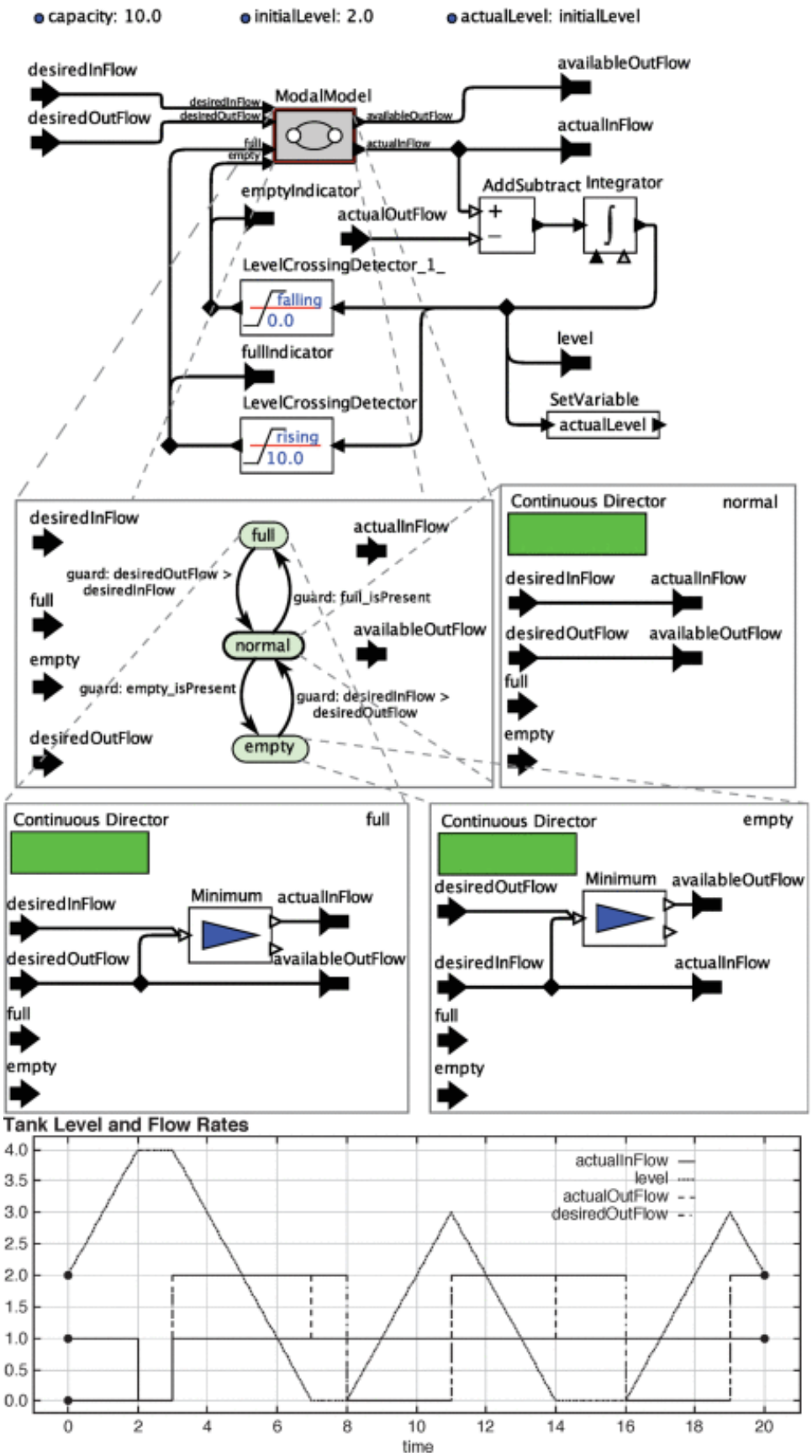


**Figure 8.6** ModalTank: Improved model of a fuel tank using modal models.
[Source: Derler, P., Lee, E. A., & Sangiovanni Vincentelli, A. (2012)]

A rigorous MoC provides determinate semantics for such hybrid systems. It has influenced the development of commercial tools such as Simulink and LabVIEW and is embodied in the open-source tool HyVisual. Additionally, the notation of abstract semantics has been leveraged to integrate these hybrid systems with other MoCs like synchronous/reactive and DE models. This integration enables heterogeneous models to capture interactions between software, networks, and continuous physical processes.

The rigorous hybrid systems MoC implemented in Ptolemy II can enhance the tank model. The model, depicted in **Figure 8.6**, utilizes a modal model to describe different operational modes based on the tank's state. In this model, the net flow equals the difference between the actual input flow and the actual output flow. The model comprises three modes: normal mode, where the tank is neither full nor empty; full and empty modes, where either the actual input or available output flow is limited. Transitions between modes are triggered by guards, predicates shown adjacent to transitions in the figure. This model ensures determinacy and avoids chattering.

In a manner quite analogous to **Figure 8.6**, modal models can serve to encode adaptation strategies necessary for all CPSs to cope with uncertain environments and faults. For instance, if a tank supplying an engine becomes empty while there is still fuel in other tanks, this state might be considered an error condition. A modal model could articulate a strategy for adapting to such a situation. Additionally, an analysis of the model's dynamics could pinpoint conditions under which such an error might occur.

Ptolemy II's hybrid systems semantics adeptly address the discontinuities in mode transitions and the event detection performed by LevelCrossingDetector actors. This semantics ensures determinism within the model, mitigates solver-dependent behavior and aids in identifying Zeno conditions. These aspects contribute to fostering confidence in the models, consequently instilling confidence in the entire system.

In the lower section of **Figure 8.6,** the plot illustrates the system's behavior in a test scenario where the desired input flow remains a constant 1.0, while the desired output flow alternates between zero (for three-time units) and 2.0 (for five-time units). Such a scenario serves as a practical regression test for assessing the tank model's behavior under various conditions, including full and empty states.

### 8.4.5 Heterogeneity

Integrating diverse MoCs to enable their interoperability, termed as multi-modeling, is a non-trivial task. Past efforts concentrated on tool integration between different vendors, resulting in fragile tool chains. This approach faced challenges due to inadequate extension points in many tools, demanding substantial effort for maintenance. A more effective strategy involves focusing on the semantics of interoperation rather than grappling with the intricacies of tool integration. Understanding the semantics of interoperation facilitates the emergence of robust software architectures.

A key aspect in handling heterogeneity is concentrating on the interfaces between MoCs. Various modeling, analysis, and simulation tools have been developed based on distinct MoCs, such as DE for network, hardware, and real-time system modeling, synchronous-reactive for safety-critical concurrent software, dataflow for signal processing, process networks for asynchronous distributed systems, and continuous-time models for physical dynamics. The design emphasis across these MoCs has been on providing deterministic behavior and enhancing concurrency models compared to prevalent thread-based models in software engineering.

Ptolemy II's hybrid systems MoC are constructed using interfaces between MoCs. For instance, the modal model in **Figure 8.6** is built using a Ptolemy director unaware of continuous-time modeling, it

collaborates with a director specialized in continuous-time modeling. This interoperability extends to other Ptolemy directors, allowing modal models to be employed across diverse modeling styles. This is a departure from approaches like Statecharts, which are designed for specific concurrent MoCs, typically synchronous/reactive.

Supporting heterogeneity systematically aids in addressing by reducing the likelihood of model components diverging, facilitating the evolution of different system pieces from abstract to detailed models, and enhancing the modeling of distributed behaviors. In the hardware design community, SystemC, influenced in part by this work, can realize multiple MoCs, though less emphasis has been placed on interoperability.

**8.4.6 Modularity**

Modular design, where modules possess well-defined interfaces and their composition can be verified for compatibility, is crucial for the effective design of complex systems. Ensuring the correct composition of modules and enabling reuse and customization are key challenges in this context. While type systems provide basic protection, stronger protection is desirable to prevent misinterpretation of data between modules.

Ptolemy II, like some other modeling frameworks, incorporates object-oriented design principles for modeling. The approach in Ptolemy II is unique, utilizing classes to define the interface and behavior of an actor. Inheritance is employed to articulate relationships between objects. Actors' instances implement the specified behavior, and subclasses can inherit, extend, or override the parameters of the superclass. Notably, updates to classes propagate to instances even during interactive model development.

In the fuel system models presented, the Tank component is defined as a class instantiated in various parts of a model and different models. The class definition of the tank is maintained separately, with instances like Tank1 and Tank2 adhering to this class. This design allows for easy updates and consistency across instances when editing the class definition. The same strategy streamlines the maintenance of regression tests, assuring that behavior remains consistent as the tank model evolves. **Figure 8.7** outlines a conceivable UML class hierarchy for the Tank models, showcasing how the tank model can evolve while maintaining consistency across multiple instances in various models, including regression tests.

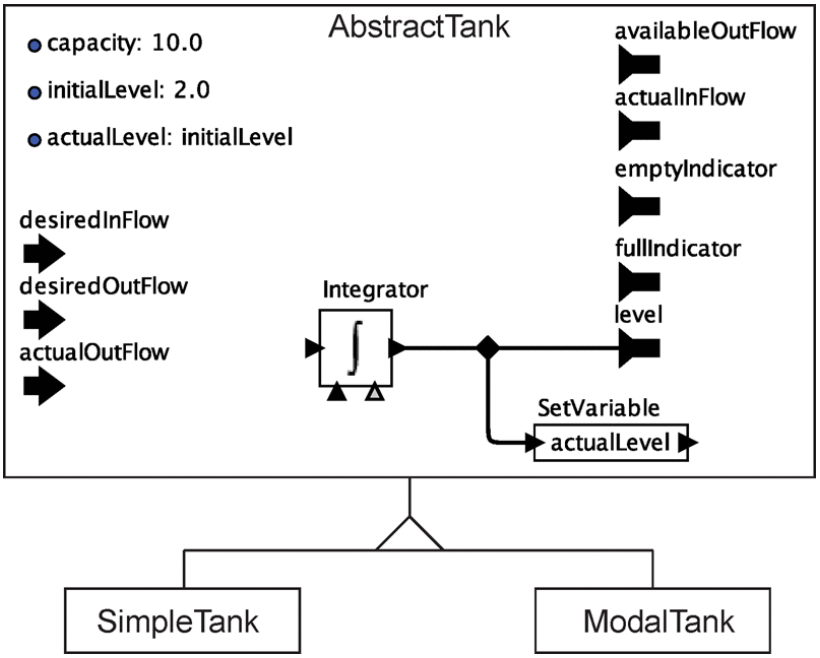


**Figure 8.7** UML diagram for abstract and concrete tank classes.
[Source: Derler, P., Lee, E. A., & Sangiovanni Vincentelli, A. (2012)]

It demonstrates the adaptation of object-oriented principles such as classes, inheritance, and polymorphism to concurrent, actor-oriented components, rendering them more conducive to CPS. Additionally, various other techniques can enhance modularity in modeling. Notably, it has developed sophisticated type systems tailored for component compositions, enabling type inference, and checking across extensive models containing polymorphic components. These types of systems have been further refined to encompass domain-specific ontology information, ensuring the correct utilization and interpretation of shared data. Moreover, there are devised methods to verify the compatibility of protocols in compositions and to generate interface adapters for components defined separately.

It exemplifies how a domain-specific ontology, utilizing the methodologies. In **Figure 8.8**, the upper right portion illustrates a straightforward ontology for dimensions employed in the fuel system, delineating essential concepts like Level and Flow. The objective is to forestall inadvertent misinterpretation by model builders, thereby preventing a flow from being mistaken for a level or vice versa.

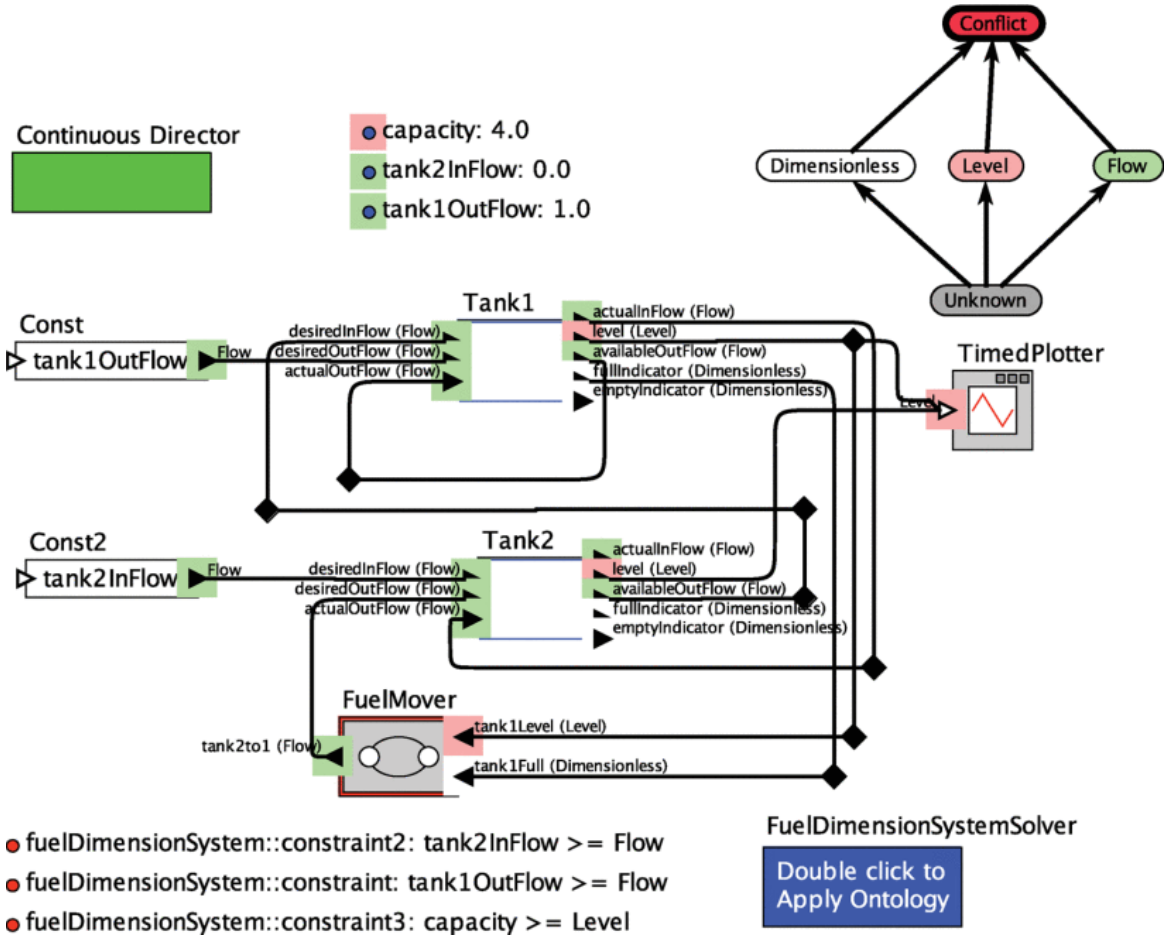


**Figure 8.8** Domain-specific ontology and solver.
[Source: Derler, P., Lee, E. A., & Sangiovanni Vincentelli, A. (2012)]

A model can incorporate annotations representing the domain knowledge of the model builder. These annotations, depicted in the lower part of **Figure 8.8**, associate parameters like tank2InFlow and tank1OutFlow with the concept of Flow, while the capacity parameter is linked with the concept of Level.

The framework can deduce concept associations across a model with just a few annotations. This is achieved through actors imposing specific constraints. In the depicted basic ontology, it is asserted that an Integrator actor converts a Flow to a Level. Consequently, if its output is a Level, then its input must be a Flow, and vice versa. Leveraging such constraints and parameter associations, the ontology solver derives associations across the entire model. These inferred associations are illustrated as annotations near the ports of the actors in the model, color-coded to correspond with the ontology's color scheme. The component labeled FuelDimensionSystemSolver in the model oversees the execution of the inference algorithm. With a well-designed ontology, errors akin to those in **Figure 8.5** can be identified by the solver.

Constraints on model components, such as actors, enforce proper relationships, and checkers like the type of system infrastructure in Ptolemy can deduce these properties and identify errors. By enabling users to visually specify ontologies and describe constraints on model elements, domain knowledge can be systematically built up. Overall system ontological information can then be automatically inferred from the relatively concise constraint set, enabling the detection and automatic reporting of inconsistencies.

### 8.4.7 Linking Behavior to Implementation: Quantity Managers

To facilitate the assessment of design decisions, modeling frameworks must enable the integration of a variety of models covering different aspects of a system. For instance, the choice of a networking infrastructure can impact temporal behavior, power consumption, and susceptibility to faults. An inherent challenge lies in establishing connections between models that represent disparate aspects of the same system.

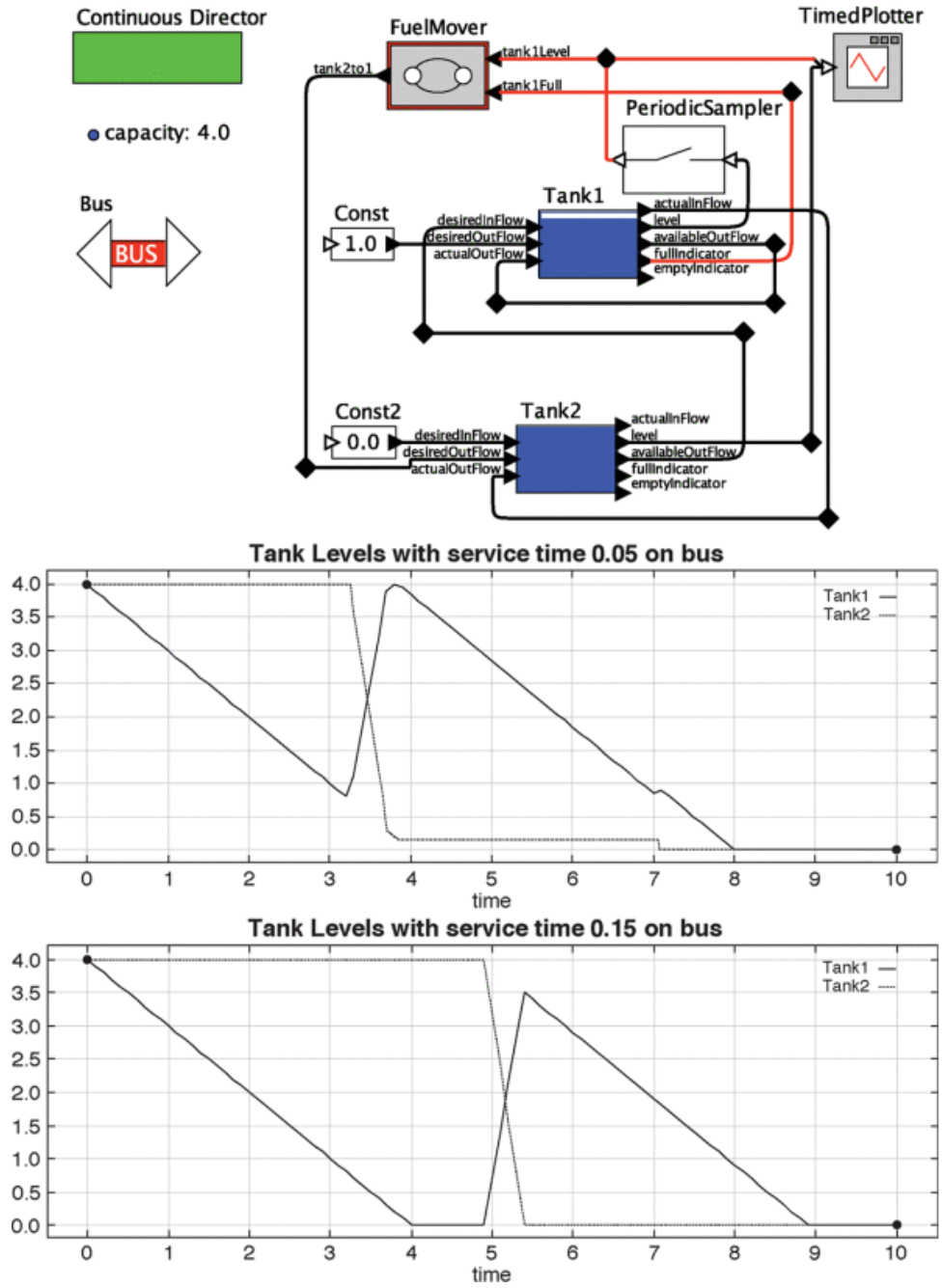


**Figure 8.9** Fuel system model.
[Source: Derler, P., Lee, E. A., & Sangiovanni Vincentelli, A. (2012)]

The Metropolis initiative introduced the concept of quantity manager, a component within a model that serves as a bridge to another model. For example, a functional model depicting idealized behavioral characteristics of a flight control system could be linked to a model representing a

distributed hardware architecture utilizing a specific network infrastructure. This linkage enables designers to evaluate how the properties of the hardware implementation influence the functional behavior of the system. For instance, they can analyze how a time-triggered bus protocol impacts timing within a distributed control system and how these timing effects alter system dynamics. Similarly, a functional model could incorporate a quantity manager to monitor power consumption and identify potential overloads resulting from unexpected, synchronized interactions across a distributed system.

Quantity managers offer a capability akin to aspect-oriented programming in software engineering. Independently developed models can be seamlessly integrated using quantity managers, analogous to the weaving of separately designed classes in aspect-oriented design.

**Figure 8.9** illustrates a modified version of the model depicted in **Figure 8.4**, augmented with details about the implementation. Notably, the two inputs to the fuel mover component are implemented on a network bus, introducing communication delays. The plot at the bottom of **Figure 8.7** compares the fuel levels of the tanks under two scenarios. In the first scenario, the bus's service time is 0.05, while in the second scenario, it is 0.15. The latter exhibits a clear degradation in behavior. Between time 4 and time 5, Tank1 fails to receive fuel from Tank2 despite running out of fuel at time 4. In a real-world scenario, this could lead to a plane crash or severe system instability.

### 8.4.9 Semantics-Preserving Transformation and Implementation

Effective utilization of models necessitates well-established connections between the models and the systems they represent. Often, models serve as specifications from which implementations can be synthesized. The primary challenge lies in ensuring that such synthesis maintains the semantics of the implementation. Code generation from models is an active area. UML tools like Rational Rose can generate code from executable models and templates from non-executable models. Additionally, there exist code generators for actor modeling languages like Simulink (such as TargetLink from dSPACE and RealTimeWorkshop from The MathWorks). LabVIEW Embedded and LabVIEW FPGA have capabilities to generate code and hardware designs, respectively, from dataflow models.

## 8.5 The State of the Art

Despite significant advancements in this field, the code generation from models is still in its stages. The efforts thus far are smaller than those in compiler technology, even though the technical challenges are equally daunting. Furthermore, numerous issues persist only partially resolved, including modular code generation and model transformation.

Despite notable advancements in languages, notations, and tools, significant challenges persist. In practical terms, issues like system integration, adaptation of existing designs, and the interoperability of heterogeneous subsystems continue to be major stumbling blocks leading to project failures. the model-based design, as currently practiced, often fails to fully leverage the principles of platform-based design due to insufficient attention to the semantics of composing heterogeneous subsystems.

Take UML 2, a widely employed tool for modeling software systems. Its derivative, SysML, offers features potentially beneficial for CPS. SysML's internal block diagram notation, based on UML 2 composite structure diagrams and featuring flow ports, holds promise for modeling intricate systems like aircraft fuel systems. However, it suffers from significant shortcomings that hamper its ability to address system design challenges. The SysML standard specifies the syntax of these diagrams but lacks defined semantics. While the standard states that flow ports are intended to be used for asynchronous, broadcast, or send-and-forget interactions, it fails to define the semantics of such interactions. Consequently, tool implementers have the freedom to interpret this intent, resulting in

a modeling language whose semantics are dictated by the tools rather than the language itself. With numerous semantic alternatives, the same SysML diagram may be interpreted differently by different observers.

Similarly, the Modeling and Analysis of Real-Time and Embedded (MARTE) systems avoid defining the execution semantics of models, focusing instead on providing alternative descriptions of current ad hoc, non-composable design practices such as concurrency-based threads. Mere standardization of notation falls short of enabling effective analysis methods and unambiguous communication among designers. Without defined semantics, the modeling framework lacks a foundation for effective design. Regrettably, the flexible nature of these modeling notations may contribute to their success, as designers can achieve "standards compliance" without altering their existing practices by merely adapting their notation.

Moreover, UML notations can be reinterpreted freely by defining a profile, diminishing the notation's value as a communication tool and design aid. It contends that constraints leading to well-defined and interoperable models offer significantly greater value. Crucially, such constraints are indispensable for these modeling frameworks to become central to a platform-based engineering practice. The challenge lies in identifying constraints that provide the most value while still permitting useful designs.

The incorporation of Statecharts into the UML standard by OMG has helped reduce variability for certain modeling problems. However, in many instances, the exact semantics are dictated by the implementation details of the supporting tools rather than by agreed-upon standards. Statecharts suffer from inadequate standardization, with various variants emerging despite their common origin. Even widely used Statecharts implementations claiming standards compliance exhibit subtle semantic discrepancies significant enough to render a model written in one formalism ill-formed in another. In numerous implementations, including IBM's widely used Rhapsody tool, the semantics are inadvertently nondeterminate.

### 8.6 Chapter Summary

The inherent diversity, parallelism, and time-critical nature of CPSs present numerous modeling hurdles. Many existing modeling approaches lack robust semantics to effectively tackle these challenges. Several promising technologies offer potential solutions, such as hybrid system modeling and simulation, concurrent and diverse Models of Computation (MoCs), leveraging domain-specific ontologies to enhance modularity, and integrating the modeling of functionality with implementation architectures.

### Problems

1. Specify the significance of the codesign methodology in the cyber-physical system.
2. Distinguish the modeling and simulation between the Metropolis and Metro II.
3. Describe the modeling and simulation of Ptolemy.
4. Explain the modeling cases of the vehicle management system (VMS).
5. Describe the six modeling issues of the codesign methodology of a fuel system.
6. Detail the key elements of addressing issues of the codesign methodology.
7. Give the state of the art of the codesign methodology.

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# Chapter 9

# Digital Twin

**Chapter Objectives**

- Learners distinguish the Digital Twin associated with cyber-physical systems.
- Learners can describe the Digital Twin of a CPS-based smart city system.
- Learners understand the impact of the Digital Twin on the smart city.

Digital twins are rapidly gaining traction across various sectors, leveraging advancements on the Internet of Things, Machine Learning, and Big Data. Both industry and academia are increasingly utilizing digital twins. This chapter examines the state of digital twins in smart cities, drawing comparisons with their application in Industry 4.0. While digital twins have been extensively studied in the Industrial Internet of Things, their adoption in smart cities has been comparatively limited. The detail gives the existing challenges in this area, emphasizing that digital twins in smart cities should be treated as cyber-physical (systems of systems) due to their unique scale, complexity, and requirements. Additionally, it advocates for the use of established tools and methods from the smart city community, such as co-creation, to effectively address the specificities of this domain.

## 9.1 Introduction

Since the late 1990s and early 2000s, significant advancements in microcontrollers, MEMS sensors, actuators, and networking technologies have propelled discussions and research efforts toward bridging the gap between the physical and digital realms. Initially, this was spearheaded by the research community's work on wireless sensor networks, followed by the rapid adoption of the Internet of Things (IoT), which has swiftly become an integral part of our daily lives. Cyber-physical systems (CPS) have further facilitated this transition, particularly in contexts like smart manufacturing and Industry 4.0.

Building upon these technological strides and the convergence of Machine Learning (ML), Deep Learning (DL), and Big Data from digital sources, the concept of the Digital Twin (DT) has emerged to expand the applications and scope of this digital-physical domain integration. As CPS evolves as a fundamental concept leveraging IoT technologies and bridging Information Technology and Operational Technology, Digital Twins have emerged as strategic tools, offering virtual representations of the physical world. They simulate the behavior of physical entities across their lifecycle while maintaining continuous connections between their physical and virtual counterparts. Thus, Digital Twins can be seen not only as an engineering practice but also as standalone cyber-physical systems, facilitating data exchange and interconnection across various domains.

Moreover, to comprehend the driving forces behind these trends, it's essential to recognize the disruptive potential of digital twins in simulating large, complex systems. Previously, simulation scenarios required trade-offs between model complexity, execution time, and accuracy, often relying on limited datasets for offline analysis. However, with advancements in ML, Big Data, and IoT enabling the development of digital twins, simulations can now continuously evolve based on real-

world data. Particularly in smart manufacturing, where applications like predictive maintenance showcase the potential of digital twins, their adoption has surged. For instance, General Electric reported saving $1.05 billion annually through the use of digital twins, while market projections estimate substantial growth from $3.1 billion in 2020 to $48.2 billion by 2026. Digital twins are already making a significant, tangible impact.

Besides the evident impact of DT technologies on system simulation, numerous benefits have arisen from the increasing number of DT applications. While simulation primarily aids in the initial stages of conceptualization and system design, the growing necessity for continuous monitoring and control of systems and products throughout their lifecycle demands the development of data-driven models capable of real-time data acquisition and analysis for complex systems. DT offers a comprehensive view of large and intricate physical systems in real-time, a feat that would otherwise be nearly impossible to accomplish. The abundance of real-time data can enhance system efficiency by providing users with deeper insights into system operation, while the ability to manage complex physical systems digitally opens new avenues for safety.

As highlighted earlier, lifecycle management has become crucial not only for individual products but also for entire operational systems. Hence, tracking changes in system implementation is vital for troubleshooting and finding optimal solutions. DT provides the means to maintain versioning information on an evolving variable system, enabling system designers to access data on implemented changes and backtrack to previous implementations to test new ideas during redesign stages.

Reflecting on the origins of DTs, we've witnessed a progression from their inception in NASA, initially used for simulating space systems, to holistic representations of more complex processes and systems. The term “Digital Twin” was first mentioned in its current context in 2003 within the realm of product lifecycle management (PLM). Subsequently, digital twins swiftly transitioned to smart manufacturing and are now primarily associated with the Industry 4.0 concept. However, it is also witnessing their adoption in other domains such as smart cities. Consequently, DTs are continually evolving, and their definition has also evolved, with initial definitions being more tailored to the industrial and smart manufacturing sector and gradually adopting more flexible interpretations.

The state-of-the-art in this domain, it has become evident that defining DTs is complicated by the involvement of multiple communities implementing them in various application domains. Each community views DTs from its perspective, contributing to the evolving nature of their definition, which may not solely be based on technological considerations. This complexity is further pronounced when comparing DTs in smart manufacturing and smart cities: unlike industrial DTs, technology alone is insufficient when discussing DTs in the context of smart cities, as they involve the participation of multiple communities. Additionally, DTs are gradually being introduced into various key application areas within cities, such as urban planning, smart mobility, and environmental monitoring. However, as DTs emerge as a novel tool in these areas, numerous challenges persist. These challenges encompass both technological aspects, including standardization and the implementation of complex systems of systems as well as community-related issues, such as engaging various stakeholders in smart cities and utilizing established tools and methodologies, such as co-creation.

Regarding the structure of this chapter, it provides a brief overview of the history of DT concept development and its definition, along with a discussion on its predominant application in smart manufacturing. Subsequently, it delves into the smart city domain, exploring differences and specific requirements for utilizing DTs in this context. The existing literature shows the digital twin domain, along with related reference models and standardization activities. In that, the DT-related works are

presented in smart cities across various application domains, discussing recent and ongoing projects, prototypes, as well as existing DT tools and products. A discussion on open challenges is then provided, followed by the conclusion in the final section.

### 9.2 Representation of Digital Twin

While the concept of the DT is not new, it has garnered significant interest, particularly in its applications within smart manufacturing and Industry 4.0. The concept's origins trace back to NASA's Apollo 13 mission in 1970, where multiple simulators were utilized to train astronauts and ground control staff on various failure scenarios, marking the first actual DT associated with a physical asset. Despite this early application, the term "Digital Twin" did not gain widespread recognition until its appearance in literature in 2003 within the context of product life management (PLM). Subsequently, it re-surfaced in NASA's Draft Roadmap on Modeling, Simulation, Information Technology, and Processing in 2010, with the final release in 2012. Early works on DTs primarily focused on aircraft and the aviation industry, with manufacturing-related works emerging in 2013.

The evolution of the DT concept is evident in various definitions provided:

- A virtual representation of a physical object or system utilizing data, machine learning, and the Internet of Things (IoT) to optimize processes and deliver new services.
- A virtual representation of a physical object or system across its lifecycle, leveraging real-time data for understanding, learning, and reasoning.
- A dynamic, simulated view of a physical product continuously updated throughout its lifecycle, evolving in parallel with the physical object.
- In the context of Digital Built Britain, a realistic digital representation of assets, processes, or systems in the built or natural environment.

These definitions highlight the emphasis on dynamicity, learning, and evolution in current DTs, which transcend static representations of real-world objects. Furthermore, there is a shift towards focusing on systems rather than individual objects or entities, as seen in definitions closely aligned with smart cities and urban planning applications. Looking ahead, it anticipates the emergence of additional DT definitions tailored to new application domains and enabled by future technological advancements. For instance, cognitive digital twins are presented, offering predictions for future DT instances. Overall, the DT definition continues to evolve, guided by prevalent trends, and uses within specific application domains.

Returning to the landscape, the DT concept has significantly shaped the industrial domain, particularly in smart manufacturing and the context of Industry 4.0 transformation. To address specific technical challenges within the manufacturing industry, such as modularity, autonomy, and ubiquitous connectivity, DTs offer novel perspectives by enabling new production opportunities. These opportunities encompass distributed manufacturing, automated planning, and execution of orders, dynamic response to new orders or disruptions for automatic production rescheduling, and improved decision support. Achieving these objectives necessitates seamless data collection and availability throughout the production process lifecycle.

The integration of the IoT, CPS, and DTs serves as a fundamental enabler for these advancements. CPS represents the convergence of computation with physical processes, where embedded computers and networks monitor and control physical processes, and vice versa. Unlike traditional embedded systems focusing solely on computation, CPS equally emphasizes computation and communication between computing and real-world entities. CPS incorporates sensors and actuators

to interact with the physical environment, benefiting from and facilitating the rapid expansion of the IoT.

The IoT establishes a network of interconnected physical objects or things via the Internet, enabling interactions and cooperation among various entities toward common goals. CPS can be viewed as IoT-connected entities that, when combined with data analytics and artificial intelligence, facilitate the development of smart systems across different application domains, including smart cities. CPS, operating at the intersection of the physical and digital worlds, influences real-world processes through their physical and digital components, extending real-world objects to the digital realm and directly associating with their digital counterparts or DTs. DTs, serving as comprehensive collections of digital artifacts with meta-information and semantics, offer simulation capabilities and support model-based systems engineering, providing valuable services across numerous application domains throughout their lifecycle.

Despite the growing prominence of DTs, there is a degree of ambiguity surrounding their definition and dimensions. Some studies propose various dimensions, including the physical part, virtual part, connection, data, and service, while others emphasize theoretical foundations such as modeling, simulation, verification, validation, data fusion, interaction, collaboration, and service. Industrial applications of DTs span product design, production processes, and prognostics and health management (PHM), with underexplored areas including dispatching optimization and operational control. Challenges related to DT implementation in the industry encompass methodology and standardization, data fusion, complexity, model fidelity, servitization, security, and cost.

Efforts to address these challenges include the proposal of "Experimentable Digital Twins" (EDT) for simulation-based engineering processes, enabling simulation-based engineering, optimization, reasoning, verification, validation, control, and human-machine interfaces (HMI). DTs also play a role in enhancing security in industrial control systems and CPS by detecting deviations between expected and real system behavior, incorporating threat detection and prevention measures, and facilitating testing against diverse attacks without risking real operating physical systems.

### 9.2.1 Principal Components

A Digital Twin comprises three main components:

- Physical entities representing real-world systems.
- Digital representations existing in the digital domain.
- Interconnecting links that bridge the digital and physical components.

**1) The physical world**

The physical domain encompasses various elements such as end-users, machinery, resources, specific rules, and environmental conditions within the dynamic industrial setting. This intricate environment involves a range of assets necessary for production, including those involved in data collection, manufacturing processes, and associated software tools. Although each component operates within its designated sphere, they must all interconnect through various IoT systems. The physical world comprises two main components:

- **Devices:** These are the tangible physical objects, also known as twins, which serve as models for the Digital Twins (DTs).

- **Sensors:** These are electronic components physically attached to the twins, from which data and information are collected. Common types of sensors include Programmable Logic Controllers (PLCs), quick response codes, and radio frequency identification (RFID) devices.

**2) The digital world**
The digital realm further categorizes it into two components:

- **Virtual Environment Platform (VMP):** This platform facilitates integrated 3D simulations for implementation applications and enables various functions to validate the operation of different algorithms. There exist multiple connections between the VMP and DTs, with the former offering essential frameworks for the creation and deployment of DTs.

- **Digital Twins (DTs):** These entities support numerous processes and mirror the lifecycle of their physical counterparts, including functions such as prognosis and control.

**3) Services**
Digital twin technology utilizes machine learning algorithms to analyze and identify patterns within extensive sensor data. Artificial intelligence (AI) and machine learning (ML) offer data insights related to efficiency, maintenance, emissions outputs, and performance optimization.

**4) Links Between the Physical World and the Digital World**
Regarding the links between the physical and digital realms, the nature of these connections varies depending on the methods employed by individual researchers. These connections are commonly referred to as middleware or plumbing. Middleware as a set of methods is designed to facilitate interactions among systems characterized by complex features and heterogeneity. **Figure 9.1** illustrates the connection between the physical and digital worlds.

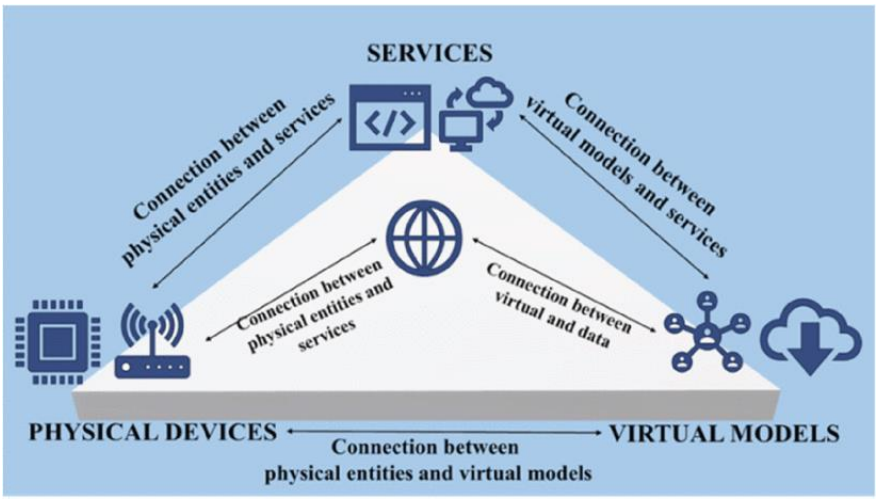


**Figure 9.1** Links between the real and virtual world.
[Source: Manickam, S., et al. (2023)]

**9.2.2 Terms Used in Digital Twins**
The terms used in DTs introduce the following concepts:

- **Digital Twin Prototype (DTP):** This term refers to the set of tasks necessary for creating a specific object. For example, it includes a list of essential tasks for producing an entity.

- **Digital Twin Instance (DTI):** This concept elucidates the components of a specific instance of an entity. It includes specifications and the names of components required to manufacture the entity. Additionally, it encompasses the real-time sensor data connected with the entity.

Each instance of the entity has its own Digital Twin Instance and is created using the Digital Twin Prototype (DTP).

- **Digital Twin Aggregate (DTA):** This refers to an aggregation of multiple Digital Twin Instances (DTIs). The group collectively obtains data from various objects.

### 9.2.3 Integration Levels in Digital Twins

The terms DT, Digital Model (DM), and Digital Shadow (DS) are used interchangeably in various contexts, but they can be distinguished based on the level of integration of information between the real-world entity and the digital twin. A classification based on the degree of integration of data in DTs is proposed as follows.

**1) Digital Model**

A Digital Model refers to a simulated representation of a real-world entity that does not involve any automated data exchange between the real and digital entities. The simulation may provide a basic description of the real-world entity and may include certain characteristics (physical or behavioral) of the entity as long as there is no automated information exchange. Information can be manually entered for creating prototypes and replicas. Changes in the real-world entity do not directly affect the simulated object, and vice versa. **Figure 9.2** illustrates a Digital Model.

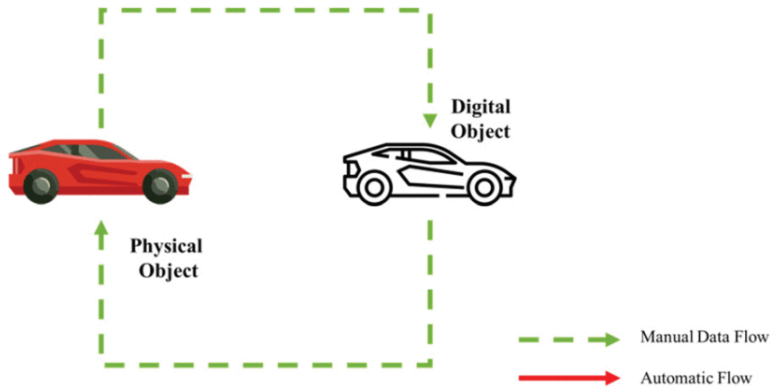


**Figure 9.2** A digital model.
[Source: Manickam, S., et al. (2023)]

**2) Digital Shadow**

When there is an autonomous one-way data exchange between the state of the real entity and its virtual counterpart, it is referred to as a Digital Shadow. Any updates made to the real-world entity are automatically mirrored in the virtual representation, but changes in the virtual entity do not affect the real-world entity. For instance, a Digital Shadow might be utilized to transmit information about the Digital Twin to stakeholders who may not be technically proficient. **Figure 9.3** illustrates a Digital Shadow.

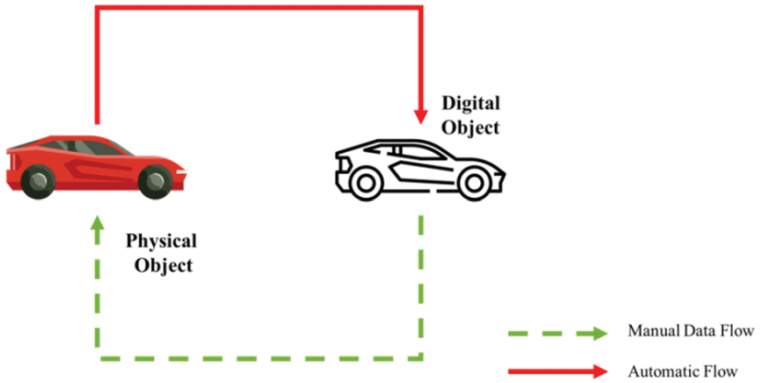


**Figure 9.3** A digital shadow.
[Source: Manickam, S., et al. (2023)]

An illustration of this concept can be seen in the real-time monitoring of energy consumption and system efficiency within smart buildings. Sensors installed in these buildings track various metrics such as energy usage, HVAC functionality, and lighting conditions. This data is then processed by the digital twin, generating a digital representation that mirrors the energy consumption patterns and system efficiency. Facility managers can leverage this digital shadow to pinpoint areas where energy optimization is needed, simulate the effects of adjustments, and implement sustainable practices.

Similarly, consider the monitoring of public spaces, including crowd density and security incidents, as another example of a digital shadow. Surveillance cameras and sensors installed in public areas continuously gather real-time data, detecting crowd movements and potential security risks. The digital twin analyzes this information, creating a digital shadow that reflects the current state of public safety. Law enforcement and emergency response teams can utilize this digital shadow to monitor crowd behavior, proactively respond to incidents, and enhance overall public safety.

**3) Digital Twin**

When there is a two-way exchange of information between the real-world entity and its virtual counterpart, it is termed a Digital Twin. Any updates made to either the real or virtual entity are automatically synchronized with the other. **Figure 9.4** illustrates the concept of a Digital Twin.

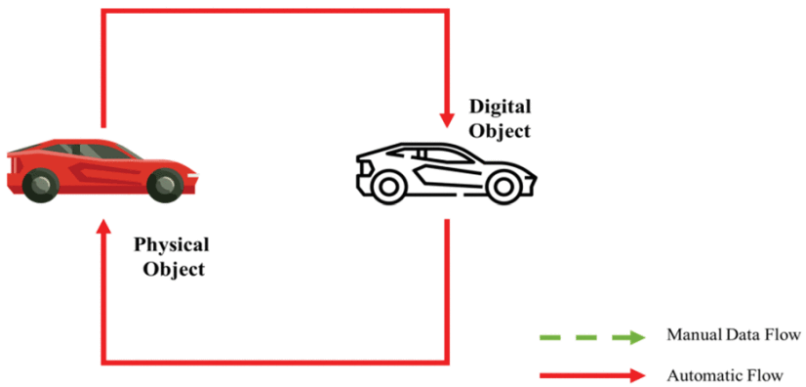


**Figure 9.4** A digital twin.
[Source: Manickam, S., et al. (2023)]

### 9.2.3 Framework and Types

The concept of Digital Twins can vary significantly across different domains, including procedures, usage, guidelines, and the technologies involved, depending on the specific information needs of each domain. The rationale for implementing a DT environment in each domain is determined by addressing relevant business-case questions. However, a comprehensive framework for DT architecture consists of three essential elements: the real world, the digital world, and the various connections that bridge these realms. These elements encompass a wide range of components tailored to the creator's specific requirements. Key elements include sensors for data acquisition within the physical world, a physical counterpart, edge processing capabilities, data security measures, digital twins, data processing capabilities utilizing technologies such as big data, AI, and ML, as well as communication interfaces such as web, Bluetooth, and satellite communication networks.

An important aspect of the DT framework involves data interpretation for end-users. As depicted in **Figure 9.5**, the physical world includes objects, processes, sensors, and actuators, along with various processing elements. In contrast, the digital world comprises ML algorithms, digital twins, databases, and data processing elements. These two realms are interconnected through communication elements with multiple guidelines and interfaces, including Wireless Fidelity (WiFi), Bluetooth, and various wired connections. This model ensures seamless visualization and continuous monitoring for end-users. It should be noted that the definition and classification of Digital Twins in their current state are dependent on their application domains and their corresponding levels of integration.

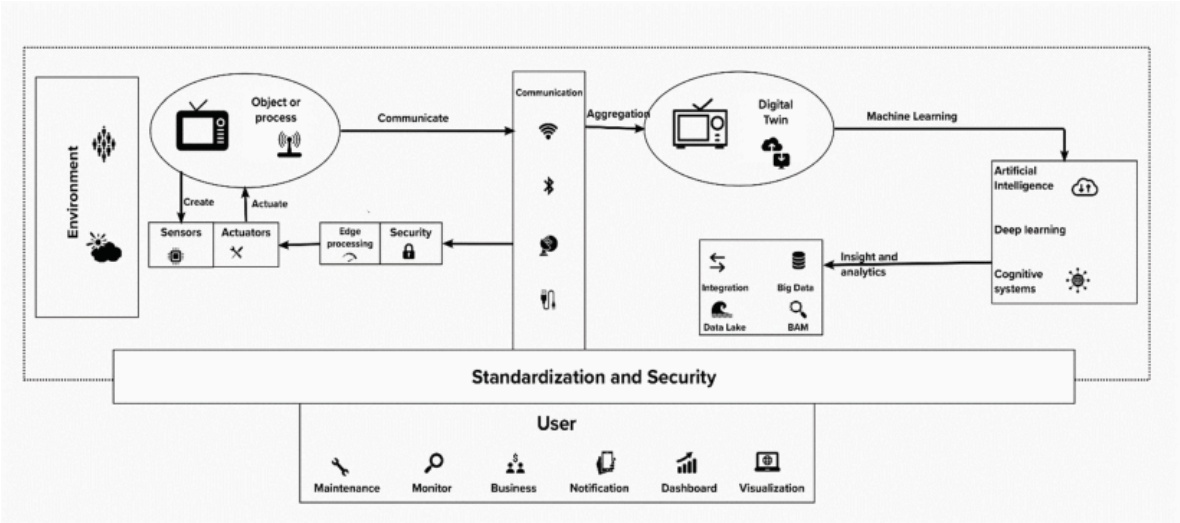


**Figure 9.5** A framework of digital twins.
[Source: Manickam, S., et al. (2023)]

DT can be categorized into two types based on when they are created during their life cycle: before the prototype creation, which occurs during the design phase, or after the final product is manufactured, which happens during the production phase. **Figure 9.6** illustrates the different types of DTs.

1) **Digital Twin Instance (DTI):** A DTI represents a digital counterpart that persists throughout its entire life cycle. Once a physical entity is constructed, data is exchanged between the real and virtual domains to monitor, analyze, and predict the behavior of the system. This exchange enables verification of whether the system exhibits the intended behavior and ensures that any undesired scenarios are effectively mitigated. As the connection between

the two systems is bidirectional, any modifications made to one will be reflected in the other. Some researchers refer to a collection of two or more DTIs as DT Aggregate.

2) **Digital Twin Prototype (DTP):** The DTP encompasses the necessary knowledge for manufacturing or creating a physical replica from a virtual model. This includes data such as bill of materials (BOM), computer-aided design (CAD) models, design files, and information linking the manufacturing process with production chain stakeholders. The production cycle commences with the creation of the DTP, which undergoes various tests, including destructive ones before the physical counterpart is produced. This approach effectively reduces production costs and operational time by identifying potential risks and flaws of the physical twin before manufacturing. The accuracy of the virtual representation aids in determining the quality of the real-world counterpart.

### 9.3 Uses of Digital Twins

With its ongoing integration with the Internet, big data analytics, cloud computing, and other technologies, the DT is now being considered for implementation in various fields that entail mapping, co-evolution, and fusion between physical and virtual spaces. As illustrated in **Figure 9.6**, DT applications can be observed in healthcare, smart cities, cargo shipping, construction, the automobile industry, drilling platforms, manufacturing, electricity, and more. Some of these applications have been explored in this part.

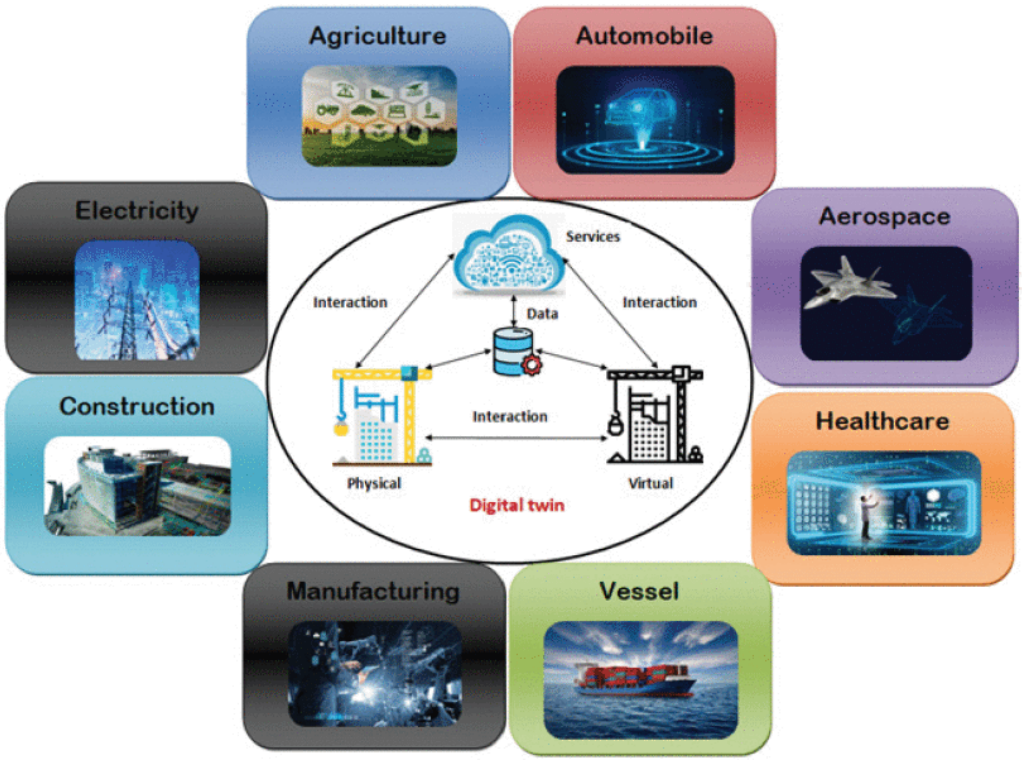


**Figure 9.6** Application areas of digital twins.
[Source: Manickam, S., et al. (2023)]

#### 9.3.1 Digital Twins in Healthcare

There exists a significant demand for enhanced healthcare and medical resources. Leveraging deep learning (DL), data science, and AI techniques can greatly improve healthcare management by providing more personalized healthcare services to the public. Such technologies have led to

advancements in various healthcare tools, including diet monitoring applications, brain-computer interfaces (BCIs), and the diagnosis of cardiac and liver diseases. The concept of a Human Digital Twin is introduced, which essentially represents an individual in cyberspace. It serves as a model or database storing personal information such as age, weight, gender, relatives, and other relevant details, akin to a digital counterpart. This digital representation, stored on a computer or cloud server, is continuously updated to reflect any changes in the individual's information. Synchronization of information relies on connectivity between the physical world and the internet through technologies like 4G, 5G, WiFi, and others. Data from sources such as smart clothing sensors, mobile phones, hospitals, or other institutions are collected and transmitted to the internet, updating the database accordingly. Beyond mere data recording, an HDT performs intricate tasks, considering complex human characteristics such as behavior, reactions, and thoughts, which can be unpredictable at times. This complexity presents significant challenges for HDTs, particularly in accounting for various factors influencing human traits, including genetics, inheritance, and culture.

It is seen that Human Digital Twins was developed for an athletic team. Data on metrics like heart rate, steps taken, physical activity, and sleep duration, as well as manually entered information on food intake, performance, and mood, were collected. The study introduces the SmartFit app, which collects and processes data, feeding it into predictive models for analysis. The insights derived from these models are then presented to trainers and coaches in a user-friendly format for monitoring, recommendations, and corrections. To ensure accuracy and reliability, DL and ML algorithms are employed to adjust data or fill in missing values, considering both historical and future trends. However, the sheer volume of data presents a challenge for this type of Digital Twin.

A DT designed to replicate human responses to viral infections is described. This DT operates at various scales, including multicellular, subcellular, organ, whole-body, and tissue levels, each simulating specific factors related to viral infections. The experimental aspect of the DT is crucial, relying on data from sensors and medical records for accurate simulations and predictions.

A method for a collaborative city DT concept is proposed aimed at generating data for city crisis management. Employing city-scale models for communicating DTs, another study facilitates data-driven decision-making and develops comprehensive plans to address health crises, such as the COVID-19 pandemic.

The use of sensors for Digital Twins is emphasized, likening them to humans' five basic senses. These sensors gather information about the twins and their environment, which is then stored in the cloud network serving as the DT's memory. Data processing, utilizing analytics and AI algorithms, maps the DT's intelligence, enabling decision-making and feedback transmission to the real twin. Feedback mechanisms, such as haptic actuation, notifications, or environmental changes, aim to enhance the real twin's well-being and health.

The application of Human Digital Twins (HDTs) is beneficial for real-time monitoring of the elderly, virtual surgery training, remote diagnosis, and health consulting. The system may transmit alerts to cloud networks accessible to medical personnel and institutions, enabling them to take preventive or emergency action by continuously assessing patients' physiological data in real-time. **Figure 9.7** illustrates a typical HDT framework.

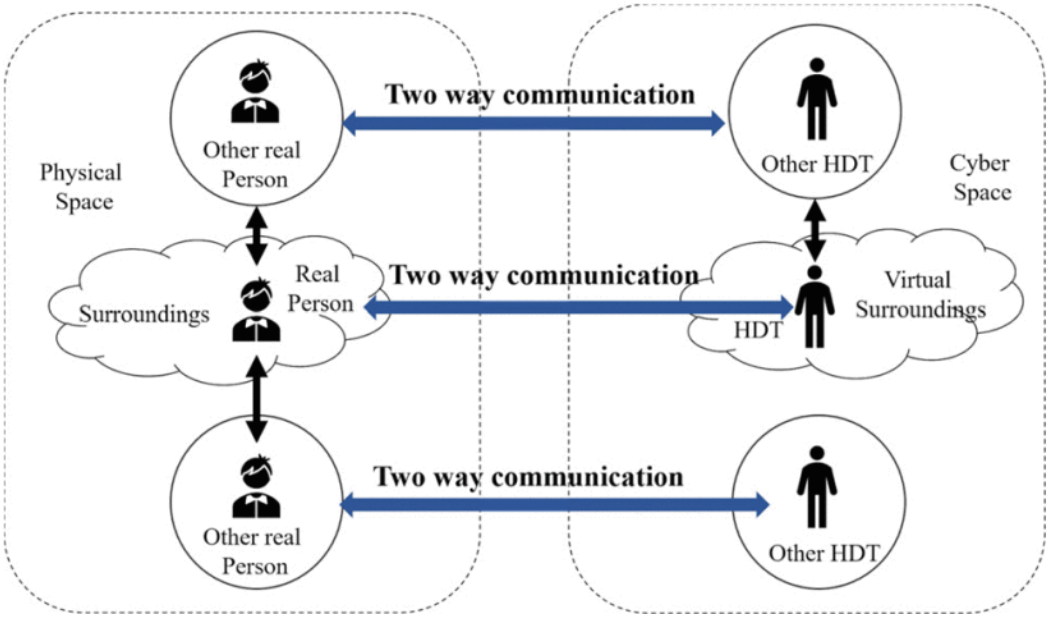


**Figure 9.7** Human digital conceptual model.
[Source: Manickam, S., et al. (2023)]

### 9.3.2 Digital Twins in Cargo Logistics

In the global landscape, the cargo and freight logistics industry stands as a significant sector where DTs are making considerable strides. Given the intricacies involved in decision-making across international networks, integrators and shippers must adhere to specific transport modes while complying with strict rules and regulations to prevent future obstacles. A real-time business scenario employs a four-corner model solution to facilitate synchro-modality throughout a particular industry unit's logistics network and its suppliers. Here, the DT concept is utilized for streamlining processes and handling verified gross mass (VGM) formality documents. The focus lies on fostering collaboration networks among stakeholders to ensure reliable, interoperable, and secure data exchange at a low cost, without necessitating significant IT developments.

It concentrates on last-mile operations, proposing a data and model-driven approach to support decision-making in urban distribution, with a case study in Bogota, Colombia. Utilizing machine learning and real sensing data, the DT concept aims to replicate various scenarios and generate actionable insights to aid retailers in decision-making. The significance of the DT in this context lies in its use within a simulator to predict future situations and devise optimal strategies for dispatchers across various industries such as companies, restaurants, and retail establishments.

As highlighted, efforts to enhance service competitiveness have led retailers and logistics service providers to deploy express fulfillment services, such as same-day or next-day delivery, through omnichannel distribution channels. This shift has introduced new challenges, including fragmented and downsized shipments, increased delivery frequency, shorter delivery times, and uncertain demands and returns, driven by evolving e-commerce behaviors. Consequently, the integration level and complexity of DTs are escalating to address these modern challenges, as shown in **Figure 9.8**.

The advancements in management emphasize the importance of DTs in operations, particularly focusing on digitization and integrated management requirements. This approach is anchored on the IBM platform and gate infrastructure, aiming to seamlessly integrate sensing data into management systems.

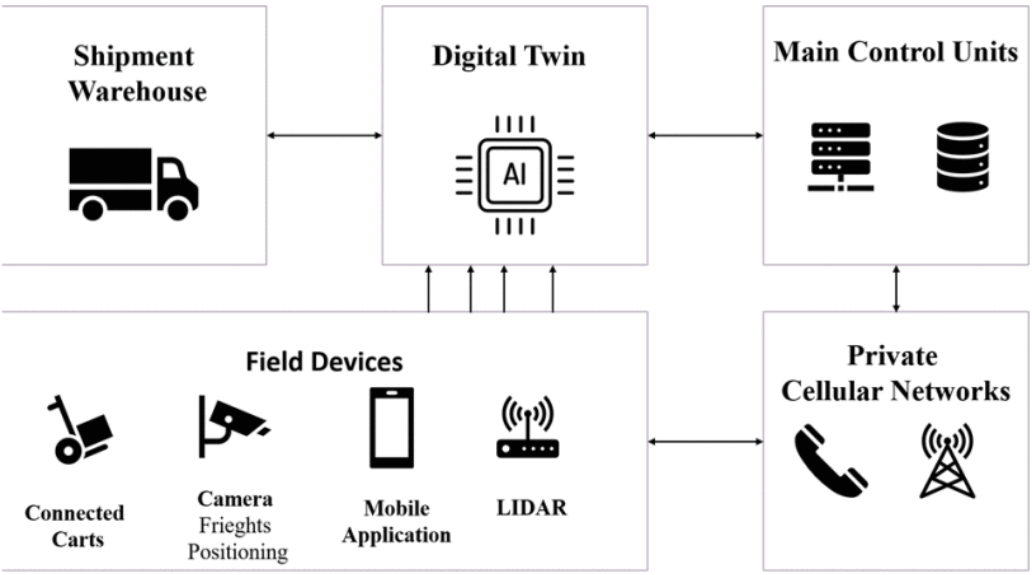


**Figure 9.8** Scheme of main components of port logistics.
[Source: Manickam, S., et al. (2023)]

### 9.3.3 Digital Twins in Engineering

The DT concept plays a pivotal role in simulating, modeling, and optimizing CPSs. Its ability to integrate metaphysical, multiscale, and heterogeneous systems is its primary rationale. By leveraging the most accurate depictions available, both physically and virtually, it aims to emulate and mirror the operational conditions of corresponding real-world systems. This facilitates a deeper understanding of complex physical activities through services such as diagnosis, simulation, optimization, monitoring, and health management. The utilization of DTs spans various sectors, evidenced by the increasing number of DT-related developments and patents. Manufacturers benefit from DTs by making more informed predictions, judgments, and strategies. Two key advantages of DTs include predictive capabilities, enabling the forecasting of future behavior and performance of physical entities, and interrogative functionalities, allowing querying of current and historical DT virtual model data to support decision-making.

The term "DT model" does not always imply a spatial or visual representation. Emphasis should be placed not only on the data entity but also on the process flow and relationships supporting it. However, employing augmented reality (AR) and virtual reality (VR) tools for remote simulation through DTs provides an additional layer of security and expanded capabilities, particularly in hazardous areas and remote access scenarios. Deep interaction and integration of physical entities with virtual objects are essential for enhancing social productivity. Engineering applications of DTs are diverse, with approximately 18% focused on design, 35% on production sectors, 38% on prognostics and health management (PHM), and 9% on other areas. Different phases of the engineering product lifecycle demand various DT applications, ranging from design to end-of-life stages. Cutting-edge approaches like virtual reality and 3D simulation, alongside DT-based simulation designs equipped with effective algorithms, are recommended to enhance virtual testbeds and streamline processes while minimizing costs. Additionally, improving physics-based models with a focus on machine dynamic behavior, virtual sensors, and modeling parameters enables predictive maintenance applications in various studies.

Another study devised an automation cell for the fan-blade reconditioning segment of repair, maintenance, and overhaul (MRO) services. This involved integrating a six degrees of freedom (DoF) robot with a computer vision system and an end-effector grinder. In this scenario, a DT of the grinding process was developed to analyze the required force variables for material removal.

Applications in this domain typically revolve around predicting aspects such as the operational status of components, the structural lifespan of aircraft, the probability of wear and failure during type touchdown, temperature gradients, and cooling rates, among others.

In construction, a multi-dimensional DT model was created to monitor prestressed steel structures in real time and provide immediate safety forecasts. Another example highlights the effective utilization of DTs in electrical energy transformation systems, particularly cable systems, for estimating aging time based on the status of the cables. In vertical transportation systems, DTs are employed to evaluate the condition of proposed systems and determine appropriate corrective measures based on factors such as friction losses, discomfort, and vibration.

A DT model is described in another instance for simulating the electrostatic field of a live worker, their posture trajectory, including geometry, and safety operation components, within the context of high-voltage transmission line live operating situations. This DT aimed to fully integrate the live worker's operational physical trajectory with the spatial distribution of the virtual electric field.

**9.4 The Smart City: A System of Systems**

This part delves into the broader context of the gradual integration and utilization of Digital Twins within the framework of smart cities. Cities, by their nature, can be likened to living organisms due to their dynamic, complex, and expansive characteristics. This parallels the concept of DTs as living, evolving models, entities, and systems within the physical world. Currently, approximately 55% of the global population resides in urban areas, and this percentage is projected to rise to 68% by 2050. These demographic shifts, coupled with technological advancements that have spurred the development of DTs, have paved the way for the implementation of smart city initiatives worldwide.

When considering the fundamental objectives of DTs within the context of smart cities, it is essential to align them with the overarching goals of smart city initiatives. While the definition of a smart city has evolved, common objectives include enhancing governance through informed decision-making, improving citizens' well-being, reducing operational costs, implementing effective disaster management strategies, and fostering development and business growth. Against this backdrop, the integration of DTs into smart cities is becoming increasingly tangible.

An initial step in this integration involves replacing conventional simulations in urban settings with DTs. With the advancements in smart city infrastructure and DT technologies, scenarios such as real-time projection of traffic flow changes within urban areas on citizen mobility or forecasting the impact of a rainstorm on river water levels and devising risk management strategies are becoming feasible DT applications in smart cities. These scenarios underscore the potential of combining smart city infrastructure with DTs to empower cities to make informed decisions across various domains. Earlier smart city research projects, such as SmartSantander, laid the groundwork for this city-scale DT vision by focusing on creating new development ecosystems centered around smart city data marketplaces.

Despite the promising potential, the utilization of DTs in smart cities remains relatively modest thus far. To date, the most prevalent application of DTs in the context of smart cities involves the geospatial mapping of urban areas into 3D models, supplemented by relevant data from existing city datasets and real-time data from smart city deployments to varying extents. This early emphasis on geospatial mapping may stem from the initial interest shown by architects and urban planning communities in applying DTs to cities or their familiarity with Building Information Modeling (BIM) processes, which share similarities with DTs. However, the applications of DTs in smart cities extend beyond this point. As evidenced, DTs are being leveraged to advance the overarching goals of smart cities mentioned earlier.

To discuss smart cities, it is dealing with systems of systems. Even with small-scale deployments of Internet of Things (IoT) technology in areas such as mobility, environmental monitoring, and waste management, this scheme must also consider the myriad of existing information systems within a city. This includes the vast amount of big data generated by city-owned sensors, citizen-owned devices, and increasingly interconnected vehicles, among others. All these components collectively form a large distributed system, which differs significantly from scenarios such as having a DT for preventive maintenance of machinery within a traditional industrial environment. In industrial settings, apart from the relatively smaller system complexity, there is also a much more stable environment, except for occasional events such as reconfigurations of production lines.

Furthermore, it is essential to acknowledge the various communities and stakeholders involved in smart cities, as they influence both technological and social aspects. City authorities and related stakeholders, including politicians, typically initiate the process of implementing a city DT, with various city services poised to benefit from it. Citizens can act as both end-users and data providers for the DT, while businesses may utilize its outputs. Additionally, there are issues surrounding data ownership; data may originate from publicly owned infrastructure or private companies and citizens. These complexities are rarely encountered in the Industry 4.0 context, where data production processes are more deterministic. Public user interfaces are also crucial in smart cities, as citizens should be involved in utilizing smart city DTs and deriving benefits from them—a requirement that is not present in industrial environments. Lastly, co-creation processes involving all participating communities and stakeholders should be integrated into successful DT design and implementation strategies.

Another aspect that receives little discussion but could be enhanced by DTs is the interaction and collaboration between different smart cities. Currently, there are limited or nonexistent interrelations between smart cities for collaborative efforts in areas such as disaster management, pollution monitoring, or circular economy initiatives. One can envision scenarios where the DTs of one smart city alert civil protection authorities in neighboring cities, enabling the modeling of potential disaster management scenarios at an early stage. Given recent extreme weather events due to climate change, such as severe floods, this type of collaboration is timely. Additionally, the concept of smart city DTs as systems of systems could include collections of such DTs, creating even larger interconnected systems.

Taking to the current landscape of DTs in cities, a work focuses specifically on city-scale DTs, aligning with our perspective. It argues that DTs have predominantly been studied and applied in smart manufacturing settings, resulting in research largely confined to a technology-centric view aimed at demonstrating technical functionality. However, this limited perspective may hinder their applicability in smart cities, which are much more complex and heterogeneous systems requiring consideration of urban and socio-political contexts to develop practical solutions and meaningful results. It provides their perspective using initiatives such as the Centre for Digital Built Britain (CDBB) and the Gemini principles developed for Cambridge and the UK. They define city-scale DTs as digital representations or virtual replicas of cities that can be used as simulation and management environments to develop scenarios in response to policy problems. While this definition does not encompass all aspects of such systems, it effectively encapsulates the scope and objectives of current DTs in smart cities.

### 9.5 Domain and Standardization Activities

There has been significant activity surrounding DTs, with several documenting and reviewing progress in the field. These descriptions reflect the diverse application domains of DTs, often from the perspectives of either the research community or the industry, or sometimes specific communities

such as urban planners or the Internet of Things. However, there has been a notable lack of focus on the synergies between DTs and smart cities, partly because some of these arguments were compiled by people outside the IT community. Methodologically, these documents typically employ standard practices such as using search engines and reliable repositories to compile a set of works containing keywords related to the DT domain and then presenting the final works. It is worth noting that the number of such works has significantly increased since 2019, indicating the growing potential of the field.

One focuses on the utilization of DTs in the industrial Internet of Things (IIoT) and Industry 4.0 context and aims to discuss various definitions of DTs, their progression, and related misconceptions. It provides an overview of DT applications, with emphasis on smart cities, manufacturing, and healthcare, along with a survey of the state of the art in these domains. However, it is evident from the presented works that there is a greater focus on smart manufacturing than on smart cities. The work identifies open challenges for each of these areas and emphasizes the need for standardized data models, integration of advancements in AI and IoT, development of secure solutions, and enhanced focus on data exchange.

Another adopts a chronological approach, tracing the evolution of DT definitions and characteristics from early NASA examples to more recent ones. It explores various application domains, including manufacturing, aviation, and healthcare, and discusses design implications for DTs in these domains. Notably, it highlights the importance of a sociotechnical and collaborative design approach for DTs, particularly relevant to their application in smart cities. Open challenges such as ethics, security, privacy, and cost are identified, along with the need for improved user interfaces for creating and operating DTs.

In contrast, a different work focuses on methodologies and techniques for constructing DTs from a modeling perspective. It categorizes DTs into various domains beyond healthcare and manufacturing, including meteorology, education, cities, and energy, discussing enabling technologies in these domains. This advocates for democratizing access to DTs to ensure that the benefits of these technologies reach wider segments of society.

In the realm of DTs in cities, recent work has been influenced by the Gemini principles, with efforts directed toward producing cost-effective DTs that deliver value for cities and citizens. For example, a white paper by the IET regarding DTs in the built environment aligns with the logic of the Gemini principles and proposes an industry-agnostic maturity spectrum model for DTs to conceptualize the elements needed to deliver different levels of value for cities and society overall.

A thought-provoking perspective on assessing the state of DTs in the context of the Internet of Things is presented that the convergence of DT usage in manufacturing, advancements in Virtual Reality (VR) and Augmented Reality (AR), multi-agent systems, and virtualization lead to a unified definition of DT. They also touch on aspects of smart-city-focused scenarios for DTs, advocating for adopting open standards and considering self-organization aspects within DTs, given the vast scale of urban DTs, which may be impractical for human intervention and configuration. Furthermore, they argue that while DTs show promise across various domains, they still need to prove their efficacy beyond basic scenarios and address issues such as privacy and security.

As for enabling technologies for DTs, it delves into detail on the current technologies employed to implement DTs across different domains. This contends that due to the diversity in protocols, and formats, the current array of DT-related tools lacks integration and underscores the necessity for developing new tools tailored to DT-specific workflows.

The DT applications targeting maintenance are a popular use case for DTs. It delves into various types of maintenance—reactive, preventive, condition-based, predictive, and prescriptive—and their application fields when combined with DTs. Manufacturing has emerged as the predominant application field for DTs, with maintenance being a focal point. This identifies two major challenges in this area: data availability and the need for defining maintenance procedures.

For the oil and gas industry, the key application areas for DTs include asset integrity monitoring, project planning, and lifecycle management. Challenges such as cybersecurity, lack of standardization, and uncertainty in scope and focus are highlighted. It concludes that while DT usage in this domain is growing, it is still relatively nascent.

Turning to city-scale DTs, the work delves extensively into such aspects, albeit from an urban planning perspective, with less emphasis on other smart city areas. However, it underscores the importance of involving stakeholders and end-users in the design and implementation of such systems due to their complex nature. They highlight visualization as a key challenge for fully harnessing the potential of urban DTs and present an overarching agenda and challenges for the field.

In terms of standardization efforts in the DT arena, ISO/IEC JTC 1 Information Technology Advisory Group 11 (AG11) has initiated activities on DTs, while the Joint Advisory Group (JAG) Group on Emerging Technology and Innovation (JETI) between the IEC and ISO Joint Technical Committee (JTC 1) is also exploring DT-related aspects. However, there remains a dearth of such initiatives despite calls from various works for action on defining common open standards, particularly for urban DTs. Efforts such as the Digital Twin Consortium, led by the Object Management Group, and the Industrial Digital Twin Association are striving to address this gap, focusing respectively on cross-industry DT reference architectures and definitions, and exclusively on industrial aspects of DTs, with participation from several prominent manufacturers.

For the definition and classification of DTs, a taxonomy is based on seven dimensions consisting of data link, purpose, conceptual Elements, model accuracy, interface, synchronization, and data input. The integration of AI, ML, and Big Data in DT implementation is conducted in the current landscape. It delves into the issue of defining DTs, tracing its historical trajectory and practical applications thus far. The work offers an in-depth examination of these technologies and their interaction with DTs, while also exploring the array of tools employed for such purposes in DT applications, many of which are not DT-specific. Smart cities are highlighted as one of the fields with market opportunities for DTs, alongside optimization, predictive analytics, process monitoring, and healthcare, suggesting that this domain is still evolving in comparison to DT applications in smart manufacturing.

Among the works, some explicitly address aspects of DTs in smart cities to varying extents. Conversely, smart manufacturing is ongoing in all of them, and DTs have solidified their position as a tangible tool in this domain, while the situation regarding smart cities remains dynamic. Furthermore, the absence of a universally agreed-upon definition and taxonomy for DTs, coupled with the relatively limited standardization efforts to date, along with the diverse community-led initiatives, contribute to the perception that the field of smart city DTs is at a juncture, striving to chart its path forward.

### 9.6 Digital Twins in the Smart City Domain

DTs within the smart city context, showcasing exemplary endeavors across various sub-domains of smart city applications. **Figure 9.9** illustrates a top-level framework for a city-wide DT, outlining essential technologies, primary components, key data sources, and the application domains discussed in this section.

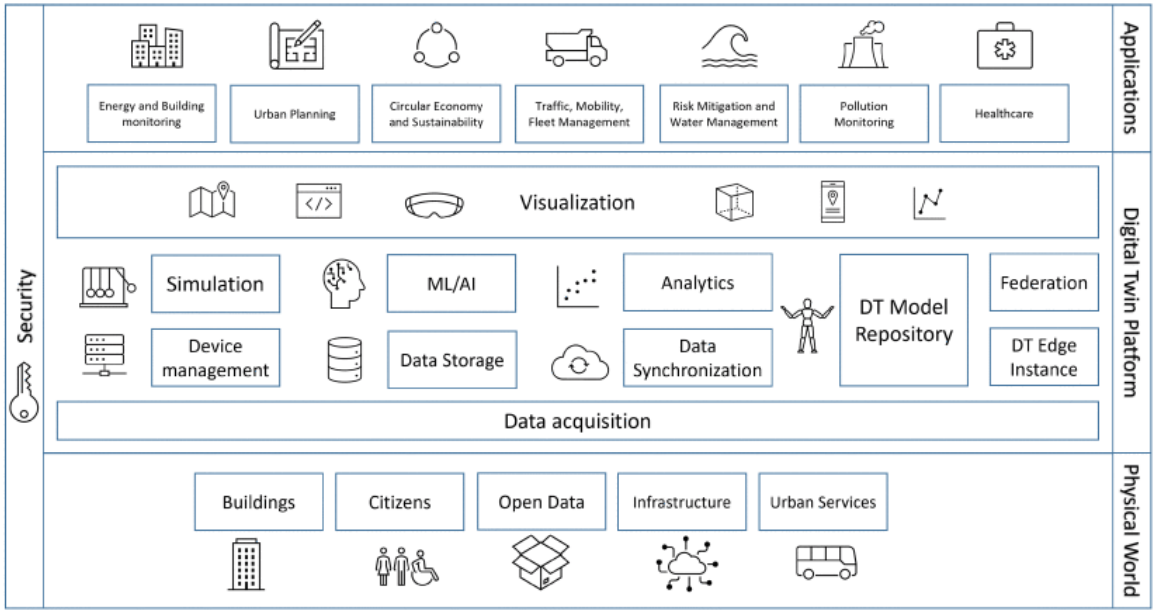


**Figure 9.9** A high-level overview of a city-scale DT.
[Source: Mylonas, G., et al. (2021)]

### 9.6.1 Energy, Comfort, and Structural Health in Buildings

Energy stands as one of the most crucial resources for the functioning of any city, irrespective of its size. From metropolitan centers to smaller urban areas, the demand for energy to power buildings, transportation, infrastructure, and services remains substantial. Unsurprisingly, the energy sector has been an early adopter of DT technology within the realm of smart cities. The growing emphasis on building and grid energy efficiency, coupled with the proliferation of smart energy metering devices, has spurred the development of innovative DT approaches in the energy sector.

An approach to smart city DTs leverages technologies such as AI and ML, grounded in semantic modeling and data-driven rule-based reasoning. This approach facilitates data collection, processing, event identification, and automated decision-making across various city domains, including infrastructure, services, and the environment. Each domain is represented using ontology classes and properties, with specific operational rules defined for each. This combined framework forms the data model used as input for ML techniques, enabling clustering, classification, and association of city objects. The implementation of this architecture in a case study for the city of Chicago demonstrates its efficacy in categorizing buildings based on energy usage, extracting parameters for identifying buildings within specific areas, and segmenting the city based on energy usage patterns. This enhanced situational awareness and decision support aids city stakeholders in managing urban infrastructure effectively.

The concept of urban-scale energy models and their growing role is examined in evaluating the energy performance of buildings within city-scale simulations. Using a city building dataset, they construct a 3D representation of the city structure. Subsequently, three different models are applied to simulate energy consumption and assess building energy efficiency: a machine-learning consumption model, a GIS-based engineering model for predicting space heating consumption, and a software simulation model for estimating energy demand and use. Implementing these models in the case study of Fribourg, Switzerland, demonstrates the potential of urban-scale energy models in

identifying smart energy solutions for sustainable cities, informing policies, and supporting energy and environmental objectives.

The focus shifts to a unified open-source optimization framework designed to address the challenges posed by multi-vector smart energy systems in the context of smart cities. The solution involves integrating an intermediate software control and coordination layer, termed the sustainable energy management system, between the smart city digital twin and the city's actual assets. This layer employs ML algorithms and model predictive control strategies to deliver energy efficiency solutions tailored to city-scale environments, providing recommendations to lower-level actuators. The system interfaces with the DT, receiving predictions from DT energy simulation tools and updating the DT with real-time and control data. This architecture offers scalability, with each subsystem capable of independent consideration and integration, facilitated by a coordination layer that imposes higher district-level constraints and limitations.

The significance of DT enables energy management platforms to facilitate energy efficiency prioritization and near-real-time decision-making. They highlight the importance of visually representing energy-related data and metrics within the city DT, transforming them into actionable information such as temporally segmented building energy benchmarks. This visualization can assist city energy managers in adopting optimal energy efficiency strategies for large-scale building areas.

DT-based approaches regarding intelligent recommendation systems for energy services and demand-side management are provided. The increasing popularity of intelligent recommendation systems in the energy sector, along with the growing utilization of the DT concept. They also offer a set of policy recommendations for the adoption of DT in the energy sector.

The usefulness of a DT city model in raising citizen awareness on energy-related matters is highlighted. By showcasing energy-related data, including consumption and renewable energy generation, along with real-time data from smart metering devices and weather sensors, users can visualize their city's energy usage. This citizen information center demonstrates how DT implementations can enhance citizen awareness and provide valuable feedback to communities and decision-makers on energy efficiency and environmental protection.

A DT application merges BIM and IoT technologies to enhance city energy efficiency and promote sustainability. The application focuses on user comfort, which is linked to indoor environmental quality (IEQ). Various IEQ parameters are combined to measure occupant satisfaction, and environmental data from sensors is used to calculate energy efficiency indices, triggering actuation instructions for regulating energy consumption and internal comfort conditions. Facial recognition algorithms analyze occupants' facial expressions to gauge their emotional state, and all processed data is visualized in a 3D environment, integrating energy measurements, comfort indices, and emotion detection in real time.

In the building structural health section, A DT approach for monitoring the stress and strain conditions of functional bridges in real-time, visualizing IoT sensor data in a BIM 3D environment. The DT integrates physics-based numerical modeling and data-driven statistical modeling to enhance bridge performance monitoring and improve whole-life management.

Another application for bridge structural health monitoring aims to automate and enhance risk inspection procedures using 3D scanning and visualization in a DT environment. This allows for better-informed decisions without the subjectivity of manual inspections and enables simulation of human-imposed risks like heavy traffic during construction and operation monitoring phases.

The geospatial point clouds are utilized to generate a 3D BIM of a bridge, integrating data from the structure and real-time IoT sensors. Machine and deep learning techniques are employed to reduce uncertainty in the manual configuration of critical variables for bridge structural health.

The DT paradigm is gaining momentum in the energy efficiency sector, closely linked to the smart city concept. The abundance of real-time data on building energy performance via IoT technologies provides a foundation for energy efficiency calculations. BIM technologies visually represent building energy performance, offering user-friendly platforms for decision-making and citizen participation. AI and ML technologies process big data to prioritize energy-related interventions. DT models simulate different scenarios, providing city officials with knowledge of achievable results and potential risks in city operations.

**9.6.2 Urban planning**

Urban planning is crucial for the sustainability of metropolitan areas due to the increasing population and limited resources. DT applications can assist in urban planning while enhancing citizen participation in policy-making.

A method of creating spatial 3D models is used in city-scale DTs. The approach involves utilizing near real-time data from Light Detection and Ranging (LiDAR) point clouds to develop a 3D representation of the city. The method includes clustering objects based on their symmetric properties, demonstrated in a car park in Dublin. This approach addresses the challenge of unknown taxonomies of city objects when modeling them in 3D environments like DT applications.

To integrate various technologies such as cyberGIS, BIM, AI, ML, laser scanning, and IoT devices into a unified data management system to create a dynamic DT of a city. This system enables stakeholders and experts to access dynamically created point clouds via cloud-based platforms for decision-making processes. It focuses on construction planning and assessing the impact of new structures on city development, highlighting challenges such as spatial big data analysis requiring high-performance computing environments.

A city-scale DT is used to promote citizen interaction with authorities and facilitate their involvement in city planning. The DT model comprises six discrete layers: terrain, buildings, infrastructure, mobility, smart city, and virtual layer. These layers exchange data and information to simulate different scenarios and present outcomes to citizens and authorities for feedback and re-planning.

Urban planning involves complex decision-making processes, selecting measures with minimal disturbance, and involving citizens. The DT model integrates various technologies to support this process by dynamically representing city environments through point-cloud technologies. This enables visual presentation of planned city changes before implementation, while scenario simulation provides feedback on planned interventions to officials and citizens.

**9.6.3 Circular Economy and Sustainability**

In the realm of circular economy and sustainability, numerous works delve into the emerging concept of circular cities and their technological underpinnings, which essentially form parts of a city DT. The conceptualization of circular economy and its application within circular cities, identifying the need for addressing consumption alongside production to facilitate circularity at the city level. Key resources like land and infrastructure are recognized, emphasizing the importance of localization and adaptation for cities to become more circular. The conceptualization outlines three circular actions—loop, adapt, and regeneration of the urban ecosystem—alongside four support actions: localize, substitute, share, and optimize, aligning with the UN Sustainable Development Goals (SDGs) to guide sustainable city development.

The core aspects of circular cities emphasize the application of circular principles in urban planning and the role of ICT solutions as technical enablers for the circular economy. Challenges such as technological lock-in are addressed, proposing standardized ICT integration to facilitate circular cities. The integration of IoT devices is explored, leveraging blockchain and edge computing to tackle security and privacy concerns. Hierarchical edge computing is suggested as a suitable architecture for smart city contexts.

Several works explore the intersection of DTs with circular economy and circular city concepts. The remanufacturing in construction and DT applications highlights challenges such as data integration and information exchange in the remanufacturing chain. A laboratory application case supporting Circular Economy with Industry 4.0-based technologies, employing CPS, IoT, and DTs to virtualize waste testing and optimize energy performance. Similarly, the role of DTs in sustainable production outlines requirements and proposes a top-down perspective for addressing sustainability challenges in production systems.

In the realm of sustainability assessment in buildings, the Sustainable Digital Twin (SDT) framework for dynamic real-time monitoring of sustainability indicators, was exemplified in an academic building pilot deployment in Italy. Although waste management is a critical concern in smart cities, there is currently limited research linking DT applications with it. Waste management in smart cities highlights the importance of incorporating key elements for cities to become zero-waste sustainable. While the application of DTs for circular economy and sustainability in a smart city context is currently limited, ongoing efforts in remanufacturing, sustainable production, and building sustainability assessment suggest potential future applications of DTs in waste management and other sustainability domains.

### 9.6.4 Traffic, Mobility, and Fleet Management

In the domain of traffic, mobility, and fleet management, the inception of DTs in urban settings can be traced back to mapping services, where the detailed mapping of cities necessitated the transformation of real-world features into digital counterparts, updated periodically. Currently, there are competing visions in this evolving space, with DTs serving as a foundation for services either from private companies or city authorities.

Private sector initiatives often entail building closed-source DTs to provide mobility-focused features, particularly with the rise of autonomous driving. Companies like Uber are leading efforts to deploy fleets of self-driving taxis, leveraging DTs for advanced autonomous driving features and passenger itinerary scheduling. Conversely, city authorities may favor open or open-source DTs to implement applications such as dynamic congestion pricing or disseminating timely road event data like accidents.

The Open Mobility Foundation (OMF) has introduced the mobility data specification (MDS) to standardize data interoperability in the mobility sector, enabling cities and companies to utilize data consistently. For example, e-scooter fleet operators could utilize MDS to report relevant data. Studies employ DT-based simulations to analyze transportation modes' efficacy in reducing travel time in cities, using real mobility data.

The electric vehicle (EV) sector is leading in Advanced Driver Assistance Systems (ADAS) and IoT-based technologies. DT technology is used in electrified vehicles, emphasizing the benefits of in-vehicle health management, battery management, and intelligent charging, despite challenges like standardization and security concerns. Other reports emphasize DTs for predicting vehicle operation

and maintenance, proposing frameworks for vehicle-to-cloud ADAS, and studying EV charging at scale.

In managing commercial EV fleets, the organized adoption of electric public transportation in China has led to software solutions for monitoring fleet status in real-time, exemplified by the Shenzen fleet of 38,000 electric vehicles. Additionally, DTs are being explored in last-mile logistics, such as the LEAD H2020 project, which aims to create DTs of urban logistics networks in European cities to evaluate alternative logistics strategies.

Maritime traffic and smart container tracking in ports, as seen in Rotterdam, also benefit from DTs, demonstrating their utility beyond road-based mobility solutions. These applications underscore the versatility of DTs in managing diverse transportation systems and logistics networks, driving efficiency, and informed decision-making in urban environments.

Proposals and prototypes for integrating DTs into mobility, traffic, and fleet management have sparked concerns among privacy experts regarding potential data misuse. The prospect of private entities or public authorities accessing data that could be deanonymized in this domain is a significant factor driving public discourse around DTs in mobility and traffic management and for valid reasons. Data generated from smart vehicles and city infrastructure poses various privacy risks to vehicle occupants and even bystanders in certain scenarios. A DT-based prototype equipped with mechanisms to detect privacy anomalies and mitigate privacy risks in smart vehicles.

Overall, DT technologies appear well-positioned to leverage advancements in autonomous vehicles and complement the ongoing trend toward mobility electrification. Both private and public entities demonstrate considerable interest in employing such approaches to realize the vision of autonomous driving and enhance traffic management. Currently, it appears that this represents a strong use-case scenario for DT utilization. However, given the nascent nature of the field, challenges persist, including standardization, scalability, and concerns regarding security and privacy. Nonetheless, advancements in smart cities, vehicle electrification, and the software-driven transformation of the automotive industry are expected to accelerate progress in addressing these challenges.

**9.6.5 Risk Mitigation and Water Management**

The impacts of climate change manifested through an increasing frequency of extreme weather events, have become increasingly apparent, resulting in substantial global costs. A significant proportion of these events are water-related, including droughts and floods, while projections for rising sea levels in the coming years are cause for significant concern. Concurrently, the COVID-19 pandemic has underscored deficiencies in disaster risk management worldwide. The concept of resilience has gained prominence in discussions surrounding cities and communities, highlighting the need for robust risk mitigation mechanisms. These developments have reignited interest in leveraging recent technological advancements to develop smart city solutions for crisis management, utilizing available information streams to gain a more accurate understanding of the factors influencing the outcome of such events.

An effort to outline a generic framework for a city-scale disaster management system proposing a system based on multi-sensory data streams, data integration and analytics, game-theoretic decision-making, and dynamic network analysis. The current challenges associated with each component and the role of AI in this context. Similarly, the use of participatory sensing to enhance existing DT data, such as 3D models, through crowdsourced visual data, with small-scale case studies conducted in Houston, USA.

In addressing health crises such as the COVID-19 pandemic, a DT-based approach utilizing federated learning, whereby a shared model is produced while data is kept locally for privacy reasons, to facilitate COVID-19 response planning. Simulation results over a real-world dataset demonstrate the promising potential of this approach in crisis management.

Regarding water-related events, the hydrological DTs can serve as valuable tools for creating safer urban areas, focusing on floods and interconnecting with other DTs, such as those focused on traffic or urban planning, to enable more efficient communication among city stakeholders. Similarly, a DT prototype for the water network system was developed in Newcastle, UK, capable of tracking network malfunctions and the effects of heavy rainfall on water levels in specific areas or buildings, facilitating improved response planning. Meanwhile, the implementation of a DT model for the water distribution network in Valencia, Spain.

While risk mitigation holds significant potential as an application domain for city-scale DTs, the number of implemented DT-based prototypes and solutions remains limited. Additionally, the scale of implementation in most deployments is relatively small, suggesting potential hidden costs and complexities associated with implementing and operating such DTs in practice.

**9.6.6 Pollution Monitoring**

Pollution monitoring stands as a critical endeavor in every urban setting, as reducing pollution levels significantly impacts citizen health and overall well-being. DT applications have emerged to address this domain, primarily focusing on air quality and secondarily on noise pollution within urban environments.

A prototype of a city-scale DT is introduced to assist policy-making in tackling four significant urban challenges: congestion, air pollution, growth management, and limitations in local energy infrastructure within the Cambridge city region. Similarly, the same system as a prototype illustrating the interconnectedness among transport, air quality, housing, and energy infrastructure in the area. The model follows three interlinked tasks: identifying past trends, developing and executing scenarios, and integrating with existing city models to facilitate coordinated policy-making. The prototype development aligns with the "Gemini Principles" for creating city-scale DTs.

Meanwhile, the development of GIS-based city monitoring and management applications necessitating the fusion of various technologies such as GIS, BIM, and IoT. IoT nodes offer real-time information on critical data, including air and noise pollution indices, which are integrated into the data layer of the model, comprising BIM objects. A GIS system serves as the integration platform and facilitates visualization of the acquired information.

A city-scale DT prototype for Herrenberg, Germany, integrates BIM and visualization technologies with computational methods utilizing sensor-acquired data to simulate scenarios for city monitoring and decision-making. Computational fluid dynamics applications are employed for air flow simulations, with sensor data input used for air pollution simulations, addressing a primary concern for the city. Similarly, the process and challenges in creating a geographically focused DT for Vienna, discussing the impact of city 3D representation on simulations calculating noise pollution dispersion within city structures.

Additionally, a city-wide DT employed in Zurich, leveraging a spatial 3D model of the city updated and enriched with real-time data to facilitate applications such as noise and air pollution modeling. The ongoing work continuously expands the 3D spatial data, covering various applications such as thermal monitoring of the city and encouraging active citizen participation in urban planning through attractive data visualization.

Pollution and environmental monitoring DT applications in the smart city domain predominantly concentrate on air and noise pollution. Utilizing sensor-collected air pollution data coupled with computational fluid dynamics algorithms enables visualization of air pollution levels across the city. Moreover, simulating noise propagation through city structures using a 3D GIS layer enhances understanding and awareness of common environmental issues among citizens, promoting eco-friendly practices and resource usage.

**9.6.7 Healthcare in Smart Cities Using DTs**

Healthcare has witnessed a significant surge in the utilization of sensors and IoT technologies, emerging as one of the most active domains in both research and commercial applications. The integration of health-related sensors and services into smartwatches and smartphones has become commonplace, with these technologies now extending their utility beyond personal health management to community-level applications, as demonstrated during the COVID-19 pandemic through initiatives by companies that provided publicly available statistics on changes in mobility patterns using mapping services and mobile device location history data.

This dual approach of targeting health-related applications at both individual and community and organizational levels is gradually transitioning to the realm of Digital Twins (DTs) as well. Sensors from personal devices such as smartwatches, coupled with smart city sensing infrastructure, can facilitate such applications. For instance, DTs of human organs can simulate the effects of treatments, while smart cities can leverage DTs to respond to potential and actual health hazards, such as air pollution affecting citizen health in specific urban areas.

Smart city infrastructure and mobile sensors, along with ML, can enable more effective and cost-efficient healthcare services for smart city residents. Various use cases for ICT-based healthcare at both personal and community levels are presented, alongside considerations of aspects like city planning and walkability. Key challenges highlighted include privacy, security, accessibility, usability, and interconnection with smart city services.

In the broader context of healthcare, the evolution and application of DTs in various healthcare sectors, including human digital twins, disease and virus-specific DTs, and composite DTs combining different health-related aspects. Additionally, the use of CPS in the health sector proposes the utilization of DTs at an organizational level or for modeling individual treatment processes, with a focus on energy and smart-grid aspects of healthcare organizations. Challenges identified include energy flow among CPS components, system integration, delay/latency, and security.

For practical implementation, the architecture frameworks for healthcare-related DTs. The role of DTs in providing healthcare services for the elderly, presenting conceptual and reference models for DT healthcare systems, and referencing key enabling technologies. An ISO/IEEE 11073-based DT framework for healthcare and well-being services provision, discussing the architecture of a cloud-based system targeting individual health and well-being.

Overall, DTs for healthcare represent a promising application domain with significant potential, particularly due to the widespread adoption of personal devices like smartwatches. Moreover, several aspects mentioned in this domain can be interconnected with other application sectors such as air pollution or traffic management. Key challenges include privacy, ethics, policy-related considerations, and implementation challenges inherent in handling sensitive health data.

### 9.7 City-Scale Digital Twins

DTs are implemented in cities worldwide, aiming to illustrate the current state of the art in existing solutions. Additionally, insights into the existing DT tools and products from the industry sector.

#### 9.7.1 Projects and Prototypes

While city-scale DTs are still relatively scarce, there is a growing number of prototypes and projects employing the DT approach in urban contexts. These prototypes can generally be categorized into two types: those primarily focused on 3D representations of the built environment, often geared towards urban planning, and more recent ones adopting a broader approach in terms of data utilization and application development, often integrating co-creation and collaborative activities.

NASA stands out as one of the pioneers in utilizing a DT philosophy in practice, having developed a large-scale DT at the Langley Research Center, spanning a campus with over 200 facilities. Over three decades, NASA has extensively mapped both the interior and exterior of these facilities and curated applications across various domains. These applications range from space allocation tools for personnel and equipment to public safety and security measures, as well as flood vulnerability analysis. The data has also enhanced maintenance and operations, enabling NASA to handle tasks more systematically and quantitatively, such as through specific public bids for maintenance services.

Singapore has emerged as a leader in the DT space, with Virtual Singapore being one of the most prominent city-scale DTs. As one of the world's most densely populated urban areas, Singapore's DT primarily targets urban planning. While it boasts an extensive and detailed 3D mapping of the urban area, the integration of real-world live data into the system remains somewhat unclear. An interesting, related project is Singapore Underground, which focuses on further mapping the underground areas of the city to provide a more comprehensive representation of its physical structures.

The New South Wales DT aims to provide a range of scenarios where the developed DT can benefit the public. These scenarios include transport, urban planning, water resources, natural disaster prevention, and climate change risks, among others, leveraging extensive datasets. Live data is available for transport and air quality, supplemented by a public web interface for data access. A series of additional apps utilizing the DT's data focus on scenarios such as land cover or traffic congestion prediction, making it one of the most ambitious city-scale DT projects to date.

Another DT prototype was developed for implementation in the town of Herrenberg in Germany. While it operates on a much smaller scale compared to, for instance, the NSW Digital Twin, it supports a variety of applications and places emphasis on collaborative elements by incorporating data collected from citizens and providing avenues for interaction with decision-makers and urban planning professionals. Notably, there is a focus on the availability of end-user interfaces, including options for virtual reality. The project centers on scenarios such as mobility, transportation, and air quality, with an added dimension of co-creation integrated into its framework.

The ongoing DUET H2020 project endeavors to develop DT prototypes in three European cities to facilitate the transition from smart to responsive cities. Like most recent DT prototypes, it is developing a suite of 3D and 2D interfaces for engaging with end-users. A distinguishing feature of the project is its emphasis on co-creation aspects, following established practices from previous smart city-related initiatives. The LEAD H2020 project concentrates on constructing urban DTs for last-mile logistics, with prototype deployments across six European cities. Urban logistics planning has become a notable scenario in the urban setting, particularly in the post-COVID era. The SPHERE H2020 project places more focus on energy aspects, aiming to provide BIM-based prototype implementations of DTs. Although the scale of implementation is relatively small compared to other

urban DTs, pilots are spread across four European countries, representing a diverse range of climate and socio-cultural settings.

While not a DT prototype in itself, valuable insights into the process of designing a city-scale DT and the related steps utilized for the case of Cambridge in the UK. Overall, the UK has been more proactive in promoting the use of urban DTs compared to other countries. Initiatives like CDBB (Centre for Digital Built Britain) and the associated National DT initiative are exemplary of how the DT concept has evolved to encompass additional aspects of smart cities. Other DT-related initiatives in the UK include the SCENE project, focusing on energy aspects in urban neighborhoods, with real-world deployments in Nottingham. Citizen interaction with energy-focused interfaces related to DT has reportedly heightened awareness about energy-related issues in urban homes. Future City Glasgow is another smart city initiative related to the utilization of DTs in this context.

Several other European cities have recently begun investing in the use of DTs, including Dublin, Zurich, Rotterdam, Antwerp, and Helsinki. While some European cities have shown activity in DT, such as Vienna, many of these initiatives appear to be in the early stages of consultation or preliminary design phases. In the case of Dublin, the focus is on urban planning, with demonstrated interfaces for citizen interaction regarding urban planning issues and new buildings, as well as green spaces, enabling citizen feedback on proposed changes. In Zurich, 3D spatial data for urban planning, with arguments in favor of DT models as open government data rather than closed-source solutions. A need for multiple visualization options and interfaces for DTs to enhance citizen understanding and support for city DTs.

Rotterdam, home to the largest commercial port in Europe, is developing a DT to enhance situational awareness, sustainability, and aid in the deployment of autonomous ships within ports. The port's efficiency and safety are explored through simulations utilizing the port DT. Another DT initiative in Rotterdam targets common urban planning use cases with a more open approach, offering open availability of the city's 3D models. Similarly, in Antwerp, a DT prototype is employed, integrating IoT data on air and noise pollution as well as traffic information for a city-scale implementation. Additionally, like Rotterdam, Antwerp is also pursuing an initiative to create a port DT.

In Helsinki, several DT initiatives have emerged in recent years, focusing on 3D modeling at a city scale, although differing in their approach to open data. One initiative concentrates on tourism, offering an elaborate 3D model of the city through web and VR interfaces. Other DT initiatives utilize 3D models of the city, coupled with semantic modeling, for urban planning use cases. The models are openly available in various formats, offering varying levels of detail for each modeled building, which sets them apart from other DT projects that offer minimal detail within city buildings, aside from their 3D exterior and basic semantic tags.

Regarding city-scale DT prototypes in China, a DT of Shanghai has been developed in recent years, featuring 3D models of buildings covering an area, potentially making it one of the largest DTs in terms of covered area. In terms of city-scale DTs in India, Jaipur serves as an example, employing 3D modeling of urban areas to create a 3D DT of the city. However, limited information is currently available in the public domain about this specific DT. Amaravati is another Indian city with a notable urban DT referenced in recent literature, which is said to be the first example of a new city, with its DT being built in parallel with the actual city. However, while construction activity had commenced in previous years, the development of the city appears to have stalled. In the US, Boston presents an urban DT prototype utilizing 3D modeling of city buildings to enable scenarios for urban planning, such as simulating the impact of high-rise buildings on surrounding areas, such as the effect of a skyscraper's shadow on green areas or solar energy generation.

Key aspects of the urban DT prototypes and projects focus on the applications covered by each DT, the extent to which co-creation aspects are utilized, the integration of IoT data, the type of user interfaces employed, and the current status and degree of maturity of each project. While information regarding such aspects may be somewhat sparse in many cases, significant patterns emerge from the brief presentation provided in this section.

To elaborate, it is evident that urban planning currently stands as the predominant use case scenario in city-scale DTs, closely followed by traffic and environmental monitoring, with energy-related scenarios also gaining traction. While there are some intriguing scenarios related to specific aspects such as port management and tourism, these often align with urban planning initiatives. Surprisingly, there are only a few urban DTs that heavily leverage data from IoT and sensor networks, despite the extensive work dedicated to smart city aspects in recent years and the widespread adoption of IoT in daily life. Additionally, although there is much discussion about how urban DTs revolutionize urban application domains through collaboration with citizens and stakeholders, there are currently very few examples that have integrated co-creation aspects into their design and implementation, or there appears to be a lack of tools to facilitate interaction with such groups. Presently, 3D maps and related web interfaces are the predominant choice for user interfaces in DT implementations. VR is utilized in some cases, such as in Helsinki or Herrenberg, but there is generally a limited selection of user interfaces exclusively targeting citizens of the cities where these DTs are deployed.

### 9.7.2 Existing Digital Twins Tools and Products

DT applications were predominantly utilized within manufacturing systems and industrial processes. However, there is a notable shift occurring as they are increasingly recognized as valuable components within smart cities. Embracing the principles established in manufacturing environments, digital twins in smart cities must amalgamate 3D representations, spatial modeling, and numerical and physics-based simulations of electrical and mechanical models, along with bidirectional data flows from sensors dispersed across various IoT devices within city buildings and infrastructure. The prominent digital twin-based software solutions and products are currently available.

The 3DEXPERIENCE platform is employed for developing city-scale digital twins like the Virtual Singapore project. Its suite encompasses various tools for designing and constructing 3D models, creating, and simulating digital twins of objects and processes, and intelligently managing information. This platform offers a comprehensive approach for urban planners to make informed decisions across different time instances.

Microsoft offers a Platform as a Service (PaaS) solution for generating knowledge graphs based on digital representations of entire environments through its Azure Digital Twins platform. The platform introduces a JSON-like open modeling language called Digital Twins Definition Language (DTDL) for defining digital entities representing real assets, including their state properties, telemetry events, commands, components, and semantic relationships. The data models produced by DTDL can be utilized by other Azure IoT services such as IoT Plug and Play and Time Series Insights. The Azure Digital Twins explorer facilitates visualization of the live graph representing the environment, constructed based on the models defined by DTDL. This live execution is synchronized with IoT devices via the IoT Hub or custom REST APIs.

Another platform aiming to deliver Smart City digital twin solutions is the HxDR platform by Hexagon. HxDR, a subscription-based Software as a Service (SaaS) platform, primarily focuses on providing the essential tools and data for creating 3D replicas of urban environments. The platform offers a library of real-world cities that users can manipulate and extend easily. It seamlessly

integrates heterogeneous input data from various sources, such as laser scanners, aerial photography, mobile mapping data, and indoor and outdoor terrestrial scan data. While the HxDR platform excels in the design and development of 3D models, it appears to prioritize this aspect over IoT sensor data integration.

SmartWorldPro is a digital twin tool designed to consolidate Building Information Modeling (BIM), Computer-Aided Design (CAD), Geographic Information Systems (GIS), documents, and IoT sensors into a unified 3D platform built on the Unity game engine. This platform allows users to access all relevant data, including design, legal, financial, parcel, energy, maintenance, and security information, through a single dashboard. Users can seamlessly scale their applications from single buildings to thousands of buildings. SmartWorldPro offers two basic offerings: a standalone version and a cloud-based Software as a Service (SaaS) version. Additionally, CityZenith provides services such as 3D/4D baseline asset modeling, API integration, and custom user interface development to support end-to-end solution implementation.

51WORLD presents another innovative approach with its DT city operating system, 51City OS-POS. This system leverages the 51WORLD digital twin all-element scenario platform to integrate and control the virtual world. It incorporates information flows in various formats, including surveillance streams, building information, relational databases, and IoT sensors. Moreover, it offers a visualization front-end capable of real-time data visualization and comparative analysis. 51EngineTools, a 3D modeling tool, facilitates model transformation and error checking. Additionally, 51WORLD provides tailored solutions such as traffic management, personnel and asset management, energy efficiency monitoring, and surveillance.

Twin Builder, developed by ANSYS, enables the creation of 1D models of physical systems using wiring block diagrams. These models range from simple numerical equations to complex simulations in the form of Reduced Order Models (ROMs). While primarily supporting the design, development, and execution of simulation scenarios, Twin Builder can integrate with live IoT platforms to receive real IoT sensor data. It offers a variety of simulation models for mechanical, electrical, electromechanical, electric, and embedded systems.

Bentley Systems, a key player in DT technologies, offers the iTwin Platform as its main asset. This open, scalable cloud platform provides APIs and services for building DT applications, consuming engineering data from various modeling tools and creating synchronized DTs. The platform also facilitates visualization in web browsers using Bentley cloud services and integrates with NVIDIA Omniverse for AI-enabled real-time visualization. Additionally, Bentley Systems offers OpenCities Planner, a city-scale DT planning and visualization application.

Deloitte's Optimal Reality is a DT capability based on simulation techniques initially used in Formula One racing. This platform ingests real-time data to produce a dynamic model accessible through a single web portal, focusing on delivering insights into air traffic, road networks, and incident scenarios.

ESRI's ArcGIS framework integrates GIS, Reality Capture, and BIM data with real-time IoT feeds and AI algorithms. This Platform as a Service (PaaS) offers data hosting, content management, and a range of tools and applications for creating custom mapping and spatial applications. ESRI provides ready-to-use location services via REST API.

IES company introduces the Intelligent Communities Lifecycle (ICL) Digital Twin, a single platform integrating 3D models with a physics-based simulation engine, real-time data, and AI algorithms.

This platform scales from single buildings to entire cities, offering data-driven insights on energy, operation, carbon, and capital savings.

In the manufacturing sector, General Electric (GE) and Siemens offer mature DT solutions integrated into their IoT platforms. GE provides SmartSignal and Asset Performance Management (APM) solutions for creating Asset Digital Twins, as well as technologies like ADMS, GIS, and AEMS for Network Digital Twins and Process Digital Twins. Siemens' cloud-based IoT platform, MindSphere, hosts DT applications alongside a suite of software tools for mechanical design, simulation, and factory digitization.

Descartes Labs offers a cloud-based analytics geospatial platform for creating a DT of the physical world, providing forecasting capabilities across various industries such as mining, shipping, agriculture, energy, and financial services.

### 9.8 Challenges for Digital Twins in Smart Cities

The prominent challenges facing city-scale digital twins are derived from application domains presented earlier, followed by a broader perspective on this domain.

1. **Data Availability and Sources**

Despite data-enabled cities and digital marketplaces for smart cities, there remains a significant gap in terms of accessible data for city-scale digital twins. The success of recent technological advancements like ML, Deep Learning, and big data heavily relies on the availability and quality of data. Securing appropriate datasets for real-world digital twin implementations remains a recurring challenge. Moreover, ownership of urban datasets introduces additional complexity, with data ownership in specific industrial settings being less contentious. This discrepancy may partly explain the slower adoption rate of digital twins in smart city applications compared to smart manufacturing. Urban data ownership can vary among stakeholders, including the city itself, academia, and private companies involved in city projects, and entails costs related to data quality and anonymization.

It's worth noting that data requirements for urban digital twins may differ significantly from those in industrial settings. While industrial scenarios may demand high sampling rates in the kHz range, urban measurements might operate at rates as low as several Hz. However, this slower data frequency may involve a vast number of components dispersed across a large area, susceptible to faults, or requiring extended periods of unattended operation. Consequently, issues related to data quality and maintenance become crucial in ensuring the reliability of city-scale digital twins. Mechanisms such as ML-based sensor calibration and data imputation can play vital roles in enhancing the quality of urban datasets.

2. **Data Standards and Interoperability**

A critical area unanimously acknowledged by previous surveys in the digital twin domain is the urgent need for common standards to accelerate digital twin implementation and ensure interoperability with existing systems, such as smart city platforms. Efforts to address this need are evident through initiatives like the Digital Twin Consortium (DTC) and the Industrial Digital Twin Association. International standardization bodies, such as ISO/IEC JTC 1/SC 41, are also actively engaged in this space, highlighting widespread interest in addressing this open challenge. DTC, for instance, aims to establish a library of reference implementations for digital twins, potentially expediting the resolution of interoperability issues.

Practically, standards are beginning to impact various aspects of city-scale digital twin implementations, with initiatives like the Mobility Data Specification being introduced. Public

initiatives like the Centre for Digital Built Britain (CDBB) also play significant roles in promoting digital twins at a national scale, potentially accelerating the release and adoption of related standards.

**3. Co-Creation and Stakeholder Collaboration**

City-scale digital twins necessitate involvement from various actors and stakeholders for effective operation. The diverse backgrounds, structures, and organizations of these parties often preclude a top-down approach to design and implementation. Consequently, co-creation mechanisms become essential for collaborating with communities in smart city implementations preceding city-scale digital twins. Given the evolving nature of digital twin definitions and the lack of established methodologies and tools, the co-creation of use cases, tools, and procedures is crucial. Initiatives like the LEAD project and DUET emphasize co-creation with communities in multiple use cases, utilizing methodologies like living labs to engage with stakeholders effectively.

To deepen collaboration with stakeholders like citizens, the digital twin community can explore tools and methodologies from the smart city domain, such as crowdsourcing, participatory sensing, and citizen science. These approaches can enhance data quality, expand coverage, actively engage stakeholders, and integrate them into digital twin design processes.

**4. Enhancing Data Accessibility and Comprehensibility for City Stakeholders**

Building upon the previous challenge, it is imperative to continuously engage and inform the various stakeholders involved in city-scale digital twins to garner their ongoing support. Ensuring that stakeholders are informed about the capabilities and outcomes of digital twins, and keeping them engaged with the process, is crucial. Therefore, a key challenge lies in making the data generated by city-scale digital twins more accessible and understandable to the public, enabling stakeholders to grasp its potential and assess its actual public value. Thus far, most public user interfaces (UIs) of such digital twins have relied on 3D maps delivered through specialized applications or dedicated websites. While this approach provides a basic understanding of the digital twin, there is still room for improvement in interfacing with end-users. Some prototypes, such as those in Herrenberg or Helsinki, have expanded on this concept by offering VR or AR views of the digital twin. However, the challenge of effectively interfacing with end-users remains open in many cases. In order for city digital twins to enhance governance and empower stakeholders to make well-informed decisions, there is a need to effectively communicate the benefits of the digital twin approach. This may not be adequately addressed by UIs solely based on 3D representations. Indeed, in certain scenarios, such interfaces may even have adverse effects, as the sheer scale of the digital twin alone can be intimidating. Introducing additional interactivity in digital twin user interfaces, allowing end-users to explore potential what-if scenarios in urban areas, can enhance understanding of the digital twin's potential and the value it brings to communities and local authorities.

**5. Addressing Privacy, Security, and Ethical Concerns**

Privacy, security, and ethical considerations are paramount in city-scale digital twins, mirroring the challenges faced by smart cities. Preserving privacy while ensuring data security poses significant ethical challenges. For example, in digital twins related to traffic management, there is a risk of misusing location-sensitive data from vehicles, potentially compromising individual privacy. Regulatory frameworks like the General Data Protection Regulation (GDPR) in Europe provide a foundation for addressing privacy concerns, but additional measures may be necessary. Distributed Ledger Technologies (DLT), such as Blockchain, offer potential solutions for enhancing privacy and security. Approaches like Federated Learning have also been explored to decentralize machine learning processes and bolster privacy protections. Moreover, ensuring transparency and accountability is essential for building trust in city-scale digital twins. Stakeholders must be convinced of the public value digital twins provide and their adherence to privacy and security

standards to prevent indifference or hostility. Initiatives like the Digital Twin Consortium (DTC), which is developing best practices for security, privacy, and trustworthiness, can accelerate digital twin implementation by addressing these complex privacy-related aspects.

**6. Evaluating the Cost and Benefits of Digital Twin Implementation**

An overlooked challenge is the hidden costs associated with implementing them for various application domains at scale. These costs may arise from the need to install new sensing infrastructure, insufficient documentation of existing infrastructure, or challenges in altering current systems without complete reinstallation. While city-scale digital twins offer numerous proposed use cases, translating hype into reality requires understanding how they can be practically applied across multiple domains. Guidelines and examples provided by organizations like the DTC are crucial for digital twin designers to comprehend current technological limitations and deployment requirements from financial perspectives. By disseminating peer use cases and providing access to pools of experts, initiatives like the DTC can help mitigate the risks associated with capital projects. Additionally, insights from projects such as LEAD and DUET are instrumental in establishing blueprints for city-scale digital twins.

**7. Magnitude and Complexity**

City-scale DTs present unique challenges due to their potential size and complexity, which exacerbates the difficulties outlined earlier. Even when focused on specific application subsets or areas within an urban environment, such as the Rotterdam port DT, the inherent complexity of these systems is heightened. This complexity stems from the diverse array of technologies comprising the underlying IoT/sensor infrastructure, tailored to meet various area-specific requirements or due to staggered deployments over time. Cities, as dynamic ecosystems, may undergo rapid evolution, with city-scale DTs sometimes being developed before the city itself materializes, as seen in certain projects in India. While existing research on smart cities addresses many of these issues, the impact of such challenges on the actual value generated by DTs, as well as how DT application requirements affect the scale and complexity of infrastructure, remains to be fully understood.

**8. Distributed Intelligence and Edge Computing**

Another crucial aspect of utilizing DTs at an urban scale is optimizing computing and storage resources to minimize reliance on communication infrastructure. Placing these resources closer to information sources, such as sensing infrastructure, reduces the burden on communication networks, accelerates the convergence of DT models with real-world behavior, and conserves resources. While this approach may introduce challenges, such as additional data exchange across nodes for training purposes, DTs can facilitate strategic allocation of intelligence across edge and core components based on urban service dynamics. While most current DT deployments focus on cloud-based processing or centralized islands, advancements in edge computing, driven by ML hardware acceleration, are poised to make edge-centric DT architectures more prevalent. This trend aligns with the need for heightened privacy and security in DT systems by reducing data movement across hierarchical layers.

**9. Communication Latency**

Communication latency is a critical concern in certain DT sub-domains, such as traffic management, healthcare, and disaster response, where real-time data propagation is essential. Existing smart city sensing infrastructure, often operating with sampling rates of several seconds or minutes over low-bandwidth wireless networks, may not adequately address latency requirements. Technologies like 5G hold promise in addressing this challenge, but infrastructure upgrades or complementary technologies may be necessary to achieve low-latency capabilities. Distributed intelligence and edge computing approaches can also mitigate latency by streamlining data processing overhead, enabling timely decision-making to maintain or improve smart city services.

**10. Skills Development**

Deploying DTs in cities necessitates upskilling across the entire ecosystem to maximize their potential benefits. City officials require a comprehensive understanding of DTs to prioritize interventions and ensure open, interoperable deployments. Local small and medium-sized enterprises (SMEs) must enhance their capabilities to participate in DT-driven city collaborations effectively. Additionally, the public needs digital literacy to access and utilize DT services. Academic and research institutions play a vital role in developing relevant curricula and fostering advanced digital skills tailored to different stakeholder groups within the urban ecosystem.

**11. Integration of 5G Technologies**

The rapid evolution of 5G technologies presents opportunities to address various challenges associated with DT implementation. In smart manufacturing, 5G adoption is driven by its potential to support Industry 4.0 concepts effectively. Regarding DTs, 5G can accelerate deployment and alleviate certain challenges, such as latency and complexity. DTs can facilitate the gradual deployment of 5G services by providing valuable insights into network planning and optimization. The integration of 5G within city-scale DTs holds promise for enhancing scalability, flexibility, and model fidelity, particularly in urban settings. Private 5G networks, alongside existing LPWAN solutions, offer additional benefits, enabling more granular data collection and precise modeling for accurate city-scale DTs.

## 9.9 Chapter Summary

As digital twin technology is still emerging, it is crucial to address several significant challenges to fully realize its potential. These challenges include managing information complexity, ensuring maintenance, controlling costs, addressing regulatory concerns, developing standards, and mitigating cybersecurity risks and communication issues. Evaluating digital twins across three dimensions - technological advancement, social development, and practical implementation - provides valuable insights. While the applications in this context show progress, there is a growing imperative to enhance DTs to be more sustainable, autonomous, and seamlessly integrated into real-world settings as technology continues to evolve.

The application of the DT concept is particularly within the realm of smart cities. DTs offer a host of advantages that, when combined with existing smart city data and technologies, could revolutionize urban governance, particularly in areas like urban planning, mobility, and energy management. While the adoption of DTs appears to be thriving in the realm of smart manufacturing and industrial processes, their utilization in smart cities is still in its nascent stages. Nevertheless, there are already numerous examples of city-scale DT prototypes addressing various application domains, indicating considerable potential for DT-based solutions in smart cities. It has identified several of these domains and categorized a wide range of recent approaches based on DTs, shedding light on the current trends and dynamics in this field.

There remains a degree of fluidity in the definition of DT as a general term, compounded by variations in the technologies employed and their application. This variability is further compounded by the fact that different communities utilizing DT-based approaches in the context of cities tend to define the concept based on their disciplinary backgrounds. One fundamental distinction between DTs in smart manufacturing and those in smart cities lies in scale: smart cities comprise interconnected systems, resulting in significantly greater complexity and heterogeneity compared to their industrial counterparts. This exacerbates existing challenges while introducing unique aspects that attract attention from both the research community and industry. Moreover, the involvement of diverse end-user types and entities in the design, implementation, and utilization of smart city DTs

presents additional challenges, particularly in terms of public interfaces and visualization, as these DTs must demonstrate their value to end-users throughout their lifecycle.

The inherent nature of this domain, involving collaboration among citizen communities, businesses, and multiple administrative levels, underscores the importance of leveraging established methodologies like co-creation to facilitate the successful development and deployment of DT-based solutions. Other critical challenges revolve around datasets and data sources, data standards and interoperability, as well as privacy, security, and ethical considerations. While these challenges stem from the complexity inherent in large systems of systems and the involvement of multiple stakeholders and technologies, it maintains optimism that these initial hurdles will gradually be surmounted, paving the way for DTs to become integral components of the smart city landscape.

**Problems**

1. Give the concept of the digital twin in the cyber-physical system.
2. Explain the origin of the digital twin.
3. Describe the principal components of the digital twin.
4. Specify the used terms for the digital twin.
5. Distinguish the difference between the digital model and the digital twin.
6. Describe the framework of the digital twin.
7. Explain the human digital twin.
8. Describe the digital twin for the smart city domain.
9. Give the example of the city-scale digital twin.
10. Identify the challenges for digital twins in the smart city.

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# Initial Answers to Chapter Problems

## Chapter 1

**Problem 1: Detail the characterization of cyber and physical spaces?**

**Characterization:** The structure of a Cyber-Physical System (CPS) varies depending on its type and functions. Typically, a CPS requires three main components: 1) a digital twin for real-time monitoring and analysis of the physical setup, 2) an intelligent control unit for decision-making, and 3) an algorithm execution unit for implementing decisions via feedback control. CPS architecture generally consists of five levels: smart connection, data-to-information conversion, cyber, cognition, and configuration.

**Intelligent Connectivity Level:** This level focuses on acquiring accurate data from physical components using tools like the Internet of Things (IoT) and 5G communication protocols. It ensures seamless wireless data acquisition and secure communication from IoT devices to the server. Selecting appropriate sensors for data collection is crucial.

**Data-to-Information Transformation Level:** This level transforms collected data into valuable information by analyzing correlations and patterns. Structured data use distributed database systems, unstructured data use systems like Hadoop, and semi-structured data are standardized using XML. Data mining techniques like clustering and machine learning extract meaningful insights.

**Digital Level:** This level aggregates data from all CPS components to construct a digital twin, employing simulation and machine learning for decision-making. Security measures are vital due to susceptibility to cyberattacks.

**Cognitive Level:** Facilitates informed decision-making based on a comprehensive understanding of the system and analyzed data. Utilizes computational models and algorithms to execute actions within the physical structure.

**Management Level:** Supervisory control of the CPS, implementing decisions from the cognitive level in the physical space. Monitors and analyzes changes in physical space, adapting control actions for efficiency.

**Problem 5: Describe the application type of cyber-physical systems in telemedical systems?**

**Application in Telemedical Systems:** Telemedical systems comprise hospitals with patient monitoring units, tele-consultation interfaces, and various sensors transmitting data via WLAN to a collector. This data is converted into actionable information in a cloud-based medical server, enabling remote real-time assistance from doctors. Key attributes include real-time monitoring, IoT-driven decision-making, human-machine interaction, system security, and patient privacy. Computational theory aids in diagnosis, treatment optimization, and fostering trust between doctors and patients.

**Emergency Service:** In critical medical emergencies, timely transmission of vital health data is crucial. The evolutionary model prioritizes data transfer, while low-latency transmission focuses on fog-based Internet-of-Health Things, employing a weighted majority theoretic approach for selecting fog devices.

**Diagnosis and Treatment:** Computational models optimize diagnosis and treatment, consulting on liver transplantation, ensuring privacy-aware medical imaging through encryption, and employing meta-heuristic FIR filters for medical image compression. Cooperative approaches analyze clinical decision support systems, while evolutionary models determine optimal chemotherapy dosages for cancer treatment.

**Trust Management:** Computational theory fosters trust in healthcare systems, examining continuity and trust in primary healthcare. Evolutionary models assess behavioral strategies impacting public opinion on doctor-patient relationships. Security, privacy, and low-latency interoperability are crucial in medical CPS.

**Problem 11: Diagnose the challenges of cyber-physical systems?**

**CPS Challenges:** The literature highlights how CPS attributes and applications are reshaping daily life, providing essential services and enhancing quality of life. Computational theory plays a crucial role in addressing decision-making and control challenges in CPS. Despite contributions, challenges remain in harmonizing various CPS for societal benefit.

**Collaborative Building Communities:** Green buildings can share resources with neighboring buildings, potentially aiding other CPS like grid demand flexibility. However, cooperation among buildings presents challenges. Game theory could incentivize alliances to manage energy resources collectively.

**Intelligent Transport for Medical Emergencies**: Optimizing ambulance dispatch and routes is crucial. Integrating ambulances into intelligent transportation systems could enhance efficiency. Computational techniques could model scenarios optimizing ambulance response time and travel routes.

**Interference Management in Autonomous Robotics Systems:** UAV networks face wireless interference challenges. Computational theory can analyze interactions among agents, like UAVs, capturing system dynamics without extensive information exchange.

**Reinforcement Learning for Smart Agriculture:** Reinforcement learning models can optimize agricultural practices, mitigating uncertainties like weather conditions and market volatility. Such models enhance water usage efficiency and crop yield.

**Resource Recycling in Smart Cities:** Smart cities offer opportunities for resource recycling. UAVs deployed for delivery could provide security services, reducing costs and environmental impact. Modeling resource use for diverse purposes remains a challenge.

**Knowledge-Based User Engagement for Smart Grid**: Prosumers play a significant role in smart grid energy management. Educating users about energy transitions and their impacts is crucial for effective participation. Tailored courses and training modules can enhance user engagement and adoption of new technologies.

## Chapter 2

**Problem 1: Define the CPS significance for Society 5.0?**

Society 5.0, originating from Japan's 5th Science and Technology Basic Plan, focuses on integrating individuals into cyber-physical systems (CPS) at social, cognitive, and physical levels. It aims to create equal opportunities and maximize individual potential by leveraging emerging information and communications technology (ICT) to eliminate social barriers. Society 5.0 is distinct from Industry 4.0/5.0, prioritizing harmony between humanity and nature over mass production or sustainability. It seeks to revolutionize industry, living environments, and behaviors through the integration of cyberspace and physical space, emphasizing societal impact and complexity metrics.

Society 5.0 envisions seamless integration of digital and physical realms using social robots, ambient intelligence, advanced human-computer interfaces, and extended reality, alongside CPS. It focuses on human-robot collaboration and the intelligent utilization of biological resources for industrial purposes. Additionally, Society 5.0 aims to establish a super-smart society and anticipates a shift to non-monetary economies based on tokenomics.

The initiative aligns with the human-centric approach of future 6G networks, prioritizing societal challenges and human well-being. It explores robonomics, blockchain technologies, and non-monetary tokenomics to realize Society 5.0's vision, emphasizing the role of advanced blockchain technologies in human-robot interaction and societal integration. The objective is to enhance collective intelligence within the next-generation Internet (Web3) using a CPSS-based DAO framework and token engineering, ultimately advancing Society 5.0's goals.

**Problem 4: Outline Society 5.0 from Robonomics to Tokenomics?**

This outline explores the impact of blockchain and decentralized technologies on human-robot interaction and their integration into society. Blockchain serves as a ledger for recording ownership titles and financial transactions between humans and robots, while smart contracts enable self-enforceable agreements. Cryptocurrencies enable robots to hold financial obligations and engage in value exchanges with humans. The transition to non-monetary tokenomics is discussed, highlighting tokens' role in blockchain ecosystems. Tokens, created at the application layer using Ethereum, represent digital or physical assets, access rights, and permissions. They are seen as a catalyst for Web3, the token economy, rewarding individuals' contributions with tokens and enabling new use cases and business models. Unlike coins, tokens can serve non-monetary functions, incentivizing collaboration and positive behavior. The exploration of tokens and their roles is still evolving.

**Problem 7: Describe the Implementation of Society 5.0?**

This description outlines a method for operationalizing human intelligence tasks (HITs) using the ImageNet image database. Individuals are tasked with tagging images to uncover purpose-driven tokens, with the aim of mapping hidden rewards. The process involves crowdsourcing on Amazon Mechanical Turk (MTurk) and validating responses using a blockchain oracle-based decision-making system. Collective intelligence (CI) is measured as the ratio of discovered tokens to the total number of purpose-driven tokens. The HIT platform, illustrated in Figure 2.8, utilizes

JavaScript to facilitate image tagging by humans, with data transmitted to MTurk and Amazon Web Services (AWS) via an intermediary server. Responses are evaluated by an on-chain oracle using ERC-20 tokens, with purpose-driven tokens distributed accordingly. Finally, discovered tokens are recorded on the blockchain as stigmergic traces to assist others in exploring the reward map.

## Chapter 3

**Problem 1: Explain the CPS significance for Transportation 5.0?**

Transportation 5.0, inspired by reality theory, adopts Cyber-Physical Social Systems (CPSS) architecture to integrate computational, physical, and social elements within transportation systems. This approach emphasizes the active engagement of society through Decentralized Autonomous Organization (DAO), leveraging AI, communication, and data technologies. While technological advancements are crucial, optimizing transportation systems requires considering societal perspectives to avoid inefficiencies. The current system, characterized by uncoordinated subsystems, often fails to prioritize overall system performance, leading to issues like traffic congestion. Incorporating societal perspectives early in Intelligent Transportation Systems (ITS) testing phases can enhance public acceptance and support for new technologies like autonomous vehicles. IEEE ITSC's Technical Committee on Transportation 5.0 has been instrumental in advancing research and activities in this field over the past decade.

**Problem 4: Describe Transportation 5.0 with the obstacles of new social structure.?**

The emergence of advanced technology has led to a decentralized society, challenging traditional social structures and impacting the transportation sector. In this decentralized society, information channels have diversified, presenting challenges such as data silos and lack of collaboration among systems. Overcoming these hurdles requires agreed-upon data pricing methods and new industry chains like data collaboration platforms. Diverse perceptions and reactions to phenomena hinder consensus-building mechanisms, necessitating adaptable approaches that integrate local perspectives. Conflicting interests among participants, especially at the local level, complicate decision-making in transportation. While macro-level statistics have been useful, micro-level conflicts have emerged with the advent of data collection technologies. A multidimensional control approach is needed to address intricate social conflicts and navigate dynamic game dynamics effectively.

**Problem 8: Define Transportation 5.0 with the scenarios and systems?**

Emerging transportation modes like Mobility as a Service (MaaS) and autonomous driving are shaping the future of transportation. Social-participated AI testing and scenario engineering, inspired by DAO2, aim to comprehensively test intelligent agents like autonomous vehicles in diverse contexts involving various connected vehicles and traffic participants. This approach accelerates AI development by generating valuable scenarios and avoiding repetition.

Trans-scale control and Right of Way (RoW)-based traffic systems are proposed to optimize constrained road resources. Challenges include precisely determining vehicle arrival times,

seamless integration of RoW distribution, and managing vehicle movement accurately. V2X technology offers opportunities to tackle RoW ownership issues, but unified control objectives are needed. Generalized RoW is proposed to establish a trans-scale traffic control system for multi-agent joint control and resource allocation optimization.

Mobility as a Service (MaaS) consolidates various mobility services into a seamless, unified system, shifting from vehicle ownership to shared transportation modes on a per-trip basis. Many cities worldwide have embraced MaaS, offering users streamlined services and unified payment interfaces. MaaS presents opportunities for city administrators to develop and manage comprehensive transportation systems efficiently.

## Chapter 4

**Problem 1: What is the foundation of the cyber-physical system architectures?**

Industry 4.0, originating from the German government's High-Tech Strategy 2020 Action Plan, aims to revolutionize manufacturing by integrating physical, digital, human, and biological realms. Central to Industry 4.0 is the Industrial Internet of Things (IIoT), which enables the integration of industrial devices like sensors and robots through communication technologies. IIoT facilitates horizontal and vertical integration in manufacturing, leading to benefits such as converged IT and OT, reduced operations, and transformed business models.

Cyber-Physical Systems (CPS) serve as the technological backbone of Industry 4.0, bridging virtual spaces and physical reality. CPS integrates networking, computing, and storage to create interactive industrial environments, enabling real-time monitoring and control. CPS applications span various domains including manufacturing, healthcare, renewable energy, smart buildings, transportation, agriculture, and computer networks. The 5C Architecture and other reference models provide frameworks for CPS development, ensuring stability, reliability, efficiency, and security in operations across industries.

**Problem 4: Characterize the IIRA CPS architecture model?**

The Industrial Internet Reference Architecture (IIRA), developed by the Industrial Internet Consortium (IIC), is an open architecture focused on promoting interoperability among industries within the Industrial Internet of Things (IIoT) ecosystem. It consists of four viewpoints: business, usage, implementation, and functional. 1) The business viewpoint identifies participants, their business views, values, and objectives within IIoT systems. 2) The usage viewpoint outlines expected functionalities to fulfill business objectives. 3) The implementation viewpoint identifies necessary technologies for functional components, including communication protocols and life-cycle procedures. 4) The functional viewpoint zooms in on functional components and their interactions across five domains: control, operation, information, application, and business.

Each domain has specific functions aimed at system operations, including industrial control, asset management, data collection and analysis, application logic, and end-to-end system operation integrated with business functions. Additionally, crosscutting functions, such as connectivity, ensure seamless interaction among system functions.

**Problem 7: Explain the CPS architecture based on OPC UA framework?**

Innovative approaches have been developed in the field of Cyber-Physical Systems (CPS) and Industrial Internet of Things (IIoT) to enhance manufacturing processes:

1) CPS Architecture with 5C Reference: This architecture comprises five modules: Configuration, Intelligence, Cybernetics, Conversion, and Communication. It utilizes the OPC UA protocol for system information management and testing in a Smart PD3 industrial teaching plant, demonstrating accurate data transmission.
2) Cyber-Physical Machine Tools (CPMT) Platform: Leveraging OPC UA and MTConnect, this platform enables efficient data communication among machine tools and software applications. It employs a generic OPC UA information model and interoperability between OPC UA and MTConnect. Applications developed demonstrate improved production efficiency and effectiveness in manufacturing.

## Chapter 5

**Problem 1: Detail the importance of the cyber-physical system for Industry 4.0?**

The fourth industrial revolution, marked by the integration of IoT, IoS, and CPS, has led to the emergence of smart factories, reshaping industries and economies globally. CPS, combining IT and manufacturing, drives Industry 4.0, enhancing adaptability, efficiency, and intelligence. However, challenges like wireless networking and security must be addressed. CPS adoption in manufacturing, as seen in cyber-physical production systems (CPPS), improves processes and decision-making but requires cross-domain modeling. Management with CPS knowledge is essential for flexibility and competitiveness. Comprehensive training is needed to bridge the gap between existing technologies and Industry 4.0 vision. The ISA-95 architecture categorizes CPS tasks in smart factories, enabling seamless integration of production processes and activities.

**Problem 5: Describe the challenges of the smart factory?**

Implementing time-critical and safety-critical Cyber-Physical Systems (CPSs) in smart factories presents technical and managerial challenges:

Technical Challenges: Intelligent Decision Making: AI techniques like ontology and the contract net protocol enable collaborative problem-solving and autonomous decision-making. High-Speed IWN Protocol: Utilizing technologies such as 5G, mm waveform, WiFi, and optical communication ensures reliable and high-speed connectivity. Industrial Big Data Handling: Proactive data collection and efficient utilization streamline operations. Malfunction Restraints: Monitoring machine states allows for anticipatory problem identification and preventive measures. Cyber-Physical Interface: Formal methods like model-checking facilitate dynamic modeling and appropriate control methods. Security: Encryption, authorization, and secure cloud storage are essential for countering potential cyber threats.

Managerial Challenges: Initial Investment: Planning and implementing new infrastructure demand significant efforts and costs, requiring enhanced collaboration and transparency.

Competitive Market Scenario: Embracing technological advancements and improving marketing strategies are essential for survival. Value Creation: Emphasizing efficient and creative value creation processes enhances competitiveness. Supply Chain Management: Demand-driven supply chain management, supported by AI and ML, ensures efficient resource usage and logistics. Unavailability of Skilled Workers: Structured training programs and strategic HRM are essential for bridging the skills gap and ensuring success in smart factories.

**Problem 10: Explain the PROSA reference architecture?**

Holonic manufacturing systems (HMSs) utilize autonomous, intelligent agents or holons for flexible and distributed manufacturing. The PROSA architecture enhances coordination and control inspired by natural systems, enabling effective execution of process plans under changing conditions. This decentralized approach empowers product instances to autonomously drive production, bridging hierarchical and heterarchical systems. In assembly systems, autonomous processes rely on agents, facilitating plug-and-produce production systems without manual configuration. Gentelligent components collect and communicate data throughout their lifecycle, storing genetic and manufacturing information. These components possess inherent sensory properties, enabling them to autonomously collect and process data, enhancing their intelligence and functionality.

## Chapter 6

**Problem 1: Explain the development of the cyber-physical-social system.?**

The development of Cyber-Physical-Social Systems (CPSS) marks a paradigm shift in integrating human dynamics into the design of CPSs, leading to smart enterprises and industries. Humans in CPSSs serve as both consumers and service providers, contributing to citizen sensing, actuation, crowdsourcing, and crowdsensing. These roles are pivotal in shaping the feedback loop within CPSSs, enhancing energy management, and enabling distributed data analytics. Understanding human behavior in CPSSs is essential for task assignment and user engagement, necessitating dynamic behavior description models. Analyzing user-related data helps classify users and incentivize positive contributions to CPSS operation and management. Ultimately, CPSSs leverage both technology and human resources to create intelligent environments, emphasizing the symbiotic relationship between "things" and humans for transformative advancements.

**Problem 5: Provide a detail of the application of CPSS in energy distribution?**

Smart grids, driven by Cyber-Physical-Social Systems (CPSS), revolutionize energy distribution by offering intelligent solutions for various settings like homes, offices, and industrial applications. One key innovation is the Consumer-Centered Energy System (CCES), which seamlessly integrates the power grid with communication technologies, computing systems, and consumer devices. CCES employs a request-and-schedule energy management protocol to optimize energy usage and coordination efficiently.

Furthermore, CPSS implementation architecture is instrumental in enhancing the sustainability of fuel distribution systems. For instance, in public gas stations, an inventory control system leveraging CPSS efficiently manages fuel supplies based on service requirements and customer satisfaction metrics. This approach ensures that fuel distribution operations are optimized for reliability, efficiency, and environmental sustainability.

**Problem 10: Define the issues and challenges in CPSS?**

The challenges faced by CPSSs span across various domains, from energy management to security and privacy. Here's a summary of the key challenges and potential solutions:

**Energy Management:** Challenge: Balancing energy consumption with other performance indicators. Potential Solutions: Designing energy-efficient protocols. Leveraging renewable energy sources. Harvesting radio energy.

**Intelligent Caching and Computing:** Challenge: Enhancing content delivery and data processing. Potential Solutions: Implementing intelligent caching with machine learning. Utilizing intelligent computing for real-time analysis. Introducing collaborative computing for big data analyses.

**Resource Coordination and Management:** Challenge: Optimizing computation complexity in multi-resource deployment. Potential Solutions: Utilizing distributed algorithms like ADMM. Implementing context-aware techniques for efficient crowdsourcing.

**Security and Privacy:** Challenge: Ensuring robust security and privacy in interconnected CPSSs. Potential Solutions: Implementing physical layer security. Adopting differential privacy models. Developing secure communication channels.

**Cross-Layer and System Design:** Challenge: Designing standardized protocols for heterogeneous CPSSs. Potential Solutions: Updating existing protocols to adapt to CPSS architecture. Implementing cross-layer design strategies. Extending multi-resource deployment schemes to different layers and systems. Addressing these challenges will be crucial for the successful implementation and operation of CPSSs across various application domains.

## Chapter 7

**Problem 1: Describe the modeling of the structure of the cyber-physical system?**

The integration of Cyber-Physical Systems (CPSs) involves modeling both physical and cyber components, as well as their interfaces. Here is a breakdown of the modeling approach and components:

**Modeling Approach:** CPSs are represented as the interconnection of physical and cyber systems. Hybrid dynamical system theory is employed, using differential equations for continuous-time physical behavior and difference equations for discrete cyber behavior.

**Physical Components Modeling:** Modeled using differential equations to portray continuous-time behavior.

**Modeling of Cyber Components:** Modeled with discrete values and finite state machines (FSM) for control execution flow. Discrete-time algorithms are represented using difference equations.

**Interface System Modeling:** Interfaces connect cyber and physical systems, involving components like Analog-to-Digital Converters (ADC), Digital-to-Analog Converters (DAC), and Digital Networks. ADC samples physical system outputs, DAC converts digital to analog signals, and digital networks facilitate information transfer.

**Combining Models:** Individual models of cyber and physical components are interconnected to derive a comprehensive mathematical model of CPS. Combines continuous and discrete dynamics through differential and difference equations.

Additionally, advancements in CPS computational techniques aim to utilize raw data acquired by sensors for generating actionable insights. Applications in design, control, diagnosis, and prognostics rely on precise models, which can be approached through physics-based modeling or machine learning. Challenges arise due to inaccessible system parameters and incomplete specifications, leading to the development of hybrid methods integrating physics-based models with data-driven machine learning techniques like Deep Neural Networks (DNNs) to enable predictive modeling of CPSs in real-world scenarios.

**Problem 4: Analyze the collaboration between machine learning and the physical-based model?**

The collaboration between machine learning (ML) and physics-based models presents a powerful approach to system modeling. ML models rely on data to adapt to various system types, but may lack extrapolatability and interpretability. Physics-based models aim for completeness by considering all system dynamics but can be challenging to capture accurately and may simplify complex phenomena.

ML models can fit sparse data effectively, while physics-based models extrapolate system behavior but may struggle with anomalies. However, physics-based models can capture nuanced behaviors like Zeno behavior in a bouncing ball, which ML models may struggle to model effectively.

Hybrid models that integrate ML and physics-based approaches offer a comprehensive solution, leveraging the strengths of both methods. They can provide more accurate predictions and offer convenient recalibration compared to pure ML or physics-based models. Overall, hybrid models represent a promising approach for modeling complex systems like CPSs, offering a balance between data-driven and physics-driven insights.

**Problem 8: Detail the hybrid modeling directions of the cyber-physical system?**

Hybrid modeling combines physics-based (MB) and data-driven (ML) approaches to improve predictive accuracy in CPS contexts. While MB models may oversimplify complex systems, ML models struggle to capture system dynamics accurately. In a hybrid approach, ML models complement MB models by capturing residual complexity, improving predictions while respecting system physics.

One strategy integrates MB model outputs as inputs to ML models, ensuring consistent predictions with underlying physics. Synthetic data generated from MB models can supplement experimental data for ML model training, mitigating data sparsity issues. Tuned hybrid models can generate supplementary data for fine-tuning MB model parameters, enhancing overall predictive accuracy.

Hybrid modeling innovations enhance predictive accuracy while leveraging both physics-based models and sensor-acquired data. Existing works categorize hybrid modeling approaches based on interactions between MB and ML parameters, with applications spanning diverse domains. While deep learning is commonly used in hybrid modeling, similar concepts apply to other ML approaches like SVM and RF, ensuring broad applicability across CPS contexts.

## Chapter 8

**Problem 1: Specify the significance of the codesign methodology in the cyber-physical system?**

In the complex field of cyber-physical system (CPS) design, challenges arise due to the integration of computation and physical processes. Unlike general-purpose computing, CPS tasks require precise timing for correct system functioning. Concurrency, inherent in CPS, poses technical challenges in bridging sequential software semantics with concurrent physical processes. Advancements in CPS design focus on dynamic models depicting system evolution over time and structural models representing system construction.

Models offer formal properties and enable definitive statements, ensuring confidence in system abstractions. CPS applications span autonomous vehicles, industrial robots, medical devices, and smart infrastructure, posing challenges in scalability, complexity, and stringent design metrics. Co-designing cyber and physical components is crucial, yet current practices often involve isolated stages, hindering optimal system design. Novel methodologies and tools are needed to facilitate CPS co-design, capturing interactions among diverse components and exploring the design space holistically, quantitatively, and automatedly. A vehicle management system (VMS) illustration highlights modeling challenges stemming from CPS heterogeneity, concurrency, and timing sensitivity.

The challenges in cyber-physical system (CPS) design, emphasizing the need for a unified approach to co-design cyber and physical components. CPSs integrate computation and physical processes, posing unique challenges such as concurrency and timing sensitivity. Current design practices often involve isolated stages, hindering optimal system performance. This advocates for automated co-design tools to capture interactions among diverse components and explore the entire design space holistically. It highlights the importance of modeling, simulation, synthesis, validation, and verification tools for CPS co-design and presents promising approaches while identifying areas.

**Problem 4: Explain the modeling cases of the vehicle management system (VMS)?**

The complexities of modeling cyber-physical systems (CPS), focusing on the fuel management subsystem of an aircraft Vehicle Management System (VMS) as a case study. It discusses various technologies that offer partial solutions to modeling challenges in CPS, including hybrid system

modeling, models of computation catering to concurrency and heterogeneity, and the application of domain-specific ontologies. The significance of the fuel management system is illustrated through the Air Transat Flight 236 incident, emphasizing the importance of integrating models for early issue detection. It provides illustrative models created in Ptolemy II, a modeling and simulation environment for heterogeneous systems, to highlight modeling challenges and solutions in CPS. It employs an actor-oriented design approach, where components communicate via ports, and the rules of interaction are defined by the Model of Computation (MoC). This exploration provides specific modeling issues in the context of the fuel system, emphasizing the complexity and interconnectedness of physical processes involved.

**Problem 7: Give the state of the art of the codesign methodology?**

The state of code generation from models in cyber-physical systems (CPS) is still in its early stages, lagging behind compiler technology advancements. Challenges like modular code generation and model transformation remain partially resolved. Despite progress in languages and tools, issues such as system integration and interoperability of heterogeneous subsystems persist, leading to project failures. While modeling tools like UML 2 and its derivative SysML offer promising features for CPS, they suffer from shortcomings in defining semantics, relying on tool implementers for interpretation. The lack of defined semantics in frameworks like MARTE systems effective design practices. Furthermore, UML notations' flexibility allows for diverse interpretations, diminishing their value as communication tools. Challenges also arise in standardizing Statecharts, with discrepancies in semantics across implementations. Overall, addressing these challenges is crucial for advancing model-based design in CPS effectively.

## Chapter 9

**Problem 1: Give the concept of the digital twin in the cyber-physical system?**

The emergence of cyber-physical systems (CPS) and the Internet of Things (IoT) has led to the development of Digital Twins (DT), virtual representations of physical entities connected in real-time. DTs simulate complex systems across their lifecycle, bridging the gap between the physical and digital worlds. Enabled by advancements in Machine Learning, Big Data, and IoT, DTs offer continuous monitoring and control, revolutionizing industries like smart manufacturing. Their adoption is projected to grow substantially, with significant cost-saving potential. DTs facilitate real-time data acquisition and analysis, offering insights into system operation and enabling lifecycle management. Originating from NASA, DTs have evolved from simulating space systems to encompassing various domains like smart cities. However, defining DTs remains complex due to diverse community perspectives and application domains, posing challenges in standardization and stakeholder engagement.

**Problem 4: Specify the used terms for the digital twin?**

The terminology used in Digital Twins (DTs) introduces three key concepts:

**Digital Twin Prototype (DTP):** This term relates to the tasks needed to create a specific object or entity, outlining essential steps for its production.

**Digital Twin Instance (DTI):** It represents the components of a particular instance of an entity, including specifications, component names, and real-time sensor data associated with that instance. Each entity instance has its own DTI, generated using the Digital Twin Prototype.

**Digital Twin Aggregate (DTA):** This concept refers to the collection of multiple Digital Twin Instances (DTIs), collectively gathering data from various objects or entities.

**Problem 8: Describe the digital twin for the smart city domain?**

Digital Twins (DTs) in the smart city domain are driving innovation across various sub-domains, showcasing exemplary endeavors:

Energy, Comfort, and Structural Health in Buildings: Utilization of DTs for energy efficiency in buildings, leveraging AI and ML. Urban-scale energy models to evaluate energy performance and inform sustainable solutions. Open-source optimization frameworks for multi-vector smart energy systems. DT-based intelligent recommendation systems for energy services and demand-side management. DT applications for monitoring building structural health in real-time.

**Urban Planning:** Creation of spatial 3D models for urban planning using technologies like LiDAR.

Integration of cyberGIS, BIM, AI, ML, and IoT for unified data management in city-scale DTs. DT models facilitating citizen participation in city planning and scenario simulation.

**Circular Economy and Sustainability:** Integration of DTs with circular economy concepts, emphasizing sustainability in urban planning. DT applications in waste management, sustainable production, and building sustainability assessment.

**Traffic, Mobility, and Fleet Management:** Private and public sector initiatives employing DTs for autonomous driving, traffic management, and EV fleet monitoring. Standardization efforts like the Open Mobility Foundation's mobility data specification (MDS) for data interoperability. Applications of DTs in maritime traffic, last-mile logistics, and smart container tracking.

**Risk Mitigation and Water Management:** Development of DT-based disaster management systems using multi-sensory data streams and AI. Utilization of DTs for water-related event prediction and management, including floods and water network monitoring.

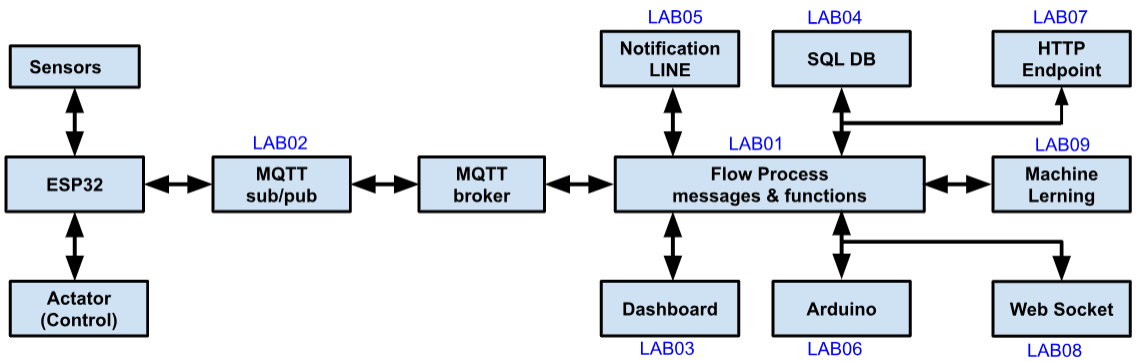
**Pollution Monitoring:** Prototypes of city-scale DTs for air and noise pollution monitoring, integrating GIS, BIM, and IoT technologies. Simulation of pollution levels and propagation using computational models and real-time sensor data.

**Healthcare in Smart Cities Using DTs:** Integration of health-related sensors and services into DTs for individual and community-level healthcare applications. Utilization of DTs in various healthcare sectors, including human digital twins and disease-specific DTs. Architecture frameworks and cloud-based systems for DT-enabled healthcare services provision.

Challenges across these domains include privacy concerns, standardization, scalability, and security. Despite challenges, DTs offer immense potential to address complex urban challenges and enhance quality of life in smart cities.

# Laboratory: Node-RED Based CPS Implementation

This section aims to transition the CPS concept from being a learner to becoming a proficient Node-RED user. Initially, learners will delve into the background of Flow-based programming (FBP) tools. Among the FBP tools discussed, Node-RED stands out. Initially created by IBM's Emerging Technology Services team, it is currently overseen by the OpenJS Foundation. Subsequently, learners will grasp a comprehensive overview of Node-RED's utility in constructing basic projects for the CPS model architecture. Learners will familiarize themselves with microcontrollers, IoT, and machine learning within the context of the digital engineering program. While the technical insights provided here will expedite their software application development, understanding the CPS concept behind the Node-RED tool will elucidate the necessity of employing an FBP tool like Node-RED. The CPS LAB organization is listed and the integration of all is illustrated in Figure below.




- LAB01: Node-RED with Message & Function
- LAB02: Node-RED with MQTT & ESP32 IoT
- LAB03: Node-RED with Dashboard Visualization
- LAB04: Node-RED with SQL/SQLite Database
- LAB05: Node-RED with Line API Node
- LAB06: Node-RED with Arduino
- LAB07: Node-RED with HTTP
- LAB08: Node-RED with WebSocket
- LAB09: Node-RED with Machine Learning
- LAB10: Node-RED with Digital Twin

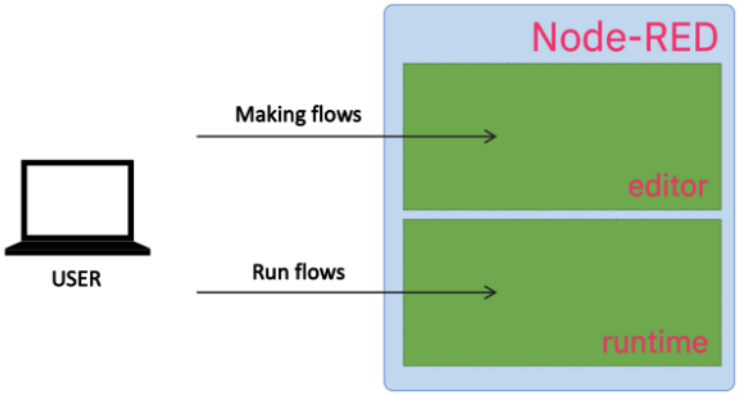
**Node-RED Flow Editor Mechanisms**

Node-RED comprises two essential components: the Flow Editor, which serves as the development environment, and the runtime environment, where the applications created in the Flow Editor are executed. It delves deeper into these components:

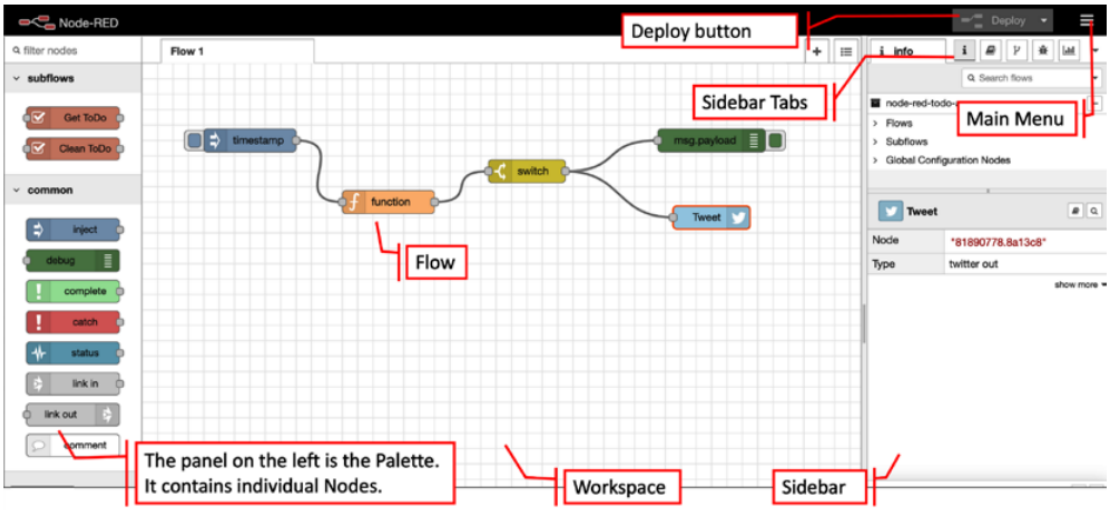
- **Runtime:** This component encompasses a Node.js application runtime responsible for executing the deployed flows.
- **Editor:** The Editor is a web application where users can edit their flows.

The primary installable package includes both these components, featuring a web server to facilitate the Flow Editor and a REST Admin API for managing the runtime. While these components are

typically installed together, they can also be installed separately and integrated into existing Node.js applications, as illustrated in the following diagram:




These functions are displayed on the Flow Editor screen in the following manner.




Before beginning to use Node-RED, it is essential to familiarize yourself with the contents of the Flow menu. While its specific items may vary based on the version of Node-RED, it typically includes universal settings such as Project management, Arrange view, Import/Export of flow, Installation of nodes from the library, and more. For comprehensive guidance on utilizing Node-RED, it is recommended to consult the official documentation as required.

# LAB01: Node-RED with Message & Function

**Objectives:** In this lab, you will learn

- The interaction with message objects by using the input with a simple payload.
- The use of functions for a general decision-making process.

**Message Objects**

A property's value can be any legitimate JavaScript data type, including:

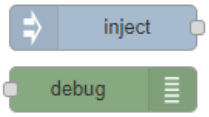
- Boolean - true, false
- Number - for instance, 0, 123.4
- String - such as “hello”
- Array - like [1,2,3,4]
- Object - represented as { “a”: 1, “b”: 2}
- Null

**Function Objects**

The Node-RED function offers versatility, serving a broad spectrum of tasks within flow-based automation and integration projects. Some typical applications of Node-RED functions include data transformation, data filtering and validation, conditional logic, mathematical and statistical operations, text processing, date and time manipulation, error handling, dynamic content generation, custom logic Implementation, and multi-step processing.

This LAB introduces the Node-RED editor and creates a flow that demonstrates the Inject, Debug, and Function nodes.

- Access the editor
- With Node-RED running, open the editor in a web browser.
- If using a browser on the same computer that is running Node-RED, you can access it with the url: http://localhost:1880.
- If using a browser on another computer, you will need to use the IP address of the computer running Node-RED: http://<ip-address>:1880.

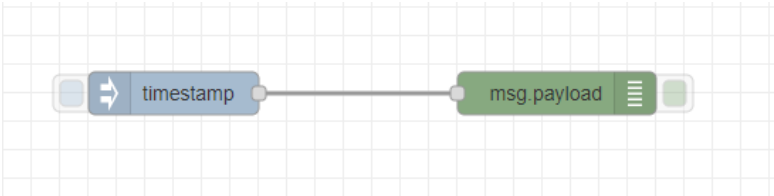



**Add an Inject Node**

- The Inject node allows you to inject messages into a flow, either by clicking the button on the node, or setting a time interval between injects.
- Drag one onto the workspace from the palette.
- Select the newly added Inject node to see information about its properties and a description of what it does in the Information sidebar pane.

**Add a Debug Node**

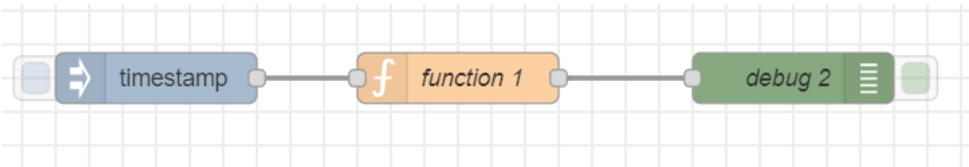
- The Debug node causes any message to be displayed in the Debug sidebar. By default, it just displays the payload of the message, but it is possible to display the entire message object.
- Wire the two together




- Connect the Inject and Debug nodes by dragging between the output port of one to the input port of the other.
- Deploy
- At this point, the nodes only exist in the editor and must be deployed to the server.
- Click the Deploy button.
- Inject
- With the Debug sidebar tab selected, click the Inject button (the small square button next to your inject node). You should see numbers appear in the sidebar. By default, the Inject node uses the number of milliseconds since January 1st, 1970 as its payload.

**Add a Function Node**

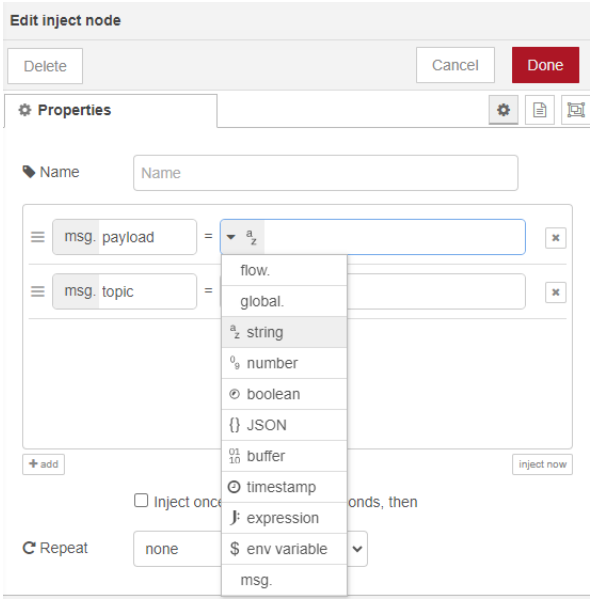
- The Function node allows you to pass each message though a JavaScript function.
- Wire a Function node in between the Inject and Debug nodes.




- Double-click on the **Function node** to bring up the edit dialog. Copy the following code into the function field:

```
// Create a Date object from the payload

var date = new Date(msg.payload);

// Change the payload to be a formatted Date string

msg.payload = date.toString();

// Return the message so it can be sent on

return msg;
```

- Click Done to close the edit dialog and then click the deploy button.
- Now when you click the Inject button, the messages in the sidebar will now be formatted is readable timestamps.
- Study the types of a payload to display a targeted response.




**Checkpoint**

- Discuss the message node objects.
- Discuss the function node objects.
- Implement the if-else statement for a decision-making process.

**References**


- https://nodered.org/docs/tutorials/first-flow
- https://nodered.org/docs/developing-flows/message-design
- https://nodered.org/docs/user-guide/writing-functions

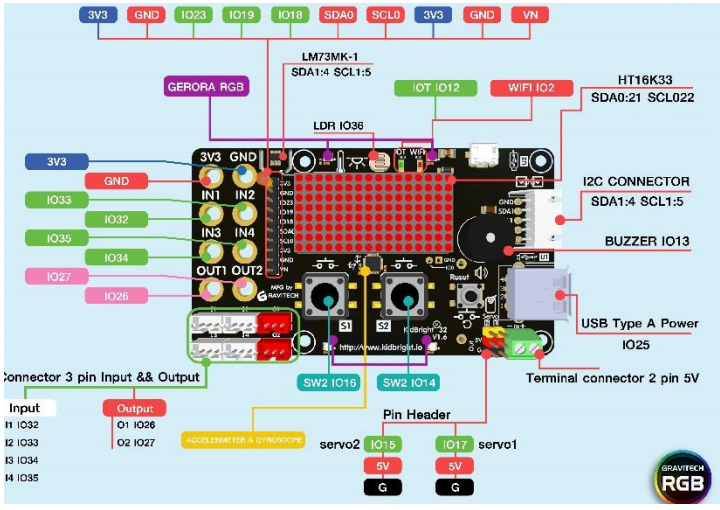
# LAB02: Node-RED with MQTT & ESP32 IoT

**Objectives:** In this lab, you will learn

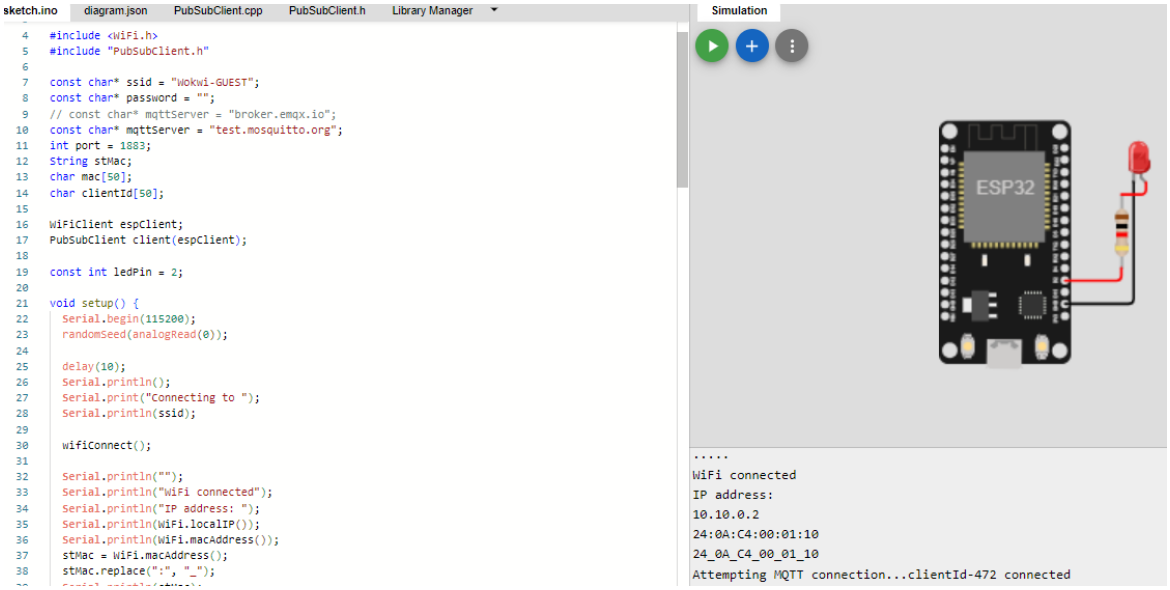
- how the IoT node works with the physical world to perceive the changes in the environmental effects.
- Implement the mockup ON/OFF machine using the ESP32 MUC to interface with electronic elements consisting of LDR and LED components working as sensors and actuators.

**Equipment:**

- ESP32 MCU board with the LDR and LED components

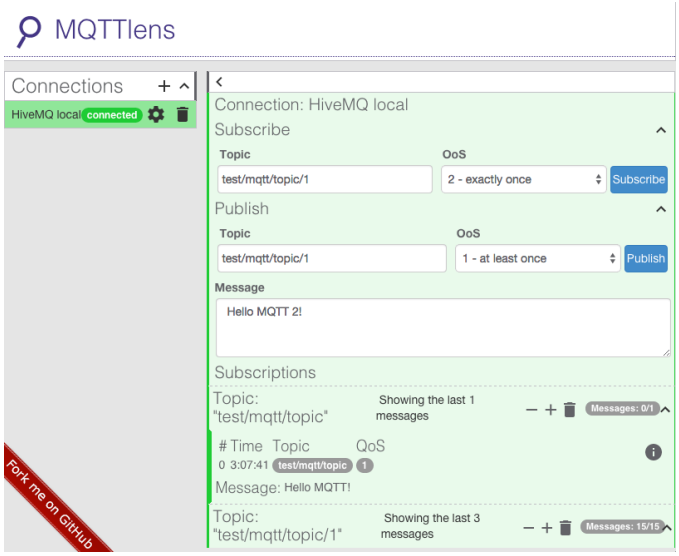



- Simulator using a ESP32 MCU and interface components like WOKWi

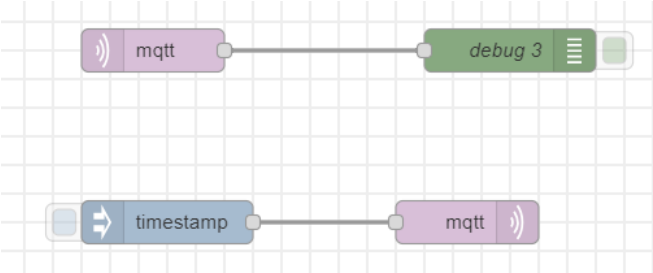



**Procedures**

- Get started to understand the Arduino IDE environment to code an ON/OFF application as a mockup machine.
- Create an ON/OFF function for two LED components using button switches with an interrupt mechanism.
- Create a sensing function for LDR components to perceive a light intensity to evaluate the ON/OFF state of the LEDs.
- Monitor all states of machine operation through Serial Terminals
- Implement internet communication using MQTT protocol and any MQTT terminals (like MQTTLens or any as you can do) to publish the state of the LEDs and an LDRs' value.



- Implement the node-RED with the MQTT protocol to subscribe to the state of the LEDs and an LDRs' value.




- Design a temperature controller for a heating effect in a mockup situation using a simulation.

**Checkpoint**

- Discuss how the ON/OFF mockup machine works via a switch controller.
- Discuss how the intensity level from the LDR perception indicates the state of the LEDs.
- Discuss how MQTT communication works with the LDR and LEDs.
- Present the design of a temperature controller and the physical environment involved.

**References**

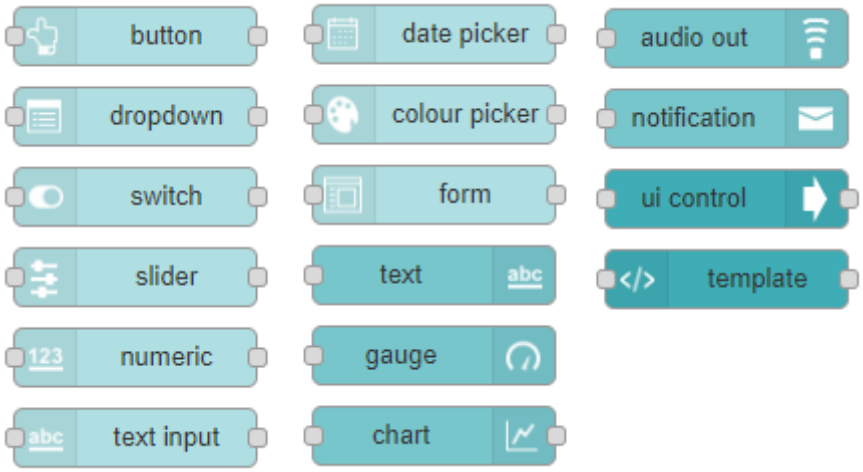

- https://wokwi.com/esp32
- https://github.com/espressif/arduino-esp32
- R. A. Light, "Mosquitto: server and client implementation of the MQTT protocol," The Journal of Open-Source Software, vol. 2, no. 13, May 2017, DOI: 10.21105/joss.00265

# LAB03: Node-RED with Dashboard Visualization

**Objectives:** In this lab, you will learn

- The interaction with visualization by basic components of events.
- The data visualization of the IoT node to perceive an environmental activity.

To install Node-RED dashboard nodes go to Menu > Manage Palette. Then, search for node-red-dashboard and install it.

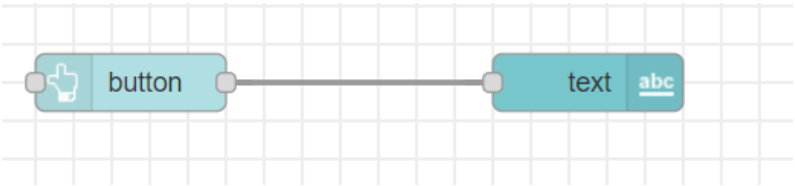



Widgets from the dashboard category present elements that are visible in the user interface (UI). The UI can be accessed using the following URL:

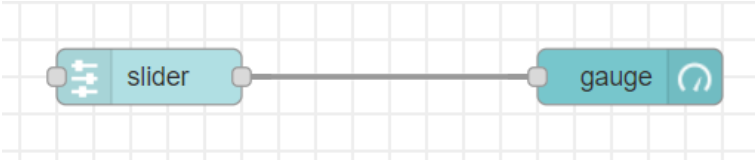
- For a local device http://127.0.0.1:1880/ui/ or http://localhost:1880/ui/
- For other devices http:// <ip-address>:1880/ui/

**Procedures:**

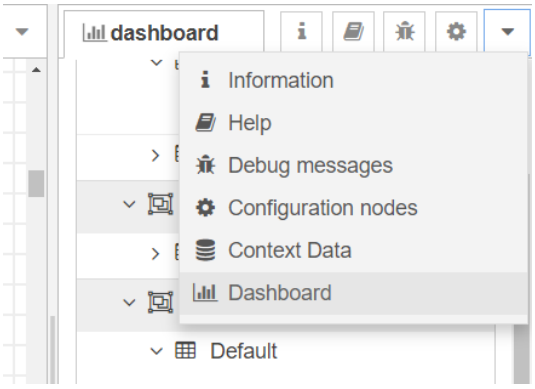
- Start with a simple Node-RED dashboard using a button and text.




- Create a Node-RED dashboard using a button and text.



- Set up a dashboard.




- Create a dashboard to monitor the state of LDR and Switch an IoT platform for an ON/OFF mockup machine.
- Verification of the dashboard in cases of an ON/OFF mockup machine with broken components (by opening a circuit).

**Checkpoint**

- Discuss the operation of a basic dashboard using a button and a text.
- Discuss the operation of a basic dashboard using a slider and gauge.
- Discuss the visualization of the states of the LDR, Switch, and LEDs on the dashboard for IoT platform monitoring.
- Present the design of the dashboard for IoT platform monitoring.

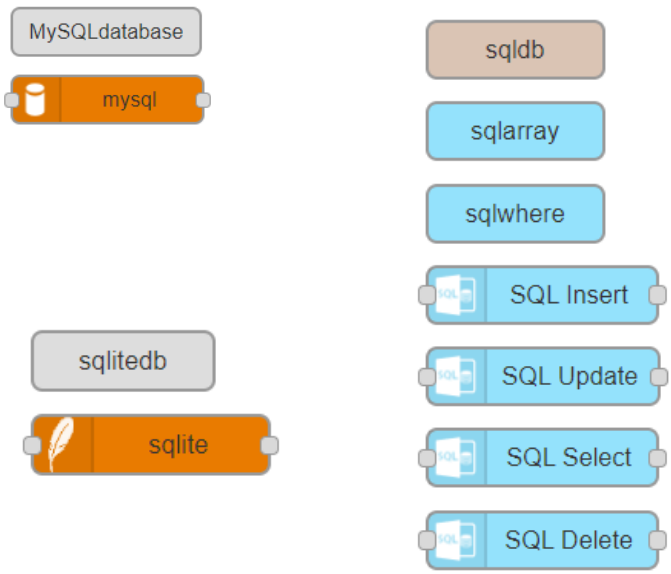
**Reference**

- https://flows.nodered.org/node/node-red-dashboard/

# LAB04: Node-RED with SQL/SQLite Database

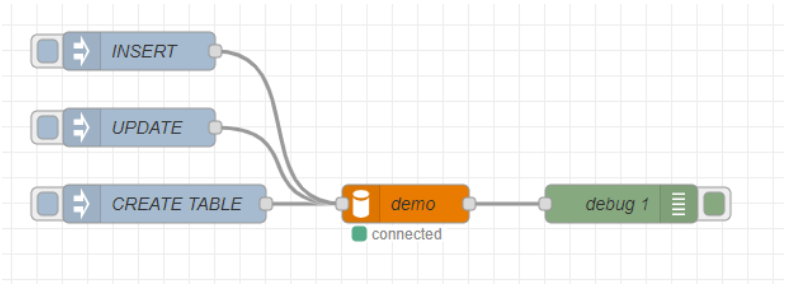
**Objectives:** In this lab, you will learn

- how the management of a database node with the data perceives the changes in the sensor responses.
- Implement the database function to interface with Data Acquisition (DAQ).




**Procedures:**

- Start with a simple database using the Inject and MySQL nodes to create, insert, and update the mockup data.




- Next, modify the database to connect to the MQTT protocol with the IoT node.
- Implement the Data Acquisition (DAQ) for LDR and Switches in the mockup ON/OFF machine.
- Implement the state of operation and verify the failure in cases of miss-operation.

- Manage the SQL database to connect two IoT nodes.

**Checkpoint**

- Discuss the operation of a database node.
- Present the design of the database for IoT platform monitoring.
- Try using the SQLite database.
- Try using the dashboard to visualize the database.

**References:**


- https://flows.nodered.org/node/node-red-node-mysql
- https://flows.nodered.org/node/node-red-contrib-sql
- https://flows.nodered.org/node/node-red-node-sqlite

# LAB05: Node-RED with Line API Node

**Objectives:** In this lab, you will learn the Line-API node with the CPS implementation.

**Procedure**

1) Start with LINE Notify API Node. NODE-RED node for publishing message notifications to LINE Notify. It can use LINE notify API through this Node, including uploading image files. Three types of messages can be sent. Text, Images, Sticker Initial usage: Create and obtain an Access Token at LINE Notify official website. Add LINE Notify Node in Node-RED workspace.

2) Try LINE Message API Push Message Node. NODE-RED node for pushing messages to LINE Messaging API channel. You can use LINE Messaging API, and push messages, through this Node.

   - Create a LINE Messaging API Channel in the LINE Developer console. Use this official document Getting Started with the Messaging API to create your LINE Messaging API.
   - Obtain a Channel Access Token and Channel Secret from your created LINE Messaging API Channel (Actually, LINE Message API Push Message Node uses only Channel Access Token, but LINE Messaging API Configuration Node requires both Channel Access Token and Channel Secret for configuration).
   - Add Messaging API Channel to LINE application.
   - Find User IDs or Group IDs for push messages. Go to How to find User ID, Group ID, or replyToken for testing Messaging API for easy finding.
   - Add LINE Message API Push Message Node in Node-RED workspace.

- Configure LINE Messaging API Channel Access Token and Channel Secret in Push Message Node. See using LINE Messaging API Configuration Node

**Checkpoint**

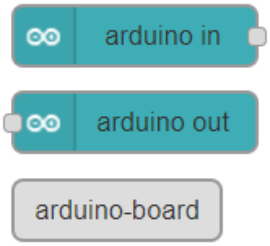
- Discuss the operation of a Line API node.
- Present the design of the messaging management for IoT platform monitoring.
- Try using the Reply Message Node.

**Reference**

- https://flows.nodered.org/node/node-red-contrib-node-line-api
- https://github.com/jatu-studiobox/node-red-contrib-node-line-api

# LAB06: Node-RED with Arduino

**Objectives:** In this lab, you will learn the Arduino node with the CPS implementation.




Input Node: Connects to local Arduino and monitors the selected pin for changes.

Select either Digital, Pullup, Analogue, or String input type. Outputs the value read as msg.payload and the PIN as msg.topic.

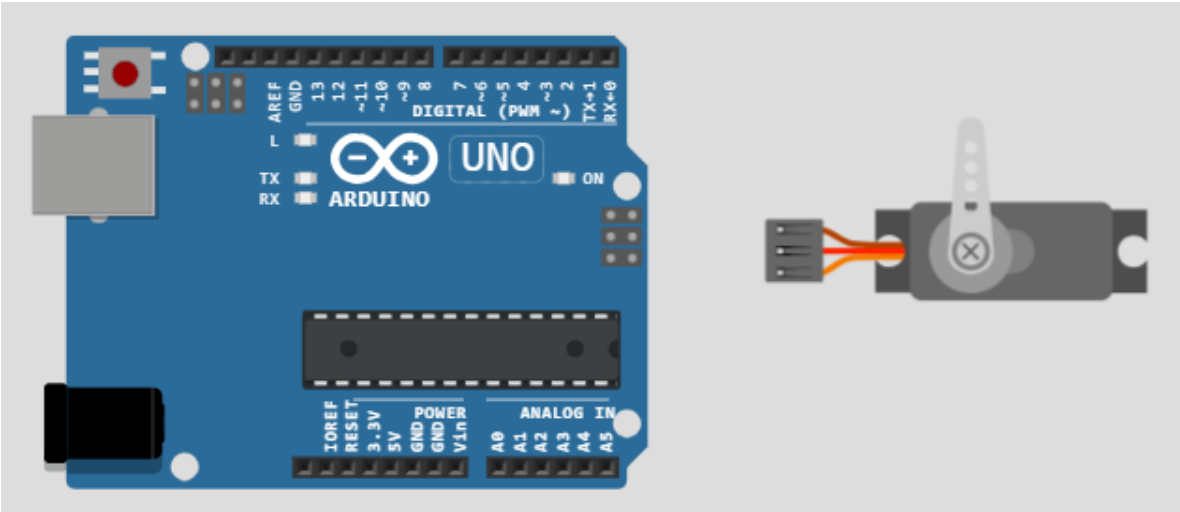
It only outputs on a change of value - fine for digital inputs, but you can get a lot of data from analog pins which you must then handle. For example, use a delay node set to rate limit and drop intermediate values, or an rbe node to only report when it changes by a certain amount.

Output Node: Connects to local Arduino and writes to the selected pin:

- Digital - accepts 0, 1, true, false, on, off.
- Analogue (PWM) - accepts Integer 0 to 255
- Servo - accepts Integer 0 - 180
- String - to send a String to the Arduino

Expect a numeric value in msg.payload. The pin number is set in the properties panel.

Note - some servos will not travel a full 180-degree range so may only accept 30 - 150 degrees for example. Please use the range node to scale the input appropriately.




**Procedure:**

- Start with a circuit with an input using sensors.
- Next, create a function to manipulate an actuator (Servo motor).

**Checkpoint**

- Discuss the use of an Arduino node.
- Implement the input function of an Arduino node.
- Implement the output function of an Arduino node.
- Present the design of the Arduino node for IoT platform monitoring.

**References**


- https://flows.nodered.org/node/node-red-node-arduino
- https://docs.arduino.cc/arduino-cloud/guides/node-red/

# LAB07: Node-RED with HTTP

**Objectives:** In this lab, you will learn how the HTTP node works with the CPS implementation.

**Procedure:**

1) Start with a basic page to create an HTTP endpoint that responds to GET requests with some static content.

```
<html>
    <head></head>
    <body>
        <h1>Hello World!</h1>
    </body>
</html>
```

2) make a simple GET request to a website and extract useful information.

3) Modify the page to respond to the ON/OFF mockup IoT machine works from the previous LAB.
4) Using a node context, a node can store data within its context object.For more information about context, read the Working with Context guide. There are three scopes of context available to a node:
   - Node - only visible to the node that set the value.
   - Flow - visible to all nodes on the same flow (or tab in the editor)
   - Global - visible to all nodes

```
// Access the node's context object
var nodeContext = this.context();

var flowContext = this.context().flow;

var globalContext = this.context().global;
```

Note: Unlike the Function node which provides predefined variables to access each of these contexts, a custom node must access these contexts for itself:

In many cases, context enables the sharing of state among multiple nodes. For instance, a sensor might consistently publish new values within one flow, while you may wish to develop a distinct

HTTP-triggered flow to retrieve the latest value. By storing the sensor reading in context, it becomes accessible for the HTTP flow to deliver.

**Checkpoint**

- Discuss the operation of HTTP nodes.
- Present the design of the page for IoT platform monitoring.

**References**


- https://cookbook.nodered.org/http/
- https://nodered.org/docs/creating-nodes/context
- https://nodered.org/docs/user-guide/context

# LAB08: Node-RED with WebSocket

**Objectives:** In this lab, you will learn how the WebSocket node works with the CPS implementation.

The Node-RED WebSocket is a communication protocol that enhances the standard TCP connection by enabling a continuous, persistent connection. This protocol facilitates bidirectional communication between server and client, enhancing server efficiency and minimizing overhead. Node-RED WebSocket offers considerable flexibility and enables data transfer between servers through a web browser.

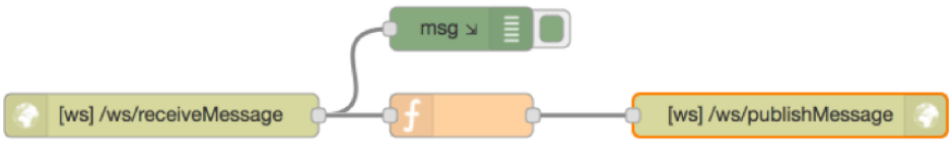
**Procedure:**

**1) Create a WebSocket Server**

Setting up a WebSocket server on Node-RED involves configuring it in server mode, where it listens for a specified URL, connects to the defined client, and establishes a connection. The steps below outline how to navigate the Node-RED WebSocket setup:

Initially to the Node-RED URL and search for the WebSocket in a filter node, as depicted below. The WebSocket node provides an endpoint for clients to connect to and transmit messages.
To create the WebSocket server, we utilize the following nodes:

- Function
- WebSocket out
- WebSocket in
- The examples provided below illustrate the flows utilized to configure the WebSocket server




The next step involves dragging the input node to the specified flow. Following that, double-click on the node to configure its settings. Then, set up the type as "listen on" in the fourth step. Define the endpoints to which the client connects to the WebSocket listener, specifying the path as /ws/receiveMessage. Select the output node of the WebSocket in this step. After selecting the output node, set the listening type accordingly. Now, add a new WebSocket listener with the path name /ws/publishMessage. Search for the function for filtering the nodes in a search bar. Use the function node to redirect the incoming message. Finally, deploy the flow by clicking on the deploy tab.

**2) Create a WebSocket Client**

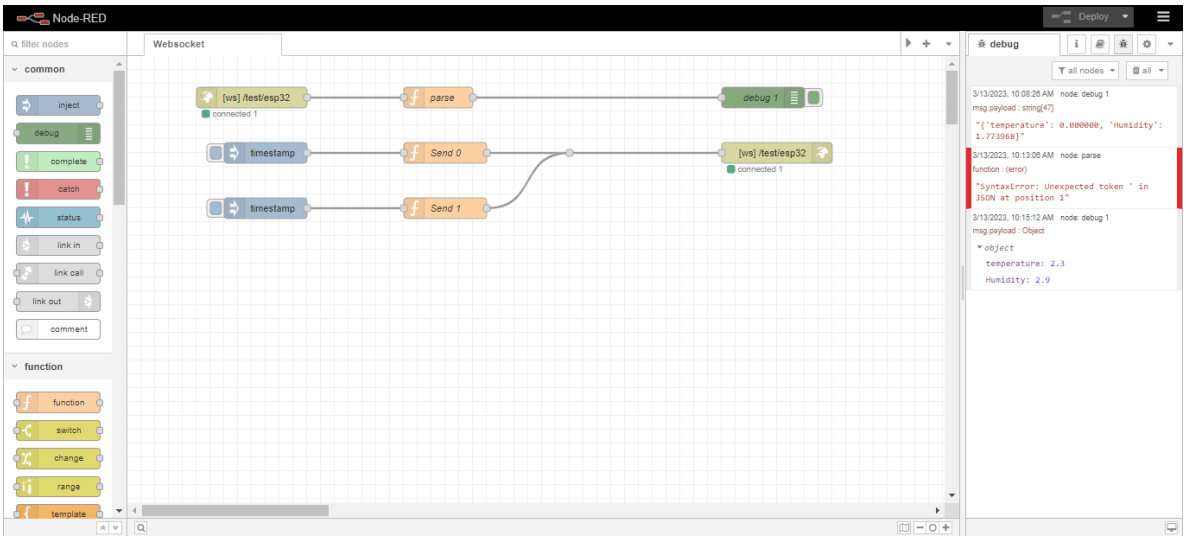
To generate a basic test web page that serves as a client for message publishing. The following steps outline the process of creating the client WebSocket:

Create a new flow for HTTP and then drag it into the HTTP node and select the HTTP node to input the access URL. Next, configure the HTML template.

Template  Syntax Highlight: HTML

```
1 <script>
2 var url = "<node-red-url>"
3 var socket1 = new  WebSocket("ws://${url}/ws/rec
4 var socket2 = new  WebSocket("ws://${url}:1880/w
5
6 socket2.onopen = function() {
7   var message = {
8     'cmd': 'Client connected'
9   };
```

Try this sample code demonstrating communication with any WebSocket server, such as Node-RED, from an Arduino device.




**Checkpoint**

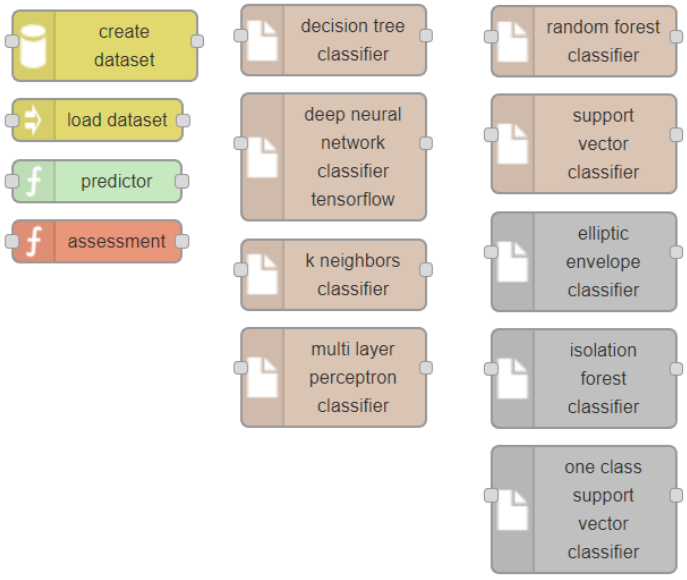
- Modify Web Socket with the ON/OFF mockup IoT machine works.
- Discuss the workflow of this implementation and the output response.
- Present the design of the physical environment involved.

**References:**


- https://flows.nodered.org/node/node-red-contrib-websocket

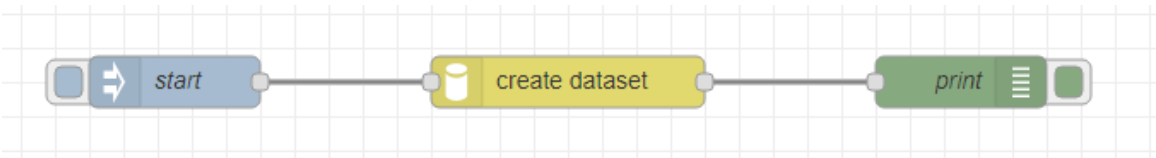
# LAB09: Node-RED with Machine Learning

**Objectives:** In this lab, you will learn how the machine learning (ML) node works with the CPS implementation.

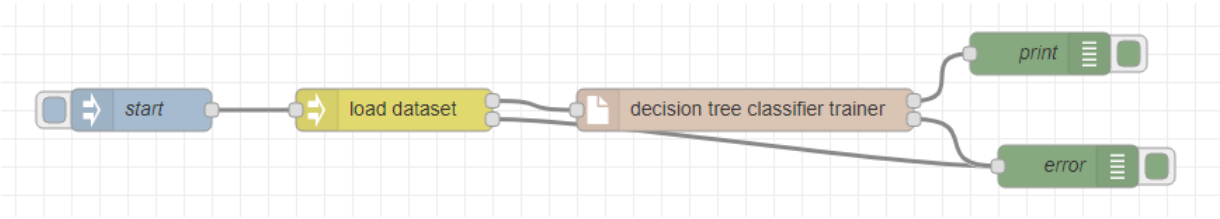



**Procedure:**

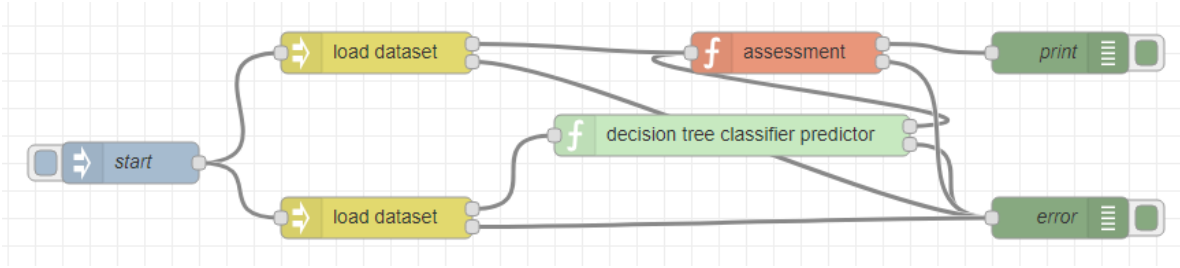
1) Start to work on this flow loads a csv file, shuffles it and creates a training and a test partition.



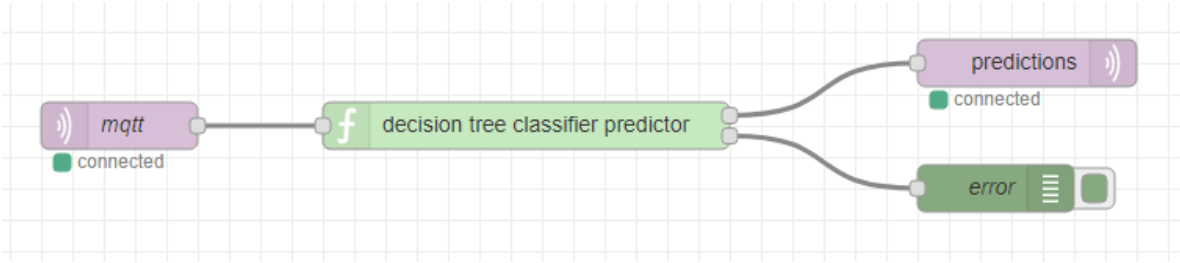

2) Modify this flow loads a training partition and trains a 'decision tree classifier', saving the model locally.




3) Modify this flow loads a test partition and evaluates a previously trained model.




4) Modify this flow shows how to use a trained model during deployment. Data is received via MQTT, predictions are made and then sent back.




Note: This Node-RED module comprises a collection of nodes providing machine learning capabilities. These nodes incorporate a Python core that utilizes popular ML libraries like SciKit-Learn and Tensorflow. With this package, tasks such as classification and outlier detection can be executed.

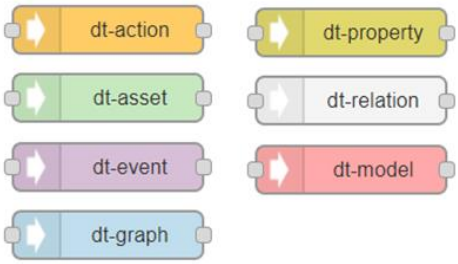
**Checkpoint:** Discuss this work to contribute to CPS implementation.

**References:**


- https://flows.nodered.org/node/node-red-contrib-machine-learning
- https://github.com/xhh232018/node-red/blob/master/node_modules/node-red-contrib-machine-learning/README.md

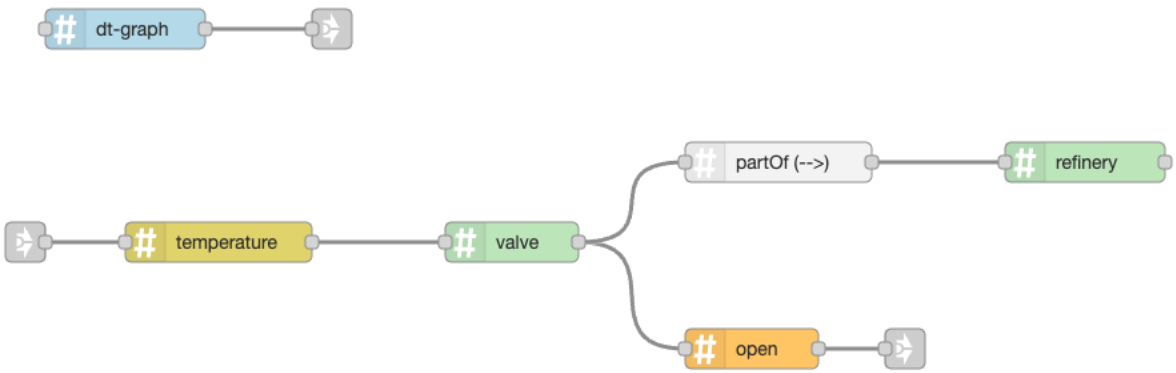
# LAB10: Node-RED with Digital Twin

**Objectives:** In this lab, you will learn how the Digital Twin node works with the CPS implementation.




**Procedure:**

1) Start with a simple flow to understand the concept.




Semantic Digital Twin Models with Node-RED

2) This gives a methodology for modeling digital twins in Node-RED. As mentioned earlier, Node-RED offers a range of nodes for modeling IoT systems, including industrial applications and home automation. Therefore, this open modeling environment serves as a foundation for this work.

**Steps for Modeling DT on Node-RED**

To establish a standardized method for modeling DTs, a series of steps has been outlined of the steps for modeling DT on Node-RED. This methodology adopts a Model-based design approach, wherein models are constructed at the outset. Each step is detailed as follows:

- Identify Observable Assets: Initially, the real-world system undergoes analysis to identify parts that can be observed individually, termed Observable assets. These assets may comprise other observable assets, and relationships between them may exist.

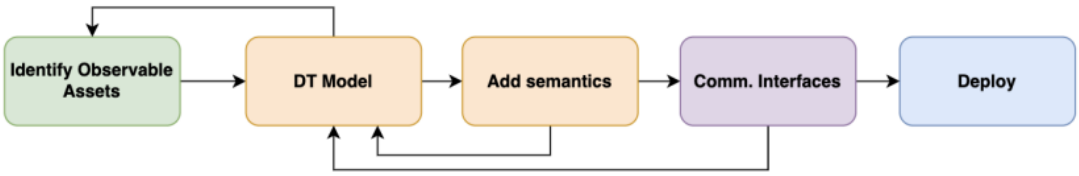
- DT Model: At this stage, each asset is modeled and linked to its properties and actions using the nodes defined in this paper (refer to Fig. 3). Relationships between assets can be defined

and semantically annotated. Refinements are possible by revisiting the organization of observable assets.

- Add Semantics: Semantic annotations are incorporated into the properties, standardizing them into a universal format. For example, if a device has a temperature attribute, semantic definitions like iot.schema.org enable configuring the semantics consistently. This step ensures all communications with the real-world are standardized with semantic definitions.

- Communication Interfaces: Once the model is established and semantics are annotated, communication interfaces are defined to enable the model to interact with the real-world application. Various components provided by Node-RED, including MQTT, REST API, sockets, and file access, facilitate this connection.

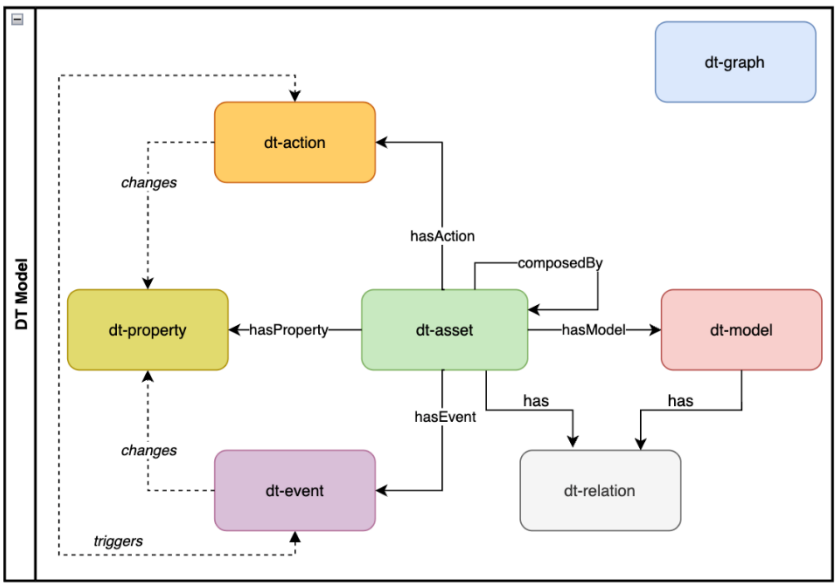
- Deploy: With everything configured, the model is deployed. Node-RED saves the model locally, and communication configurations become operational. A graph in Json-LD format containing assets, properties, actions, events, and relationships is generated. This graph can be processed and reflected in a graph database, allowing assets to be easily discovered by applications built upon the DT concept.




Applications may be developed to provide end-users with interfaces to query data, analyze it, and take actions to modify the system state.

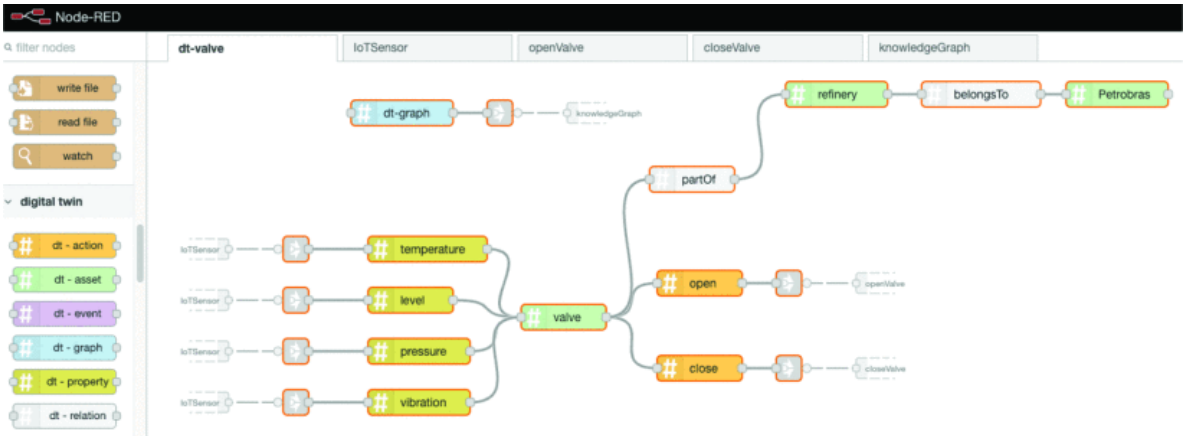
These steps, outlined in this proposal, form the foundation for modeling DT using Node-RED and semantic nodes. They are incremental, with each step building upon the previous one. However, interactive steps such as loops are also possible, enabling designers to refine or modify previous steps as needed.

3) Node-RED nodes for DT




- **dt-asset:** represents an observable asset from the real world. It can be composed of other assets.
- **dt-event:** events can happen internally or externally and can be used to trigger actions or change properties.
- **dt-action:** an asset can have actuation methods such as open(), close()...
- **dt-property:** used to define a property of an asset (temperature, humidity...)
- **dt-relation:** it can be used to (semantically) represent the relation between two nodes.
- **dt-graph:** it watches the model and creates/updates a knowledge graph every time the diagram is deployed.

4) Try a simulated industrial valve. This electric component can open and close, allowing control of how much fluid can pass through it. There are sensors on the valve that monitor variables such as temperature, vibration, battery level, torque, and so on. The figure below shows the DT-related nodes used for modeling the industrial valve.




**Checkpoint:** Discuss this feature to contribute to CPS implementation.

**References:**


- C. Steinmetz et al., "A methodology for creating semantic digital twin models supported by knowledge graphs," in 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA), Stuttgart, Germany, 2022, pp. 1-7, doi: 10.1109/ETFA52439.2022.9921499
- https://flows.nodered.org/node/@digitaltwins/node-red-contrib-digital-twin

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  Rajamangala Institute of Technology, Patumthanee, Thailand