Conceptualizing a Digital Twin Model for Natural Gas Retailing in a Geographic Area in India

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Abstract: In the fourth Industrial Revolution context, various industries are embracing advanced technologies such as artificial intelligence, machine learning, big data analytics, and the Internet of Things to facilitate Net Zero transition with digital transformation. A notable development in this field is the Digital Twin (DT), a virtual representation of the physical system. Digital transformation enhances process management, elevates business performance, and facilitates the advancement of sustainable energy transition as a viable solution for the challenges arising from climate change. India's strategic goal of achieving a gas-based economy by 2030, by providing widespread access to a local distribution network for cleaner natural gas serving 98% of the population has motivated the study of integrating advanced digital technology into gas retailing as a viable solution for decarbonized economic growth. Accordingly, this exploratory study presents a novel conceptual model of a Digital Twin for natural gas retailing. The model aims for efficient real-time management of city gas operations in India to enhance natural gas retail consumption for accelerating a gas-based economy transition. This supports India's commitment to providing affordable access to cleaner fuels under its SDG 7 framework. The research has practical implications for society to manage local climate change issues effectively.

1 INTRODUCTION

Digitalization has emerged as a prominent aspect of the Industrial Revolution (IR) that originated in the 18^{th} century. It has progressed to its present state, witnessing rapid automation of global production and supply chains having smarter networks for efficient working(Status & Trends, 2020). The contemporary period characterized by the widespread adoption of digital technologies is commonly called the "Fourth Industrial Revolution" or "Industry 4.0". The Fourth Industrial Revolution (4IR) comprises a range of state-of-the-art sophisticated technologies, including cyber-physical systems (CPS), the Internet of Things (IoT), the Industrial Internet of Things (IIoT), cloud computing, cognitive computing, artificial intelligence (AI) and machine learning (ML). CPS are intelligent systems where computer algorithms control any mechanism. The IoT constitutes a network of physical objects like sensors and devices that exchange data over the internet. The IIoT comprises interconnected instruments and sensors for industrial applications. Cloud Computing involves availing computing services over the internet. Cognitive computing is the simulation of the functioning of the human brain on a computer system. AI involves delivering human intelligence by machines. ML is an AI subdomain where the machine continuously learns from past data. Deployment of these advanced technologies significantly influences several product life cycle stages (Ali et al., 2022).

At the forefront of this 4IR technological upheaval is the concept of the Digital Twin (Aheleroff et al., 2021; Mckinsey and Company, 2023). The Digital Twin (DT) is a highly developed simulation model representing a physical product's twin. Unlike static 3D models, the DT is a dynamic, data-driven simulation model that evolves in real time based on insights from its physical counterpart (Aheleroff et al., 2021). Its core objective is to provide a comprehensive perspective of a physical entity, from design and manufacturing to operation and after-sale services (Melesse et al., 2020). Serving as a digital replica, the DT facilitates simulation,

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prediction, decision-making, optimization, and new product development. By using the DT, engineers and operators can assess the impact of design choices on product quality and functionality before committing to costly physical prototypes. A defining feature of the DT is its ability to offer a holistic view of a physical entity throughout its life cycle (Melesse et al., 2020). The DT concept finds applications in diverse fields (Jones et al., 2020), including Transportation (aircraft and automobiles), healthcare, and urban planning (smart cities) underpinning Digital Transformation.

Offlate, DT is becoming increasingly valuable as an enabler in Oil and Gas Pipeline Systems(Bo et al., 2021) for enhancing upstream production, efficiencies, and customer experience to reduce carbon footprints. The Oil and Gas Systems generate large amounts of complex data that is challenging to process and handle. These data relate to Exploration and Production(E&P), Refining, Transportation, Distribution, Pipeline Hydraulics Management, Marketing, and Sales. The data sets manifest characteristics of Big Data (volume, variety, velocity, veracity, value, and complexity), so they require powerful and innovative processing technologies for their management(Mohammadpoor & Torabi, 2020).

As the global debate on Net Zero Transition has intensified(IEA, 2021a), the application of Big Data Analytics to accelerate Energy Transition has gained momentum, with many countries aiming to achieve their decarbonization targets by 2050. In this direction, IEA argues that innovative solutions and digital transformation will be necessary to achieve this(IEA, 2021b). Further, MIT Technology Review Insights; & Shell Inc;, 2022 research finds that digital technology will be the backbone of Net Zero Transition. With mounting pressure on developing countries to combat Climate Change, the Indian Government has set ambitious targets to augment the share of clean energy in India's primary energy consumption (PEC) mix. One of the aspirations is to raise the contribution of Natural Gas (NG) in India’s PEC mix from 6% to 15% by 2030, aiming for climate management and decarbonized sustainable economic growth. NG is the cleanest fossil fuel. It burns entirely without leaving any particulate matter(EIA, 2022), hence the global choicest fuel. While NG constitutes 24.2% of the global PEC mix, it only amounts to 6.3% in India(BP, 2022). The Indian focus is shifting from conventional liquid fuels to cleaner NG, aiming to curtail GHG emissions. This transition towards a gas-based economy(GBE) necessitates substantial investments, including a $60 billion commitment to develop gas infrastructure like Liquified NG(LNG) import terminals, NG Pipeline Networks, and local distribution networks under City Gas Distribution(CGD) Projects (PTI, 2019). Such infrastructure will ensure NG door delivery and affordable access to retail customers for meeting SDG 7 targets.

Presently, 11 million households use Piped Natural Gas(PNG), while over 5700 Compressed Natural Gas(CNG) stations dispense cleaner NG fuel to the transport segment(PPAC, 2023). Under normal conditions, the CGD operators monitor the gas flow, pressure, and temperature to manage demand and supply. However, several Supply Chain Management(SCM) issues related to Marketing, Operations, Maintenance, and Safety arise while dealing with PNG household customers. These must be tactically managed in real-time to enhance customer experience and service while ensuring that the continuity of gas supply to domestic kitchens is safely maintained. Also, PNG consumption data is essential to calculate the reduction in carbon dioxide emission when NG replaces polluting fossil fuels.

The development of the CGD Network is progressing fast to attain extensive coverage of the local distribution Supply Chain (SC) network, encompassing 88% of the land area (2.89 million sq km) to achieve the stated objective of enhancing NG consumption. This network aims to provide NG access to 98% of the population (1.4 billion) residing in 295 Geographic Areas (GA's) spanning over 600 districts of the country(PNGRB, 2023). Nevertheless, managing CGD operations on a vast scale presents intricate and challenging situations. Not a single nation has hitherto undertaken such an endeavor globally. Nevertheless, AI and ML techniques involving digital technology are powerful enough to handle large volumes of real-time data comparable to those produced during CGD operations. However, DT models involving AI, ML, and big data analytics have not yet been applied for gas retailing in CGD projects. Considering these, the research question (RQ) that comes to the researcher's mind is as follows:

RQ: Can a Digital Twin Model with AI, ML, and Big Data Analytics manage the complex and intricate CGD operations to promote Net Zero Transition?

Based on the above argument, this research aims to develop a Conceptual Digital Twin Model for PNG Retailing in a GA in India. The deployment of AI and ML tools and techniques within the DT frameworks may effectively imitate the behavior of physical systems. This approach proves beneficial in monitoring and remotely controlling CGD network operations. Implementing DT solutions that effectively address real-time challenges will enhance the customer experience significantly. The rest of the article is structured as follows. Section 2 is the literature review involving (i) the supply chain for NG retailing, (ii) safety considerations during NG transportation, and (iii) DT concepts and use case applications. Section 3 presents the Conceptual DT model. The article ends with a conclusion and future research directions.

2 LITERATURE REVIEW

An integrative concept-centric review was undertaken first to present the physical elements of the CGD Network underpinning its SC and then to understand the technicalities and associated requirements for the deployment of DT for PNG retailing and CNG dispensing within a GA.

2.1 Supply Chain for NG Retailing

The retail sector comprises domestic, industrial, and commercial customers whose daily NG requirement is less than 50,000 SCMD(PNGRB, 2018) and the CNG transport segment, where vehicles use the NG as fuel. The PNGRB authorizes entities to build, own, and operate the CGD network over its lifecycle(PNGRB, 2008). The entire GA is divided into small charge areas, the potential load or demand centers for gas consumption. All the demand centers are connected with the CGD network to maintain a continuous supply of PNG and CNG. The authorized CGD entity, the SC owner, is therefore responsible for building, owning, and operating the SC network, satisfying the demand and expectations of retail customers. The physical network is designed as per PNGRB T4S regulations for CGD. The network comprises City Gate Station(CGS), an odourization unit, underground carbon steel externally coated and Polyethylene (PE) pipelines, cathodic protection (CP) systems for corrosion control, optical fiber cables to transmit data, regulator stations, gas meters, flow and pressure control valves, isolation valves, pressure, and temperature transmitters. Further, the Supervisory Control and Data Acquisition (SCADA) System is deployed to enable real-time remote data collection and control. NG characteristics, flow rates, operational pressures, and the surrounding environment are all considered during the CGD network design. According to the pressure requirement, the SC design consists of primary (medium-pressure distribution system), secondary(low-pressure distribution system), and tertiary (service pressure distribution systems) networks. The pressure regulator station is the

(i) district regulator station (DRS) at demand centers with provision to reduce pressure
(ii) individual pressure regulating station(IPRS) at customer premises
(iii) service regulator station(SRS) to maintain supply pressure.

The design ensures the supply of NG at constant volume with varying pressure and gas at constant pressure at the consumer end.

The retail SC comprises upstream gas suppliers, the CGD entity, and different segments of retail customers connected to the network. The major functions of retail SC are to:

(i) serve in market mediation to create product variety i.e. PNG (domestic, commercial, and industrial) and CNG;
(ii) safely deliver PNG continuously at contractual conditions to all segments of end consumers,
(iii) safely deliver CNG uninterruptedly at the required pressure at CNG outlets.

The typical retail SC for the CGD is in Figure 1, and the CGS is in Figure 2.

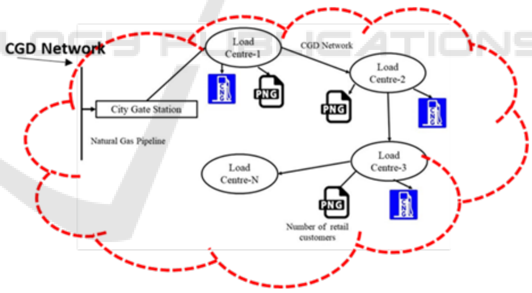


Figure 1: SC for CGD network.

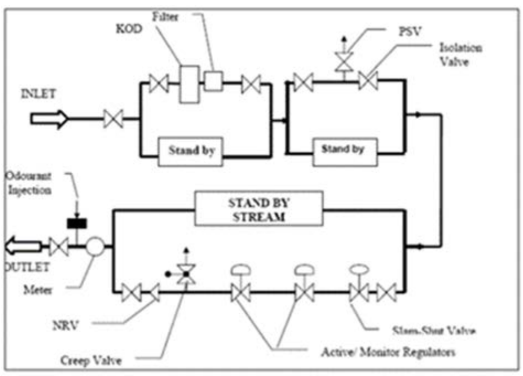


Figure 2: CGS Design (Garg, 2019).

The flowchart showing different network components and pressure ratings is in Figure 3. Each load center has CNG stations with multiple dispensers and a number of customers. Real-time data relating to total gas receipt by the CGD entity from the gas supplier at CGS(flow rate), gas consumed by each customer within the load center, gas dispensed at each CNG station, along with gas pressure, gas temperature etc., are paramount to manage demand and supply. SCADA, an industrial control system, monitors and manages field services at off-site locations. It provides access to real-time data. Different sensors like pressure and temperature transmitters are installed along the CGD network to record pressure and temperature data. The IoT devices connect and exchange these field data over the internet or other communication channels. NG metering system reconciles gas received at CGS by the CGD entity and the total gas sold. These help monitor the pipeline hydraulics, demand, supply management, gas leakage, etc. The associated parties directly connected to the CGD network in a load center and related data points of interest are in Table 1.

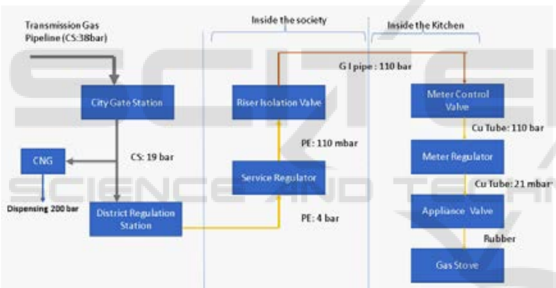


Figure 3: CGD Flowchart(Rajput et al., 2022).

Table 1: Associated Parties and Data Point.

Parties	Data Point
Gas Supplied to CGD entity at City Gate Station(CGS)	Flow rate, Pressure, Temperature, Gas Composition
PNG domestic customers	Flow rate; Gas Pressure
PNG commercial customers	
PNG industrial customer	
CNG Stations	Quantity of gas sold per dispenser

2.2 Safety in NG Transportation

NG is a hazardous, category 1, extremely flammable mixture of methane, ethane, propane, butane, and higher hydrocarbons(IGL, 2022). It is lighter than air and compressible. It is a simple asphyxiant. It ignites with static charge and sparks. It is colorless and odorless, so it is dozed with mercaptan when injected into the CGD network to provide a pungent order to detect its leak with the smell. Safety during pipeline transportation through the CGD network is paramount for ensuring safety. Different standards and guidelines published by PNGRB, OISD, and ASME are followed during the CGD network's design, operation, and maintenance, as depicted in Figure 4.

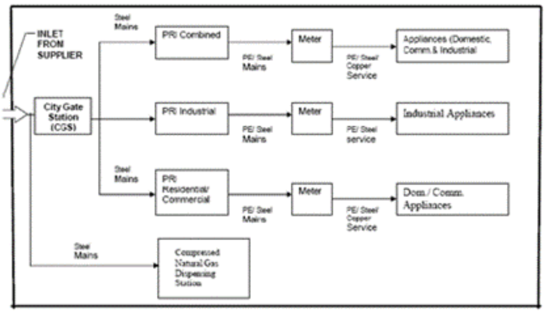


Figure 4: PNG distribution system (Garg, 2019).

2.3 Digital Twin Concepts and Use Case Application

2.3.1 What Is Digital Twin

DTs are based on the idea that there should be a one-to-one real-time correspondence between a real-world product and its digital counterpart (Bo et al., 2021). Any actions taken in the virtual world can have repercussions in the real world and vice versa. Inversely, information gathered about the physical system can be used to refine and perfect the virtual model. The effectiveness of any DT deployment depends on the degree to which the digital and physical worlds are in synchronization. DT has emerged as a critical subject within Industry 4.0. DT is "*a realistic digital representation of assets, processes, and systems that connects data between the real world and its digital representation*" (CDBB, 2020). It provides a micro and macro-level accurate virtual description of a physical system(Jones et al., 2020). DT shows how a real thing acts and keeps changing throughout its lifecycle (Opoku et al., 2021). It is a connected and synchronized digital replica of physical assets representing the elements and the dynamics of how systems and devices operate within their environment and live throughout their lifecycle. It is a synchronized, interconnected digital representation of physical assets that captures the aspects and dynamics of how systems and equipment function in their surroundings and progress through their lives(Borth et al., 2019). It is associated with 4IR

(Negri et al., 2017) as one of its enabling technologies(Melesse et al., 2020).

2.3.2 Parts of Digital Twin

DT comprises three parts, namely (i) the physical system in real-world settings, (ii) the virtual counterpart, which is the virtual entity, and (iii) the two-way link between the real and virtual entity(Pregnolato et al., 2022). Data, information, and knowledge are exchanged between the real and virtual systems that require computers, IoT, IIoT, high-speed internet, and advanced analytics (Rosen et al., 2015). High-end technologies like the AI and ML are deployed to conduct big data analytics, simulation, and forecasting.

2.3.3 DT Application

DT finds different applications, namely (i) demand-supply management, (ii) predictive maintenance and disaster preparedness, (iii) asset management (iv) simulating real situations and scenario planning in different conditions. The DT can be developed for the design, production, and service phases(Semeraro et al., 2021). It provides real-time awareness of the situation, data management, better visualization, planning, prediction, integration, and collaboration (Shahat et al., 2021). DT fosters innovation and enhances productivity, security, safety, dependability, decision-making, and adaptability(Jones et al., 2020; Negri et al., 2017). It decreases costs, risks, and design time. In machines, it enhances its visibility. It connects business processes and helps in supply chain activities, aiding financial decisions(Melesse et al., 2020). It gains importance when its design captures user-diverse experiences at the operator level. It enhances the organization's environmental sustainability, builds capabilities, and helps learn from behavior data(Mckinsey and Company, 2023). Considering these, the literature reveals that the DT model has potential use case application (Semeraro et al., 2021) for a wide variety of real-life problems of diverse nature:

(i) Aviation, Precise Medicine, Manufacturing(Barricelli et al., 2019)
(ii) Intelligent Transportation comprising operations of Electric Vehicles(Ali et al., 2022)
(iii) Smart Cities and Infrastructure(Aheleroff et al., 2021; Pregnolato et al., 2022; Shahat et al., 2021)
(iv) Industrial Operation applications like predictive maintenance, production, and after-sales(Errandonea et al., 2020; Melesse et al., 2020)
(v) Construction Industry(Opoku et al., 2021)
(vi) Smart Grid and Smart Lightning(Borth et al., 2019)
(vii) Product Design (Tao et al., 2019)
(viii) Human Health, Farming (Jones et al., 2020)
(ix) Oil and Gas Industry(Bo et al., 2021)
(x) Transportation and Storage of Hazardous Chemicals(Li et al., 2022)

2.3.4 DT Component and Architect Layers

The DT components and architect comprise three different layers, namely:

(i) Physical layer: This layer comprises sensors and devices plugged into the physical system to collect real-time data
(ii) Network Layer: To transmit the data and information from the physical system to the virtual system
(iii) Computing Layer: Consists of the virtual model to mimic or mirror the corresponding physical entity.

The critical elements in the design of a DT model are:

(i) Physical Entity/Twin(Negri et al., 2017)
(ii) Virtual Entity/Twin(Bo et al., 2021)
(iii) Data Collection and IoT(Ali et al., 2022)
(iv) Cloud Computing and Big Data(Aheleroff et al., 2021)
(v) Realization and Synchronization(Schleich et al., 2017)
(vi) Simulation and Analytics(Jones et al., 2020)

Different platforms are commercially available to implement DT, like IBM Watson, Microsoft Azure, Simens PLM etc..

2.3.5 Platforms to Implement DT and Its Dimensions

The three dimensions of the DT relate to its life cycle phases, hierarchical levels, and the intent of its implementation(everyday use). Accordingly, the DT involves different hierarchical levels like information sharing, components, products, systems, and multiple systems. Its life cycle phases are design, build, operate, maintain, optimize, and decommission. Some of its everyday use relate to digitalization, visualization, simulation, mirroring, extraction, asset interoperability, maintenance, orchestration, and prediction. A typical DT process and component are in Figure 5.

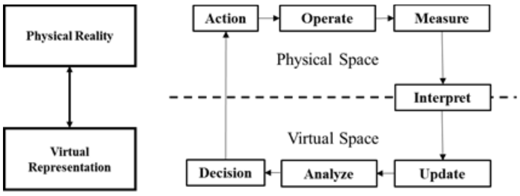


Figure 5: DT process and component (VanDerHorn & Mahadevan, 2021).

2.3.6 DT for Pipeline Service

The implementation of DT as a critical enabling technology toward achieving an intelligent pipeline system has been reported for China Russia East Line for achieving long-term goals(Bo et al., 2021). DT for a pipeline service has been defined as "a digital model constructed in virtual space, which is precisely mapped, consistent in behavior, growing together, and iteratively optimized with the actual pipe system"(Bo et al., 2021). According to this definition, the DT features are precise mapping, consistent behavior, time consistency(growing together), and iterative optimization.

The objective of DT is driven by (i) data analysis and visualization, (ii) IoT or Industrial Internet, and (iii) Simulation. However, the intelligent system requires the integration of (i) information and technology, (ii) information and automation (iii) human-computer decision-making to achieve its intended objectives. As such, the domain of DT for a pipeline system requires the integration of multiple technologies from different fields, such as IoT, data transmission, big data analytics, data visualization, simulation, prediction, knowledge networks, and other technologies. A DT design concept for Oil and Gas Pipelines proposed by Bo et al., 2021comprises entity end and application end under "two ends" with a data model and virtual model under "two core".

2.3.7 IT/OT Convergence

Deploying an industrial internet would be the key to IT and OT convergence to merge business processes, provide new insights, and implement controls into a single platform. While IT systems are used for data-based computing, OT systems manage and control physical devices. It focuses on behavior and outcomes, watching events, processes, and devices to change business and industry operations. Concurrently, the ML and AI techniques in the Oil and Gas Sector process a large amount of real-time data to improve safety, performance and ease of decision-making (Sircar et al., 2021).

In light of the above deliberations, the Conceptual Digital Twin model for managing the complex and intricate CGD operations to promote Net Zero Transition for PNG retailing within a GA is presented.

3 CONCEPTUAL DIGITAL TWIN MODEL

Digital Transformation is vital for implementing a DT facilitating 4IR principles underpinning data management of the physical system, big data analytics, AI and ML. The researcher followed the following steps to design the DT model (Tao et al., 2019):

(i) Creation of Virtual System (or product) of Physical System (or product)
(ii) Data collection, analysis, integration, and visualization
(iii) Simulation of product behavior in the virtual environment
(iv) Behaviors control
(v) Establish two-way real-time communication between the physical and virtual system or product.

NG being hazardous, the safety aspects are considered vital during the design of the physical system that facilitates monitoring the safety parameters remotely on the virtual system. As depicted in Figure 6, three layers are created to set up the DT.

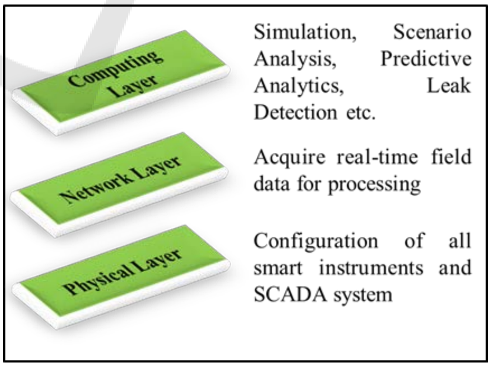


Figure 6: DT Layers.

(i) Physical Layer: This layer constitutes the pipeline network, different instruments, devices, sensors, and equipment that are installed at identified locations on the CGD network. They capture real-time pressure, flow, and temperature data. The SCADA system transmits data remotely to the central control room.

(ii) Network Layer: A network layer is created to acquire all the field data for processing through the IT system. At the unit level, this constitutes

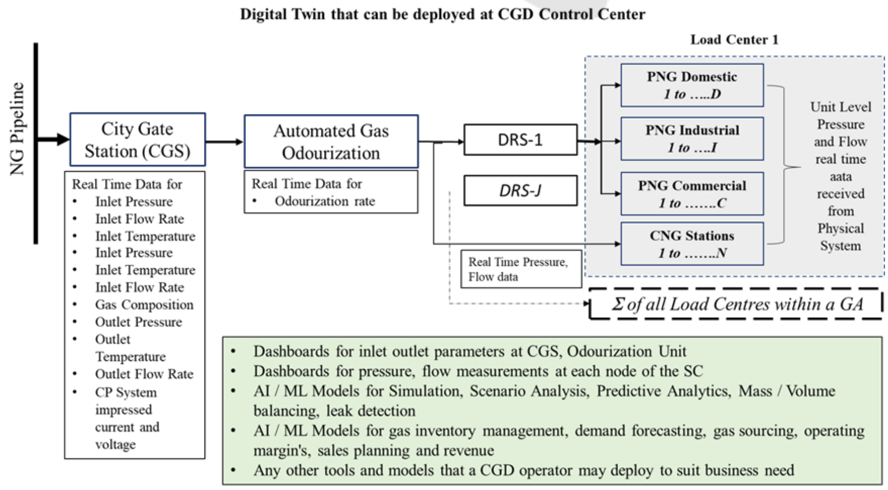
(a) the NG received at the CGS, its pressure, composition, and temperature
(b) PNG consumed by each customer
(c) CNG dispensed through CNG dispensers
(d) Data from each regulator station
(e) Current and voltage data from the CP system
(f) Data from the automated odorization unit
(g) Data from gas detectors installed at critical locations
(h) real-time audio/visual data, if required, from the CGS station or any other installation

(iii) Computing Layer: A virtual model of each charge area is to be created that comprises segment-wise individual PNG customers and CNG stations. Then, the virtual model for all charge areas within the GA is integrated to form the virtual SC for the CGD network. Different dashboards are created within the IT system to display and monitor various parameters related to pipeline hydraulics, mass balancing, leak detection etc. The convergence of IT/OT systems is vital to mimic the physical system in the virtual world precisely. Smart field instruments and devices enable real-time data acquisition and transmission. Other decisions that the CGD entity needs to take relate to data security, data storage, platforms to set up the DT, tools for simulation and predictive analytics etc. The data-driven models assist in making different operational decisions related to demand-supply management, mass/volume/energy balancing, leak detection, business decisions related to demand forecasting for gas sourcing, pricing, billing, sales revenue, enhancing operating margins etc.

Accordingly, the Conceptual DT Model is shown in Figure 7. The virtual model can be superimposed into the physical map of the district where the SC for CGD network will operate.

4 CONCLUSIONS

Digital Transformation is the global buzzword believed in providing real-time solutions to real-life business and social problems that impact the quality of life, well-being, climate change, and energy transition (EIA, 2022). Though the Indian model for GBE transition and ecological modernization is available in the literature(Prasad & Kumar, 2022), alongside physical models for CGD (Rajput et al., 2022; Yadav & Sircar, 2022), intelligent models suiting Indian conditions based on AI, ML and Big Data Analytics underpinning 4IR are scanty. As such, the conceptual digital twin model in Figure 7 proposed in this research is the first innovative step to promote the digital transformation of the Indian NG retail sector, leveraging Industry 4.0 standards.



Source: Authors Analysis

Figure 7: Conceptual Digital Twin Model for NG Retailing within a GA.

This paves the path for smarter societies since the DT model precisely measures the decrease in emissions when NG replaces carbon-intensive fossil fuels at the household level. Even though the Indian NG sector witnesses challenges in the speedy execution of pipeline projects(Prasad, 2011), a SCM framework to overcome such challenges exists that has the potential to manage delays in establishing CGD network, tackle time and cost overrun, adversely impacting delivered NG price(Prasad et al., 2023).

As the GOI aspires to achieve a GBE, the instant model will help CGD entities expand their gas retailing business with real-time accurate demand forecasting for gas supply to different segments of retail customers. This will increase NG consumption because the NG will likely replace fuels like petrol, diesel, furnace oil, light distillate oil, etc., owing to its positive attributes and environmentally friendly nature(EIA, 2022). Other advantages that the conceptual model shall provide the CGD entity relate to :

(i) Timely and accurate billing for all segments of retail customers
(ii) Quick realization of gas bills
(iii) Transparent dispute resolution in billing
(iv) Accurate gas reconciliation
(v) Minimize operating system gas loss
(vi) Quick Demand forecasting
(vii) Gas load management between different load centers
(viii) Increase operating margin and sales revenue
(ix) Tool for detecting gas leakage in real-time
(x) Improved operations safety
(xi) Better control in operations and maintenance of CGD grid.
(xii) Real-time scenario analysis for demand forecasting
(xiii) Real-time predictive analysis for price affordability range for retail industrial and commercial customers
(xiv) Real-time data for NG that replaces commercially available liquid fuels like petrol and diesel
(xv) Promote gas-based economy transition.
(xvi) Promote smart societies with ecological modernization.

The instant research is the first in delivering a Conceptual Digital Twin Model for gas retailing supporting global decarbonization aspirations to achieve SDG targets for 2030. Further scope of research exists in dovetailing multiple such models for different GA's in India to establish a DT for CGD networks at the country level. Other emerging and developing economies may refer to this model to gain insights on the steps to be followed in developing such a model and tailor the current model to suit their local requirement.

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