Smart Building Digital Twin for Interior Water Distribution System Management

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Abstract

A smart campus integrates the Internet of Things, artificial intelligence, and real-time sensor data to optimize campus functions and create a context-aware decision-support platform for effective campus management. A crucial aspect of a smart campus is the water distribution system, which faces several challenges due to bursts, leaks, and water quality issues. This study uses Digital Twin technology to address these challenges through real-time monitoring, detection, and management of campus water distribution networks. A building-level digital twin is developed for the interior water networks of the Daphne Cockwell Complex at Toronto Metropolitan University. The major components include a 3D network model capable of analysis and simulations, a smart water management system, and real-time visualization. A 3D static model of the interior water utility network is created using the Industrial Foundation Class data. The semantic and topological models based on graph models are developed for network analysis. The models are integrated into the ESRI ArcGIS Pro to facilitate BIM-GIS integration. A dynamic model is created by incorporating automatic meter readings based on IoT. Combined with the 3D model of the utility network, the digital twin monitors and visualizes building water consumption, facilitating anomaly detection and real-time maintenance by the facilities management department. This study provides practical guidance for managing water distribution systems in university buildings, with potential applications in other complex environments. Future work aims to develop a system for detecting complex event processes by integrating different utilities.

1. Introduction

A smart campus serves as a testbed for the Smart City initiative. It integrates the Internet of Things (IoT), artificial intelligence (AI), and real-time sensor data to optimize campus operations and enhance the experience of students and faculty. This integration encompasses smart infrastructure, buildings, and transportation, creating a context-aware decision-support platform for effective campus management. One critical aspect of a campus is its water distribution system, which, when properly managed and monitored, reduces non-revenue water (NRW) and prevents economic loss and water scarcity. Effective management of water distribution systems helps detect unusual activities like bursts or leaks in water pipelines, monitor water consumption, and forecast and predict water demand.

This study uses digital twin technology to address these challenges through real-time monitoring, detection, and management solutions. Digital twin (DT) technology involves modeling and connecting physical and virtual systems, data analytics, and interaction and services by providing operational settings validated by the simulation to optimize the system processes for external changes (Conejos Fuertes et al., 2020). A building's digital twin typically includes the structure, location, assets, people, and real-time events related to the building and its environment. It integrates virtual network models, optimization algorithms, real-time data, smart actuators, and Geographic Information System (GIS). This study aims to develop a building-level digital twin framework for the interior water networks of a campus building.

According to Shahzad et al. (2022), the digital twin represents the physical asset and couples the physical and digital parts to reflect changes. The physical asset in water management is the water network, while the digital part is a three-dimensional model with information linked to the physical network. Hence, modeling the water network is the initial step in developing the digital twin. GIS connects the real world and the virtual environment (Wang et al., 2022), and modeling objects in a 3D GIS environment helps manage, visualize, and query spatial data effectively. Most works on digital twins for water utilities are developed for a 2D GIS environment. Using 3D models transforms the modeling of interior utility networks, especially in large, complex buildings requiring regular maintenance. Representing these networks in 3D enhances visualization, management, and analysis.

Different modeling approaches for representing utility networks are reviewed from various perspectives, including Industrial Foundation Classes (IFC), CityGML Utility Network Application Domain Extension (ADE), INSPIRE Utility Networks, Model for Underground Data Definition and Integration (MUDDI), ArcGIS utility networks, SEDRIS, and Pipeline ML (Becker, 2011; Kutzner et al., 2019; Pavlidou, 2022). However, not all models support 3D data or have GIS capabilities. Our review confirms that the Industrial Foundation Class model comprehensively supports semantic, topographic, and topological representations. Despite the model's rich semantic and topographic information, it initially lacks GIS capabilities, limiting its utility for comprehensive spatial analysis. The IFC model is integrated with ESRI ArcGIS Pro to address this limitation, facilitate model visualization, and provide robust GIS capabilities. This integration allows for incorporating geographical context into the model, enabling spatial analysis and decision-making.

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Populating the virtual model with real-time sensor data is crucial in a digital twin setup. This process involves transforming the water network digitally through smart water management (SWM), which leverages smart water meter technologies and advanced metering infrastructure. These technologies are vital for sustaining water consumption through meticulous planning, regular monitoring, and strategic decision-making. Integrating IoT sensor data, such as automatic meter readings processed using AI algorithms, enables the creation of a dynamic model for real-time system monitoring and management.

The digital twin framework in this study provides a practical and innovative approach to effectively managing water distribution systems within campus buildings. By utilizing real-time data and advanced modeling techniques, this framework enhances the understanding and visualization of these systems and enables proactive maintenance and management strategies. Moreover, the adaptable nature of the framework suggests its potential applicability beyond campus environments, offering insights and strategies that can be leveraged in other complex building settings. Furthermore, this research significantly contributes to the field by bridging the gap between Building Information Modelling (BIM) and GIS technologies for building network analysis. Developing a network analysis toolbox for tracing and locating the components and their properties based on IFC data sets a valuable precedent for integrating these technologies in other utility systems. This framework's versatility suggests its potential for applications in various other utility management contexts, indicating a promising direction for future research.

2. Materials and Methods

2.1 Study area and data used

The study is being conducted for the Daphne Cockwell Complex building of Toronto Metropolitan University in Downtown Toronto (Figure 1). The interior water utility network of the building comprises Domestic Cold Water, Domestic Hot Water, Non-Potable Water, and Sanitary water networks.

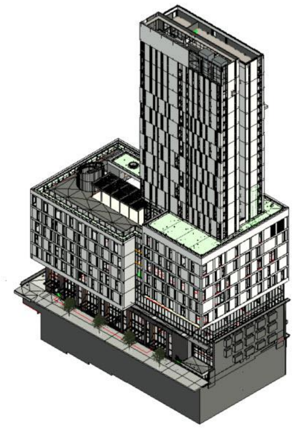


Figure 1. Study area

Data used for the static modeling includes the Revit Model of the building, incorporating architectural, mechanical, and plumbing components. The Revit Model is transformed into IFC format using Revit 2022's built-in Revit to IFC converter. The IFC model of the interior water utility network of the study area comprises 198,699 elements belonging to entities such as IfcDistributionElement, IFcBuildingElement, IfcPort, IfcElementType, IfcSpatialElement, and IfcRelationship. Various relationship entities such as IfcRelAssignsToGroup, IfcRelAssociatesMaterial, IfcRelAssociatesClassification, IfcRelConnectPorts, IfcRelServicesbuilding, IfcRelContainedinSpatialStrucutre, IfcRelDefinesbyType, IfcRelDefinesbyProperties, IfcRelAggregates and IfcRelNests are used to define the relationships among each element in the IfcObjectDefinitions. Appendix 1 summarizes the entities within the IFC model of the interior water utility network categorized under IfcDistributionElements and IfcRelationships.

Smart water meters, installed on various floors within the building, capture flow data using pulse signals to measure water consumption. These meters track Domestic Hot Water (DHW), Domestic Cold Water (DCW), Non-Potable Water (NPW), and Sanitary flow at 10-minute intervals in cubic meters. Table 1 outlines the specifics of the smart water meters on different levels.

Floors	No. of sensors	Services
Level 1	2	Incoming DCW, Fire Main services
Level 8	2	Laundry
Level 9	19	Grey water, Pumped storm for cisterns, Irrigation, Cooling Towers, Risers
Level 12	15	DCW, DHW, and NPT services
Level 13	18	DCW, DHW, and NPT services
Level 20	15	DCW, DHW, and NPT services
Level 21	18	DCW, DHW, and NPT services
Level 26	15	DCW, DHW, and NPT services
Level 27	18	DCW, DHW, and NPT services
Level 28	15	Cooling Tower, DCW, DHW, and NPT services

Table 1. Summary of the distribution of smart water meters at different levels of the DCC building

2.2 Methodology

A digital twin for the interior water utility network must accurately replicate the behavior of network elements under all extreme operating conditions, considering factors affecting flow, water quality, and maintenance operations. It simulates the network behavior, supports and facilitates maintenance and operations, and predicts demands for different service connections. The DT structure comprises three main stages: static modeling of the interior water utility network, integration of sensor data, and data analytics to support smart water management, as well as visualization. Figure 2 illustrates the DT framework for the interior water utility network.

2.2.1 Static Modelling of Interior Water Utility Network

The static modeling of the interior water utility network is conducted using IFC data to accurately depict the network's 3D geometric layout, topological relationships, and relevant semantic information. IFC employs various methods to represent 3D objects, including boundary representation (B-

Rep), constructive solid geometry (CSG), and sweep volume. The foundational class for all products is IfcProduct, with representation encompassed by IfcProductRepresentation. For the geometrical 3D modeling of utility networks, IfcDistributionFlow elements like IfcFlowFitting, IfcFlowSegments, IfcFlowTerminal, and IfcDistributionControlElements such as IfcFlowControllers are utilized.

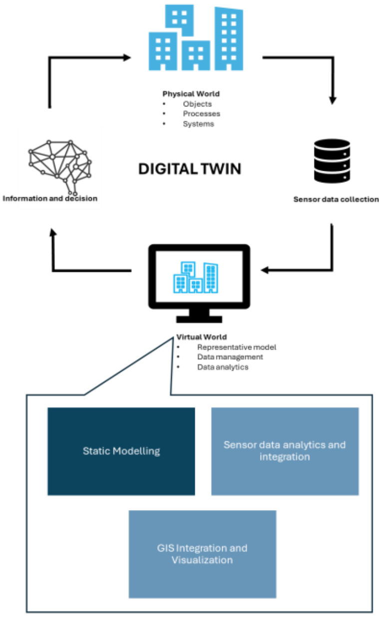


Figure 2. The digital twin framework for interior water utility network

The semantic representation of the given IFC model is based on a graph data structure. The IFC schema serves as an ontology for constructing knowledge graphs. The knowledge graph for the BIM model is developed using Cypher query language and stored in the Neo4j graph database, adhering to the principles of a labeled property graph, which utilizes node and edge relationships. The graph data structure enables unified management of IFC data and facilitates information querying through Neo4j HTTP APIs.

Deriving the topological model is based on IFC entities such as IfcRelationships, which include IfcRelAssignsToGroup, IfcRelNests, IfcRelConnectPorts, and IfcPort like IfcDistributionPort. IfcRelAssignsToGroup assigns group members to a group object, defining systems or networks such as Domestic Hot Water, Domestic Cold Water, and Sanitary and Non-Potable water networks. IfcRelNests establishes connections between IfcDistributionElements and IfcDistributionPort, while IfcRelConnectPorts defines connections between IfcDistributionPort. The connectivity between these IfcProduct and IfcRelationships is determined using the IfcOpenShell parser, and a graph-based network model is created using the Neo4j graph database.

2.2.2 Sensor Data Integration and Analytics

As mentioned in Section 2.1, the Smart water meters are installed at different levels within the building studied and connected to a centralized Building Automation System (BAS). This system enables users to access, control, and monitor all connected building systems from a single interface. The BAS stores different sensor data for analysis, including the water, gas, and BTU meters. The water meter provides 10-minute water consumption data for real-time monitoring of water consumption patterns, anomaly detection, and water demand predictions. BIM data is converted into a relational database using a defined data schema described in Section 2.2.1. This schema includes unique identifiers that establish a relationship between the sensor readings and the virtual objects.

A Convolutional Neural Network (CNN) is being used in this study to construct a multi-variable water demand model for the non-residential sector. This model incorporates various factors such as climatic variables, socio-economic factors, and population, ensuring its accuracy and effectiveness. The study also forecasts water demand to assist in resource planning and allocation. Furthermore, the model focuses on detecting anomalies in water consumption patterns and identifying irregularities or deviations from expected usage to enhance the efficiency of the water management system. An approach combining the Statistical Process Control (SPC) technique with a prediction-classification method is employed for anomaly detection.

2.2.3 GIS Integration and Visualization

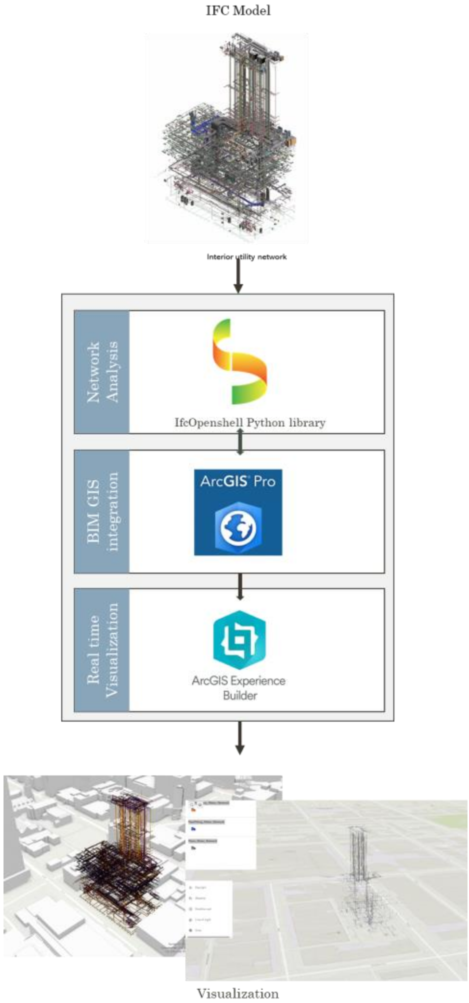


Figure 3. General workflow for BIM-GIS integration and visualization

The IFC data lacks GIS capabilities, making it essential to incorporate the digital twin into a GIS environment, especially for smart cities and campuses. GIS spatially integrates different buildings, road networks, and other infrastructure, enabling complex spatial analysis. Although this study focuses on building-level digital twins, integrating the DT into a GIS environment offers a platform to extend from building-level to city-level DT. Integrating the BIM model with GIS facilitates network analysis, advanced routing analysis, and 3D visualization. Figure 3 illustrates the general workflow for integrating the IFC model into GIS environments. Initially, network analysis is conducted using IfcOpenShell. The BIM-GIS integration is performed using ArcGIS Pro, with real-time visualization provided by ArcGIS Experience Builder.

3. Results and Discussions

This section presents the preliminary results of developing a digital twin for the interior water utility network. The 3D modeling of the network is accomplished using IFC data. Semantic relationships for the IFC data are established using knowledge graphs. Figure 4 illustrates the semantic model of the IFC data, structured based on ontology. The model comprises 72 nodes, 72 set properties, and 55 relationships.

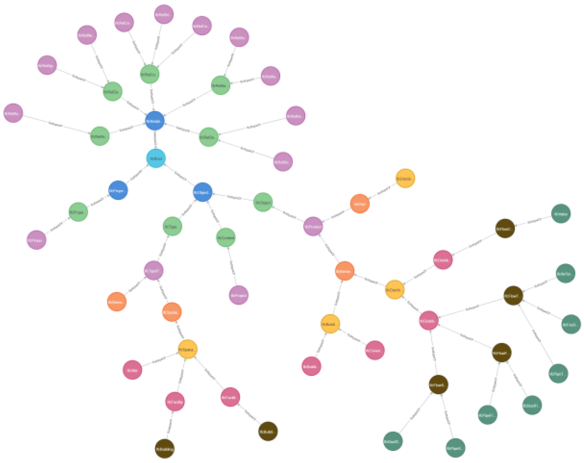


Figure 4. Semantic model of the IFC data based on ontology

The topological model of the water utility network is established in a network graph format. Figure 5 shows the topological model of the water utility network for the DCC building, while Figure 6 represents a simple network extracted from the developed model. The graph is created by establishing topological relationships between IfcRelationships and IfcProducts. Each node in the graph corresponds to the Global ID of an IfcDistributionElement, and the edges represent the "From" and "To" relationships. There are 554 networks in the given IfcModel. The Cypher query language can analyze upstream and downstream queries and identify all connected components.

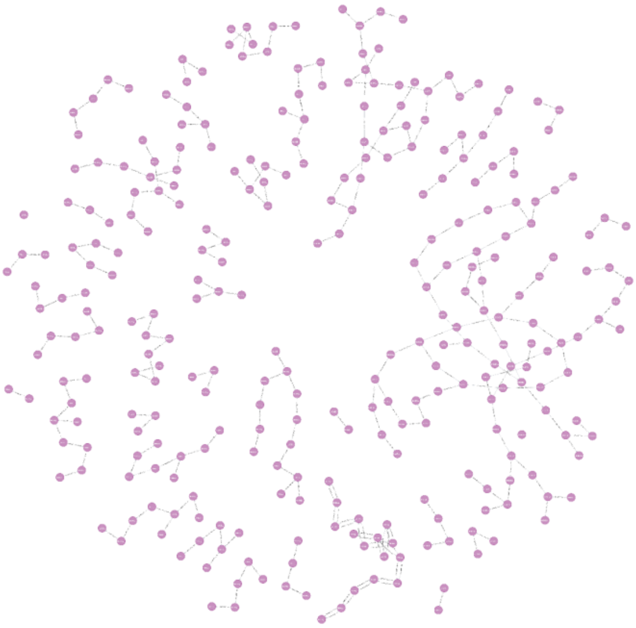


Figure 5. Topological model of the interior water utility network

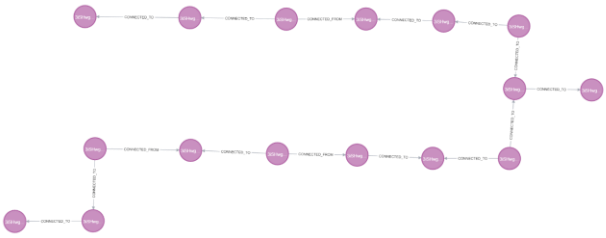
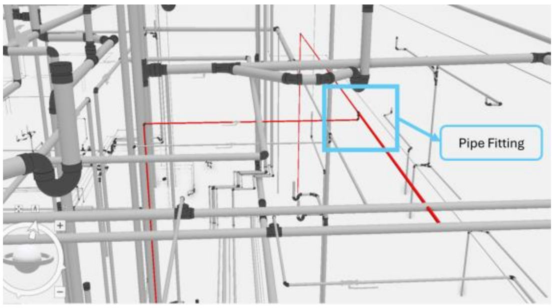
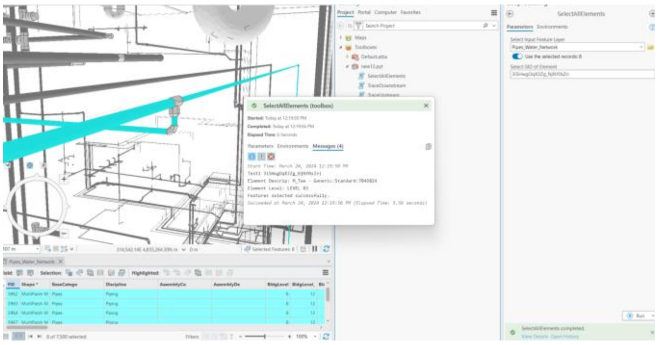


Figure 6. Topological model of a selected network

BIM-GIS integration is performed using the ArcGIS Pro platform, and a toolbox is developed for network analysis tasks such as upstream and downstream tracing, identifying all connected components, and finding the properties of chosen components. Figure 6 shows the toolbox implementation in the ArcGIS Pro platform, where all components connected to a pipe fitting are displayed in 6.a. Figure 6.b shows the properties of the pipe fittings, including their floor level, displayed using the developed toolbox.



a. All connected components



b. Properties of the selected component

Figure 6. ArcGIS Toolbox for network analysis

4. Conclusions

This study presents the initial investigations and preliminary results in developing a building-level digital twin for the interior water utility network of a campus building. The digital twin developed in this study aims to address the challenges in the water distribution system by enabling real-time monitoring, detection, and management of the water networks. The research highlights the incorporation of 3D models for accurately representing topology, geometry, and semantics of the interior water utility network through IFC data based on network graphs. Based on IFC data, the 3D modeling of the network successfully establishes a semantic framework using knowledge graphs, enhancing the representation of network components. The topological model, structured in a network graph format, allows for a detailed analysis of the water utility network's connectivity and relationships.

Despite the rich semantic and topographical information in the Industrial Foundation Class (IFC) model, its lack of GIS capabilities is addressed by integrating it with ESRI ArcGIS Pro. This integration enables spatial analysis and decision-making by providing geographical context to the model. Integrating BIM and GIS using the ArcGIS Pro platform proves effective in developing a comprehensive digital twin for the interior water utility network. It bridges the gap between BIM and GIS technologies. It contributes to the field by developing a network analysis toolbox based on IFC data for trace analysis, component location, and property access. The adaptable nature of the framework suggests its potential applicability in other complex building settings and various utility management contexts, indicating a promising direction for future research.

The next step in the study involves integrating real-time sensor data into the developed static model of the interior water utility network. By leveraging smart water meters and advanced metering infrastructure into the model, the developed digital twin can monitor and manage the water network in real-time, enhancing the system's efficiency and reliability. The future scope of this work includes developing a digital twin for the campus, integrating multiple utility networks and different sensor data based on Complex Event Processing.

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Appendix

Appendix 1 Summary of IFC entities used for the case study

IfcEntity	Type	Count
IfcPipe Fitting	M_P Trap - PVC - Sch 40 - DWV: Standard	472
	M_Tee Sanitary - PVC - Sch 40 - DWV: Standard	973
	M_Bend - PVC - Sch 40 - DWV:Standard	1527
	M_Reducer - PVC - Sch 40 - DWV: Standard	823
	M_Coupling - PVC - Sch 40 - DWV: Standard	41
	M_Pipe Combination Wye with 8th Bend - Glued: Standard	130
	M_Flange - Threaded - GI - Class 125:Standard	63
	M_Pipe Three Way Ell - Glued: Standard	7
	M_Elbow - Generic: Standard	1585
	M_Tee - Generic: Standard	444
	M_Transition - Generic: Standard	677
	Cleanout - Wall: Standard	164
	Cleanout - Floor: Standard	15
	Pipe Continuation: Standard	15
	M_Tee Reducing - Threaded - MI - Class 150:Standard	108
	M_Elbow Reducing - Threaded - MI - Class 150:Standard	298
	M_Flange - Slip-on - Steel - Class	8

	1:Standard 2	
	M_Fixture Fitting Double - PVC - Sch 40 - DWV: Standard	10
	M_Coupling Concentric Reducing - Threaded - MI - Class 150:Standard	43
	M_Pipe Endcap: Standard	19
	M_Cap - Threaded - MI - Class 150:Standard	5
	M_Pipe Elbow: Standard	3
	M_Pipe Transition: Standard	16
	M_Pipe Tee: Standard	6
	M_Coupling - Generic: Standard	2
	M_Pipe Plug - PVC: Standard	1
IfcDuct Fitting	M_Rectangular Duct Union: Standard	1
	M_Rectangular Duct Elbow - Radius:1 W	18
	M_Rectangular Duct Transition - Angle:60 Degree	5
	M_Rectangular Duct Elbow - Mitered: Standard	4
	M_Rectangular to Round Duct Transition - Angle:30 Degree	4
IfcFlow Terminal	M_Floor Drain - Rectangular:125 mmx125 mm Strainer - 100 mm Drain	19
	M_Floor Drain - Round:125 mm Strainer - 75 mm Drain	35
	M_Floor Drain - Round:150 mm Strainer - 100 mm Drain	8
	M_Floor Drain - Round:125 mm Strainer - 100 mm Drain	12
	M_Floor Drain - Round:200 mm Strainer - 150 mm Drain	2
	P_Sump Pit - Round:P_Sump Pit - Round	6
	P_Sump Pit - Square:P_Sump Pit - Square	7
	P_Catch Basin - WATTS FD410:Catch Basin	10
	M_Area Drain - Round:125 mm Strainer - 100 mm Drain	6
	P_Scupper Drain - Angle Grate:100 mm	1
	M_Roof Drain:380 mm Strainer - 100 mm Drain	54
	M_Floor Drain - Round:200 mm Strainer - 100 mm Drain	2
	P_Schluter - Grated Floor Drain:P_Schluter - Grated Floor Drain	18
	M_Floor Drain - Rectangular:125 mmx125 mm Strainer - 80 mm Drain	43
	P_Scupper Drain - Angle Grate:75 mm	1
	M_Area Drain - Round:150 mm Strainer - 100 mm Drain	1
	Hub Drain:125 mm Strainer - 80 mm Drain	28
	M_Sprinkler - Upright - Hosted:20 mm Pendant	5
	M_Floor Drain - Round:250 mm Strainer - 100 mm Drain	1
	M_Floor Drain - Rectangular:150 mmx150 mm Strainer - 80 mm Drain	6
	Hose-Bibb: Full-Turn_Cold	16
	Hose-Bibb: Full-Turn	7
	DOM NP Booster Pumps: DOM NP Booster Pumps	1
	M_Floor Drain - Round:250 mm Strainer - 150 mm Drain	1
	Hub Drain:125 mm Strainer - 100 mm Drain	3
	M_Sprinkler - Concealed - Hosted:15 mm Pendant	2
	Hub Drain:125 mm Strainer - 50 mm Drain	2
	RC50:RC50	3
	Grille - Return Air:1/2" Blade Spacing	5
	Grille - Exhaust Air:1/2" Blade Spacing	4
	Sink - Cloakroom:440 x 350mm	1
	Hub Drain:150 mm Strainer - 80 mm Drain	2
	Hub Drain:150 mm Strainer - 50 mm Drain	1
	M_Sink - Work:510 mmx455 mm	1
	DOM City Booster Pumps: DOM City Booster Pumps	1
	M_Reversomatic_Wall Box_WB-1-4in:WB-1	1
	M_Floor Drain - Rectangular:125 mmx125 mm Strainer - 50 mm Drain	1
IfcFire Supression Terminal	M_Sprinkler - Upright - Hosted:20 mm Pendant	5
	M_Sprinkler - Concealed - Hosted:15 mm Pendant	2
IfcAir Terminal	Grille - Return Air:1/2" Blade Spacing	5
	Grille - Exhaust Air:1/2" Blade Spacing	4
	M_Reversomatic_Wall Box_WB-1-4in:WB-1	1
IfcPipe Segment	Pipe Types:PVC (San&SD)	4197
	Pipe Types: Copper - Dom Water	2723
	Pipe Types: Black Steel_Threaded	574
	Pipe Types: Black Steel_Welded	2
	Pipe Types: Black Steel_Grooved	4
IfcDuct Segment	Rectangular Duct: Mitered Elbows / Taps	26
IfcValve	P_Domestic Water Manifold:P_Domestic Water Manifold	35
	M_Gate Valve - 50-300 mm:100 mm	6
	M_Y Strainer - 50-500 mm - Flanged:100 mm	1
	P_Water Flow Meter:100 mm	3
	M_Plug Valve - 3 Way - 15-50 mm:50 mm	12
	P_Water Flow Meter:75 mm	4
	M_Ball Valve - 50-150 mm:15 mm	49
	M_Ball Valve - 50-150 mm:40 mm	40
	M_Ball Valve - 50-150 mm:50 mm	19
	M_Ball Valve - 50-150 mm:25 mm	7

	M_Ball Valve - 50-150 mm:20 mm	63
	M_Ball Valve - 50-150 mm:75 mm	1
	M_Ball Valve - 50-150 mm:100 mm	5
	M_Ball Valve - 50-150 mm:65 mm	8
	M_Pressure Regulating Valve - 50-150 mm - Flanged:100 mm	5
	M_Ball Valve - 50-150 mm:32 mm	6
	M_Pressure Regulating Valve - 50-150 mm - Flanged:65 mm	2
	M_Balancing Valve - Straight - 15-50 mm - Threaded:20 mm	9
	M_Double Check Valve - 65-250 mm:150 mm	1
	M_Butterfly Valve - 50-300 mm:100 mm	6
	M_Check Valve - 50-300 mm - Flanged:50 mm	1
	M_Basket Strainer - 50-300 mm - Flanged:150 mm	1
	M_Gate Valve - 50-300 mm:50 mm	1
	M_Plug Valve - 15-50 mm:65 mm	2
	M_Plug Valve - 15-50 mm:50 mm	3
	M_Plug Valve - 15-50 mm:40 mm	15
	M_Pressure Regulating Valve - 15-50 mm - Threaded:50 mm	1
	M_Balancing Valve - Straight - 15-50 mm - Threaded:15 mm	2
	CBV:20 mm	16
	M_Check Valve - 50-300 mm - Flanged:200 mm	1
	M_Balancing Valve - Straight - 15-50 mm - Threaded:25 mm	1
	M_Motor Control Valve - 15-50 mm:25 mm	1
	P_Water Flow Meter:32 mm	1
	P_Water Flow Meter:65mm	1
	M_Pressure Regulating Valve - 50-150 mm - Flanged:150 mm	1
	M_Pressure Regulating Valve - 15-50 mm - Threaded:40 mm	2
	P_Water Flow Meter:150 mm	1
	M_Butterfly Valve - 50-300 mm:150 mm	2
	M_Motor Control Valve - 65-150 mm:100 mm	1
	M_Plug Valve - 15-50 mm:25 mm	1
	M_Plug Valve - 3 Way - Lever Handle - 15-100 mm:40 mm	1
	M_Plug Valve - 3 Way - Lever Handle - 15-100 mm:50 mm	2
	M_Pressure Regulating Valve - 50-150 mm - Flanged:80 mm	1
	M_Plug Valve - 3 Way - 15-50 mm:20 mm	1
	M_Backflow Preventer - 15-50 mm:20 mm	1
	P_Water Flow Meter:200 mm 2	1
	M_Gate Valve - 50-300 mm:200 mm	2
	M_Pressure Regulating Valve - 50-150 mm - Flanged:50 mm	1
IFC Port	_	32453
IfcRel AssignsTo Group	_	554
IfcRel Associates Material	_	70
IfcRel Associates Classification	_	2
IfcRel Connect Ports	_	15089
IfcRel Services Buildings	_	554
IfcRel Containedin Spatial Structure	_	38
IfcRel Definesby Type	_	2984
IfcRel Definesby Properties	–	54710
IfcRel Aggregates	_	112
Ifc Rel Nests	_	15617