



BIM-based methods for optimizing the design and maintenance of telecommunications infrastructure in data centres

Thesis for the Degree of Doctor of Philosophy (PhD)

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Debrecen, 2024

Hereby I declare that I prepared this thesis within the Doctoral Council of Natural Sciences and Information Technology, Doctoral School of Informatics, University of Debrecen in order to obtain a PhD Degree in Informatics at Debrecen University.

The results published in the thesis are not reported in any other PhD theses.

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Dissertation submitted in partial fulfilment of the requirements for the doctoral (PhD) degree
in Informatics

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Prepared in the framework of the Doctoral School of the University of Debrecen
(Information technology systems and networks programme)

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The date of the dissertation defense: 2024

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1. Introduction

This dissertation explores various methods for improving methods of engineers' work involved in designing and operating engineering systems in data centres. From a methodology point of view, they are divided into three levels: code level, algorithm level and user level.

A data centre refers to a high-tech and complex unit that processes, stores, and transmits information to a particular organisation, managing the organisation's information system [1]. It is a specialised facility, consisting of intricate infrastructure, including the following [2,3]:

Information infrastructure, including server equipment performing the primary functions of the data centre, such as information processing and storage. The telecommunications infrastructure facilitates the interconnection of elements within the data centre, as well as data transmission between the data centre and the users.

The research involved several stages according to the levels, including the plugin development at the code level, creation of fundamental data centre components models such as telecommunication cabinets, equipment, and cable routes and also integration between building management system (BMS) and temperature equipment's at the algorithm level. Additionally, temperature management techniques using the corridor isolation method were implemented. These blocks were selected for the study because they are rarely studied and have real-world applications at the user level, for engineers. We tested all of these blocks on various real projects at CROC company, ranging in scale from small data centres with 15 telecommunication cabinets of 2 kW each, to large commercial data centres with more than 1000 cabinets of 6 kW each, which lease their facilities to large organizations. During the testing process, we received feedback and made necessary adjustments. It can be concluded that all proposed methods are currently in use, improved, and updated.

1.1. Classification and the structure of data centre

Data centre - A building (or complex of buildings) for the housing of server and network equipment and the subsequent connection of clients to the Internet.

Ensuring the stable and trouble-free operation of the equipment it houses is the primary function of a data centre. Additionally, a data centre provides secure communication channels for exchanging data, while also allowing for permanent site access.

Data centres can be divided into four categories, based on the level of reliability and security they offer: Tier I, Tier II, Tier III and Tier IV. The Uptime Institute certification organisation has developed a reliability score called Tier, which is assigned to data centres.

A Tier I data centre is the most basic form of data centre, offering the lowest levels of redundancy and availability. It has a single path for power, communications and cooling, which means that any maintenance to the infrastructure or failure of any equipment will result in an interruption to services. Tier I data centres have no redundant components, and while they can cope with power surges and outages, they operate outside of normal business hours, such as nights and weekends. However, for regular maintenance or emergency repairs, the data centre must be temporarily shut down. The minimum uptime without shutdown is 99.671%, and the downtime per year should be less than 28.8 hours.

A Tier II data centre has a degree of redundancy in its power and cooling systems, but it is still susceptible to downtime due to maintenance or equipment failure. Like a Tier I data centre, they have one link for telecoms, power and cooling, plus redundant parts: generators and cooling equipment. This redundancy makes it possible to carry out some maintenance or preventative maintenance on the infrastructure without downtime, although downtime may still occur if a critical part fails. The data centre guarantees a minimum uptime of 99.741% without shutdown, which translates to less than 22.7 hours of downtime per year.

Tier III data centres offer greater levels of redundancy and availability than Tier I and Tier II data centres. Maintenance can be carried out without downtime according to multiple communication, power and cooling links. Tier III data centres offer greater redundancy and significantly improve availability. These centres offer N+1 system redundancy, which

means that an additional component is brought online to support the failure or scheduled maintenance of one component. The following is a breakdown of N+1 redundancy: N means the capacity required to support the full information technology (IT) load of the data centre +1 is an additional component for redundancy.

All of the IT equipment in a Tier III data centre should have dual power supplies connected to separate uninterruptible power supply (UPS) units so that one of the UPS units can be shut down without causing any disruption to the servers or loss of network connectivity. Additionally, redundant cooling systems should be in place to ensure that if one unit fails, another can maintain the temperature and humidity in the data centre rooms. Furthermore, Tier III data centres necessitate solutions that can sustain operation for at least 72 hours following a local or region-wide power outage. These data centres are equipped with systems, protocols, and equipment that enable staff to perform maintenance and repairs without disrupting customer service. The minimum uptime is 99.982%, with downtime per year being less than 1.6 hours.

The Tier IV data centre is the most reliable type with the highest fault tolerance parameters. Like the Tier III data centres, it has several communication channels, power supply, and cooling. It has redundant components that are resistant to failures, ensuring that there will be no disruption to service if one critical component fails. Tier IV data centres are designed to withstand any failures and maintenance without any impact on the services provided. Essentially, Tier IV systems have no single points of failure. Level 4 data centres have 2N or 2N+1 equipment redundancy, meaning a fully redundant infrastructure. In particular, 2N redundancy means having a completely identical system in reserve for each component, which is physically isolated and independent from the main system. In turn, this physical separation prevents local events from compromising both systems. Each component is backed up by two different power providers, two backup generators, two UPS systems, two power distribution units (PDU's) and two different cooling systems.

Additionally, Tier IV data centres require backup solutions that can support operations for at least 96 hours after a local or region-wide power outage. The minimum uptime is 99.995%, and downtime per year should be less than 26.3 minutes.

The foundation of any data centre is its engineering systems. These are complex, professional pieces of equipment that are not typically available for purchase in a local server room. If we imagine the data centre as a living organism, we can identify five main systems, the first of which is electricity supply. This is the most critical source of life for a data centre, upon which its stability and uninterrupted operation depend. To ensure 24/7 operation of sites, the building is connected to the power grid through multiple independent inputs. Additionally, an UPS system and a diesel generator are installed to provide backup power in case of a complete outage.

Usually, a continuously running machine can overheat. Therefore, the machine room must be well-cooled using professional precision air conditioners.

One important aspect is that data centres are responsible not only for hosting equipment, but also for ensuring data security and confidentiality. This can involve implementing an access control system, video surveillance, fire alarms, emergency fire extinguishing systems, and other measures. Another crucial aspect is maintaining stable and uninterrupted data transfer processes, which can be achieved through the use of dedicated channels and public internet networks with wide bandwidth.

All systems are monitored 24/7, and any detected issues are resolved using pre-developed algorithms.

The main elements of the data centre are shown in Figure 1.1.

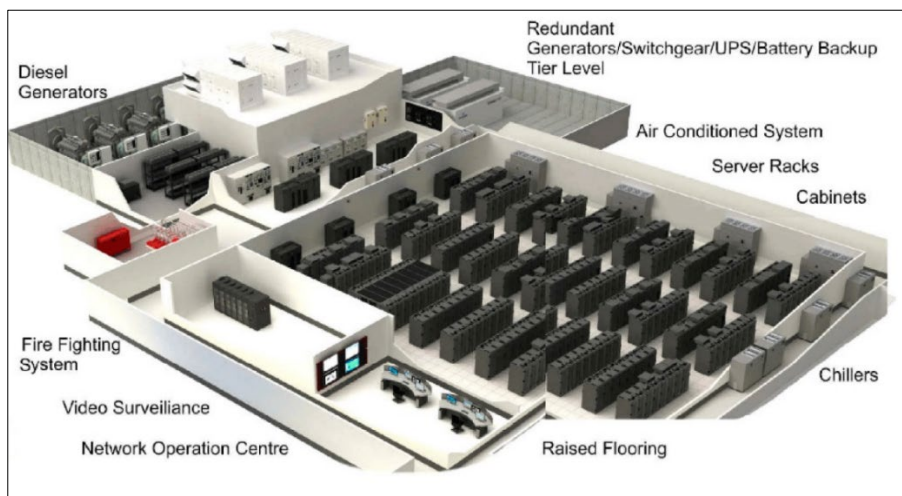


Figure1.1: Main elements of the data centre [4].

1.2. The technical background of the research

Automated equipment and cable trays design for structured cabling system in data centres

The basic elements of data centres that influence their type, scale and energy efficiency are telecommunication cabinets filled with various equipment.

Telecommunication cabinets, which are equipped with a large number of components of different types, are essential parts of data centres. They have a significant impact on the efficiency and reliability of data centres.

The layout of equipment inside telecommunication cabinets is crucial in data centres, and the ideal location of equipment inside each cabinet can be unique. Therefore, an automated process is necessary for the cabinet facade scheme design. Manually created diagrams can lead to errors. Furthermore, accurate and current information regarding the specific equipment layout in each cabinet is crucial for its ongoing operation and maintenance.

The design methods currently available do not include a function for automatically creating three-dimensional (3D) models of cabinets with equipment filling and generating cabinet façade schemes. When designing data centres, it is crucial to consider the placement of telecommunication cabinets, cable routing design, and equipment layout. These elements are integral elements of structured cabling systems (SCS). It is one of the important components of engineering systems, but it is still poorly understood in terms of Building information modelling (BIM) design. In the article [5], we analysed the use of BIM concept in connection with engineering systems and from it we can conclude that this area is still a dark spot.

The research aim is to create main elements of the model at the algorithm level for SCS.

A structured cabling system is created to organise a single cable infrastructure that can be used by various systems for transmitting and processing information, such as local computer networks, telephony systems, video surveillance, and access control.

- In data centres, cable trays serve the purpose of protecting cable lines from external influences. They perform this function for sections of cable lines belonging to different systems.

- The purpose of this system is to protect cable lines of horizontal and trunk cable systems (subsystems) from electromagnetic interference.
- Additionally, it physically separates different systems, such as fibre optic cables and low current cables, in separate trays.

SCS in telecommunication cabinets of data centres are created using functional elements such as copper patch panels, optical patch panels, cable organizers, copper cables, and fibre optic cables.

BIM based collision tracking at the intersections of different building engineering systems at the design stage

The digital information model, a three-dimensional model, allows for clear tracing of the location (x-y-z position) of system elements in space and prevents their intersection.

Chahrour et al. [6] state that collisions can occur due to design rule violations, errors, uncertainty, model inaccuracy, and tolerance. Collision detection using BIM tools distinguishes between two types of collisions: relevant and irrelevant.

If collisions result in a loss of productivity, interruptions, and rework, they are considered relevant to the project [7]. Relevant collisions are those that require resolution. In contrast, irrelevant collisions do not require resolution as they may be a single error repeated multiple times throughout the project or collisions that were deliberately created [8].

Proper identification of collisions, including relevant and irrelevant collisions, and appropriate distribution of collision resolution among BIM project teams play an important role in projects where thousands of collisions can be captured using specialised software [7].

The research primarily focused on developing detection algorithms [9,10], incorporating historical information into clash detection [11,12], and utilizing machine learning (ML) [13]. However, as noted by Pärn et al. [8], despite the benefits that ML has brought to the architecture, engineering, construction and owner-operated (AECO) sector, such as automating rule checking within BIM and controlling four-dimensional (4D) BIM, clash detection still requires significant time and labour intervention. The current process is still mechanistic, requiring a BIM manager to manually scan and analyse each clash. According to interviews conducted by Lin and Huang [14] with senior project

managers, clash reports were often selectively reviewed or completely neglected by BIM managers in Taiwan due to the significant time required to evaluate them. Additionally, Pärn et al. [8] emphasized the pressing need for automated methods that eliminate manual intervention and enable the creation of clash detection profiles.

The research aims to develop plug-in for the collision tracing and checking at the code level introducing new methodology. Also, based on the algorithm for planning specialist actions when using information modelling technologies for project work demonstrate advantages of consistent design and intersection checking for different engineering systems, eliminating duplication of work.

As a result of our research a new plug-in was developed, which makes more effective the work of engineers at the user level for modelling systems at the design stage. It identifies intersections and corrects them ten times faster, excludes duplicated intersections, and tracks the history of each. Additionally, it improves significantly the report generating process on the intersection of engineering systems.

Efficiency improvement with data centre monitoring based on building information modelling and computational fluid dynamics analysis

The literature contains limited studies linking data centres and BIM, with little research in the field of facility management (FM) application for data centres.

Significant energy savings can be achieved by maintaining proper temperature and indoor humidity ranges through continuous monitoring of data centres and using isolation systems.

There are two basic options for installing a containerisation system in an existing engine room: isolating the cold aisle or isolating the hot aisle. The limited number of articles related to data centres, particularly those concerning cooling systems and the use of air corridor insulation with computational fluid dynamics (CFD) analysis, means that each option has its own set of characteristics, advantages, and disadvantages.

To ensure the necessary reliability of data centre equipment, temperature and humidity can be controlled by regulating airflow. As the temperature rises, the equipment draws in a greater volume of cool air.

Authors in the research [15] briefly introduces the concept of using BIM for automating data centre design. The methodology is based on the extended use of BIM for the operation and maintenance of data centres.

As data centres are integrated parts of enterprise information systems, it is natural to use tools for data centre design that have been successfully used in other design and operation fields. Although this task is of great importance, it has only been discussed by a limited number of researchers. Two sources that provide studies in this field are [16,17].

Wei et al. [16] proposed the use of wireless sensor networks (WSN) to monitor thermal performance parameters and predict them. They also described an approach that integrates BIM and WSN to improve data centre thermal performance and energy efficiency.

Rossella et al. [17] reviewed various methods of data exchange between BIM and FM software. They then applied the data exchange method to the performance indication model (PIM) pilot case study, focusing on surgery rooms in healthcare buildings.

Karim et al. [18] provide examples that demonstrate the effectiveness of various methods for model preparation when constructing buildings at Qatar University, with a focus on operation and maintenance.

Improving the design and operation stages at the algorithm level, for data centres leads to increased facility efficiency and significant cost savings. Crucially, controlling temperature and humidity distribution within data centres is essential for operational efficiency. Therefore, determining the optimal parameters for the temperature and humidity sensor system, including the number and placement of sensors, is crucial for enhancing efficiency.

1.3. Research goals and methods

Our study started in 2020 and the main objective was to implement novel approach, which based on the three interconnected levels for the further design and operation of engineering systems for data centres using the BIM design concept. The study included several blocks:

- Literature review and identification of the most under-researched areas related to the design and operation of engineering systems using BIM;

- Creation novel dynamic families for the model, based on the algorithm level;
- Implementation algorithmic approach for systems design and checking;
- Developing a novel collision checking plug-in, at the code level;
- Testing of BIM elements (families) and plug-in at the user level;
- Data collection and analysis from implemented BIM elements at the operation stage.

In the process of the study the main key areas of any data centre that need to be dealt with, from the information and communication technology (ICT) point of view, have been identified. The first is the arrangement of the rows of telecoms cabinets and filling them with equipment at the design stage. Next is to decide on the cooling system and modelling of the isolation system. The equipment inside the various telecoms cabinets is interconnected by various cable lines, for which it is necessary to design cable routes, usually in trays. When designing the trays of the various engineering systems, intersections occur between them and other objects such as ducts. These intersections need to be eliminated during the design phase. When all systems are linked, a temperature analysis should be carried out to determine how energy efficient the data centre is. For subsequent monitoring of its climatic parameters, a monitoring system is also designed and then installed. The following paper describes each of the main blocks.

The result of the work was at the algorithm level: creation of own dynamic family of telecommunication cabinets, with the distribution of equipment in it; Creation of families of temperature and humidity sensors, with their subsequent binding to the monitoring system of the data centre; Implementation consequent approach for the systems design; Determination of the most effective way of cooling telecommunication cabinets and equipment in them;

At the code level, result could be presented as creation of a plug-in that facilitates checking for intersections of engineering systems between each other in the data centre.

All these units were consistently tested on various private data centres at the user level, and were applied in particular in 2023, when designing a

large data centre with a volume of more than 1000 cabinets with a capacity of 6kW each. In total, about 40 specialists in various engineering systems took part in the testing of the developed solutions.

Autodesk Revit was used as the main tools for the development of families and BIM models. Autodesk NavisWorks was used for creation of summary models and collision detection. CFD analysis study was carried out using Autodesk CFD. A plug-in for collision checking was developed in C#.

The complex of these solutions allows to conduct a full cycle of life of a data centre, starting from the moment of design and interconnection of engineering systems to its operation and energy efficiency optimisation.

Code level	Algorithm level	User level
Novel plug-in for collision tracking was developed: forms are created for data visualization and code for the logic of user interaction with the database.	Developing a new dynamic family of telecoms cabinets for server rooms and data centres, allowing for different internal equipment configurations and optimising documentation for subsequent operation.	Introduction of a novel systematic approach for design and identification of cable channels for a unified data centre cable infrastructure, allowing all cable channels elements to be automatically considered and specified.
	Creating reports and assignment by the BIM coordinator of the sequence of checking various systems for intersection, docking based on novel plug-in for collision tracking.	Based on novel plug-in the user's task is to check collisions in a certain sequence and eliminate them step by step

Code level	Algorithm level	User level
	The communication between real sensors and BIM was improved with a new approach, based on algorithm level.	

Table 1.1: Research methodology.

1.4. Literature review

Since the research includes several blocks, the literature review is also divided into several directions: one of which includes the design of key elements of SCS, the other optimization of collision detection and the last one is related to the study of energy efficiency of data centres. All blocks have correlation with the BIM methodology. The main search keywords, depending on the research block, were the following: BIM, information model, structured cabling system, data centres, collision detection, BMS, CFD.

SCS are essential for smart buildings and data centres. SCS consist of telecommunication cabinets and racks in cross rooms of buildings, copper and optical panels inside telecommunication cabinets, and telecommunication outlets installed in the offices. The cabinet and information sockets are connected by copper and optical cable lines. Cable lines are laid in cable trays and boxes.

The methodology used to conduct this qualitative literature review on the use of BIM in structured cabling design and data centre research involved a traditional literature search on the use of BIM in design and facilities management. This was followed by a qualitative analysis of the content related to the design of SCS and data centres identified in the first step. The literature sources were categorized based on three criteria that correspond to the five main areas of use for BIM tools and methods.

- Weak: there is no BIM application with the same title as suggested by the authors, nor is there a BIM application that focuses in its description on the area of structured cabling design and data centre engineering identified by the authors.

- Moderate: There is either a BIM use with the same title identified by the authors, or there is a BIM use (or more than one) that focuses on the same topic proposed by the authors, even if the description in the guide is too general and never directly related to the structured cabling design and data centre engineering discipline.
- Strong: There is a BIM application with the same title identified by the authors and its description goes into detail about the structured cabling design and data centre engineering area identified by the authors.

Our qualitative literature review identified 5 main BIM uses in ICT engineering: 1) SCS; 2) production of working drawings; 3) data centre optimisation; 4) preparation of documentation and models for further FM; 5) monitoring of system parameters.

Reference	Area of use				BIM Content		
	Plan	Design	Build	Operate	Is the relationship with the BIM	Does the article correlate with 1 of the 5 main criteria	Level of correlation with main criteria's
[15]		+			+	+	Strong
[19]		+		+	+	+	Strong
[1]		+			+	+	Weak
[3]				+			Weak
[20]		+			+		Medium
[21]		+			+		Medium
[16]		+			+	+	Strong
[18]		+			+		Weak
[22]		+			+	+	Strong
[23]		+			+		Weak
[24]		+	+		+		Weak
[25]		+			+		Weak
[26]				+			Weak
[27]				+			Weak
[28]		+		+			Weak
[29]				+			Weak
[30]		+		+	+		Weak
[31]				+			Weak
[32]				+	+		Weak

Reference	Area of use				BIM Content		
	Plan	Design	Build	Operate	Is the relationship with the BIM	Does the article correlate with 1 of the 5 main criteria	Level of correlation with main criteria's
[33]				+			Weak
[34]				+			Weak
[35]				+			Weak
[36]				+			Weak
[37]				+			Weak
[38]	+	+		+			Weak
[39]		+	+		+	+	Strong

Table 1.2: Quantitative analysis [5].

	Number of Reference Document
(1) analysis of SCS	6,9%
(2) production of working drawings	24,14%
(3) optimized data centre design	20,69%
(4) preparation of documentation for further FM	37,93%
(5) monitoring system parameters	37,93%

Table 1.3: Qualitative analysis [5].

As can be seen from the table 1.2 and 1.3, the number of papers targeting SCS in relation to the design and operation of SCS in offices and data centres is quite small. It is important to explore this area in depth as it is under-researched.

The second part of the literature review is related to collision tracking at the intersections of different building engineering systems.

Numerous tools are available to detect collisions between objects in BIM. Most of these tools use the built-in functionality of Revit and NavisWorks. The literature was analysed to identify the main shortcomings of existing methods for identifying collisions.

For example, Nursultan B. et al [40] used NavisWorks software to examine potential losses resulting from merging current project documentation into BIM models. They used one of the Nur-Sultan projects as an example. The article compares the identification of intersections using the combinatorial principle. It checks for intersections between the section on constructive and spatial planning solutions and the sections on

heating and ventilation, water supply, and sewerage. This process is repeated, and exceptional combinations are selected to check for conflicts.

During the conflict analysis, we considered the permissibility of deviations for different combinations of the main sections of the design documentation. We reviewed some of these deviations and found that the conflict identification process is not completely independent and needs improvement. To prevent errors, we recommend developing the virtual model one section at a time instead of in parallel. By following this methodology, the designer can identify any inconsistencies before moving on to the next section of the design documentation. This can help avoid disputes, reduce rework costs, and save on labour costs.

Kermanshahi et al [41] examine a physical object that includes architectural, structural, mechanical, electrical and plumbing (MEP) BIM plans, as well as MEP BIM models and their collision detection. The study used Autodesk Revit and Autodesk NavisWorks Manage as BIM tools to develop features for simplified and automatic collision detection.

The clash detection system identifies three major types of clashes: hard clashes, which occur when one building component interferes with another; soft/clean clashes, which occur when components are too close together; and time/4D clashes, which can involve contractor deadlines, equipment and material delivery, and general time clashes. The aim of this study is to evaluate the impact of BIM on the design phase of the construction process and its ability to identify all clashes in construction plans during this phase.

The authors of another paper [7] also take a similar approach. They propose using network analysis to improve collision detection from a comprehensive perspective. Since a building is a continuous entity, the effects of collisions are influenced by the dependency relationships between building components. To represent these dependencies, a building component network is constructed, which is focused on collision objects. This work defines three types of spatial dependence for building a network: collision, impact, and connection. The collision relationships are classified into four types: intersection, penetration, through, and containment, based on the intersection curves of collision objects. To enhance generality, the industry foundation classes (IFC) and boundary volume hierarchy (BVH) models are used to query geometric information. Hierarchical structures,

such as BVH, expedite the query process by eliminating irrelevant comparisons.

The paper examines the efficacy of the network method in enhancing collision detection through a real-life project. The findings validate the method's success in identifying irrelevant collisions in four scenarios, reducing their number by 17%. Furthermore, the network automatically groups relevant collisions, resulting in a reduction of over 50% of the initially reported collisions.

The article [42] recommends using a plug-in in addition to the standard Autodesk NavisWorks tools to enhance the collision detection process. The plug-in automatically groups collisions detected by BIM tools to prioritize resolution and identify irrelevant collisions. The study demonstrated that the proposed plugin can distinguish between relevant and irrelevant collisions.

The study [43] recommends the BIM Vision IFC viewer, an application developed in Poland. This manuscript discusses the collision detection process and presents three case studies based on different BIM models. The results varied depending on the methodology used, which was based on the assumed process accuracy parameters, and resulted in different numbers of reported collisions. The study presents collision numbers ranging from zero to several thousand, depending on model complexity and expected accuracy. Additionally, the study measured the duration of individual collision detection, with results ranging from less than 1 second for the residential building model to 1 minute and 20 seconds for the industrial structure model.

The authors of the study 'Clash Detection and Code Checking BIM Platform for the Italian Market' [44], conducted research in Italy and suggest using a different software product for checking interference, namely usBIM.clash, instead of the Association of Chartered Certified Accountants (ACCA's) software system.

The plugin is capable of identifying hard collisions, hard tolerance collisions, and clearance collisions in an IFC model or between models. Computational geometry algorithms are used to check each selected element individually. For each element, the system processes a list using special data structures. This list includes the remaining model elements that could cause a collision. The analysis takes into account the selected test parameters. For example, in order to determine whether two objects

collide, the algorithm first calculates the corresponding bounding boxes and checks for disjointedness. Only if this test fails, a more precise but computationally expensive test is conducted. To enhance performance, the algorithm performs similar calculations in multiple stages for all three types. If the test fails, it indicates that the two elements are not interfering. Therefore, the element can be removed from the list and the algorithm can continue with the next one.

In the case of collision detection, it is important to consider methods for the weighting of collision severity and for the correct classification of a given intersection. The authors of the study [45] prioritised collision resolution before the construction phase. Results from Autodesk NavisWorks were used to improve the collision detection process. Additionally, a fuzzy analytic hierarchy process (AHP) algorithm was employed to assign weights to criteria. The relationships resulting from the collision detection process can be used to prioritize collisions for resolution and identify irrelevant collisions. The proposed method was tested in a real project, and comparison with expert opinion showed effective collision identification. This study presents a logical and practical approach to improving the collision detection process by considering the weight and penetration degree of collision elements.

The authors of 'Clash Relevance Prediction Based on Machine Learning' [13] also adopt a similar approach. The accuracy of BIM-enabled collision detection has been questioned due to the inclusion of minor collisions in the output. These collisions may not have a significant impact on the project or can be resolved in subsequent design or construction phases. To improve collision detection quality, this paper utilises supervised ML algorithms to distinguish between relevant and irrelevant collisions.

A test case was conducted to compare six types of classifiers: J48-based decision tree, random forest, Jrip-based rule methods, binary logistic regression, naïve Bayes, and Bayesian network. The results of cross-validation and the Kruskal-Wallis test indicated that Jrip was the most effective method for predicting clash relevance. The prediction accuracy was 80% on average for both the training and test datasets, which exceeded the initial percentage of relevant clashes (59%) in the clash report recommended by BIM coordinators for the test case. This indicates the success of the proposed method.

The sources analysed above demonstrate that despite the numerous proposed algorithms and solutions, the topic remains relevant and unsolved.

A novel plug-in, developed during the research, offers enhanced functionality with regard to the intersection of disparate systems. During the work, it was identified that the same collision can appear multiple times in the report. To solve this problem, the plug-in eliminates duplicate intersections.

In the next block, the literature review aimed to identify studies related to thermal management, corridor insulation systems and CFD related to BIM in data centres.

However, the number of articles related to data centres is limited, particularly those related to cooling systems, thermal monitoring and the use of air corridor insulation.

Currently, air cooling is the most commonly used cooling system in data centres due to its ease of use and maintenance. The data centre is cooled by computer room air conditioning (CRAC) units that supply cold air. These units have powerful fans that move large volumes of air. Servers are typically located in racks and have built-in fans that draw air in from the front and expel hot air from the rear. Different arrangements can be used depending on the airflow direction in the room. For instance, air can be supplied either from the underfloor space (plenum) through perforated tiles or from the ceiling in a suspended format. It is assumed that the hot air generated by the racks will be returned to the CRAC unit without any alteration to the cold air supply. This is to prevent thermodynamic inefficiencies.

Racks are usually arranged in rows to create alternating hot and cold aisles (HACA). This arrangement aims to partially separate the hot and cold air streams. However, it is still possible for hot air to mix with the cold air or bypass it directly. To more effectively reduce the mixing of hot and cold air, our study suggests physically separating the HACA. This can be achieved by insulating either the cold ducts or the hot ducts. Additionally, a return air duct configuration can be used to separate the hot air from each telecom cabinet and direct it into the return air duct. However, each approach has its advantages and disadvantages.

Based on the application, several categories can be identified: cold aisle containment (CAC) thermal control; hot aisle containment (HAC) thermal

control; room cooling systems; optimising energy consumption through the use of cooling systems.

Reference	Area of use				Using CFD to optimise design and operation processes	Using BIM and geometry analysis to optimise design
	CAC thermal control	HAC thermal control	Room cooling systems	Energy consumption optimisation by using cooling systems		
[46]	+	-	-	-	-	-
[47]	+	-	+	-	-	-
[48]	-	-	-	+	-	-
[49]	-	-	-	+	-	-
[50]	+	+	+	+	+	-
[51]	+	-	+	+	-	-
[52]	+	-	-	-	-	-
[53]	+	-	-	+	-	-
[54]	+	+	-	+	-	-
[55]	-	-	+	+	-	+
[56]	-	+	-	-	-	-
[57]	-	-	+	-	+	-
[58]	+	-	-	+	-	-
[59]	+	-	+	+	-	-
[60]	+	-	-	-	+	-
[61]	+	-	-	+	-	-
[62]	+	-	-	+	+	-
[63]	-	+	-	+	-	-
[64]	-	-	+	-	+	-
[65]	-	-	+	+	+	-
[66]	+	+	-	+	-	-
[67]	+	+	-	+	-	-
[68]	-	-	+	+	-	-
[69]	+	-	+	-	+	-
[70]	+	-	-	+	-	-

Table 1.4: Analysis of the articles related to HACA [71].

Table 1.4 shows a detailed analysis of the primary categories. The study indicates that only a small number of papers have explored the use of BIM and CFD for aisle isolation systems. Although precise object geometry can significantly improve the accuracy of subsequent CFD modelling, the use of

BIM has received limited attention, as evidenced by the scarcity of sources. BIM enables the inclusion of all necessary details required for the operation of the data centre in the element models.

Additionally, managing temperature and humidity distribution within data centres is critical for operational efficiency.

Wei et al. [16] proposed the use of WSN to monitor thermal performance parameters and predict them. They also described an approach that integrates BIM and WSN to improve data centre thermal performance and energy efficiency.

Rossella et al. [17] reviewed various methods of data exchange between BIM and FM software. They then applied the data exchange method to the PIM pilot case study, focusing on surgery rooms in healthcare buildings.

Karim et al. [18] provide examples that demonstrate the effectiveness of using various methods for model preparation in the construction of Qatar University, for subsequent operation and maintenance.

Therefore, finding the better parameters for the temperature and humidity sensor system, including the number and position of sensors, is essential for improving efficiency. The location of these sensors for monitoring climatic parameters has a close link to CFD modelling.

2. Automated equipment and cable trays design for structured cabling system in data centres

This section outlines the essential components of SCS in data centres.

A data centre is a sophisticated and intricate facility that processes, stores, and transmits information for a specific organisation, managing its information system [1]. It includes complex infrastructure such as the following [2,3]:

The data centres' main functions, such as information processing and storage, are provided by the server equipment that makes up the information infrastructure.

The telecommunications infrastructure connects the data centres' elements and facilitates data transfer between the data centre and users.

The engineering infrastructure comprises systems and equipment that guarantee the operation of the primary data centre systems. These may include air conditioning and ventilation, UPS, fire extinguishing, low current systems, and access control. The object being serviced may require additional systems beyond those listed, depending on its specific needs [72].

Data centres are engineering systems characterised by a high density of equipment in a confined space. They typically include the following main systems: a structured cabling system, a system of cable trays, and a power supply system.

The building is equipped with an air conditioning system as well as a smoke detection and automatic fire extinguishing system.

This section discusses the two primary factors that impact various aspects of a data centre from the algorithmic point of view: cable route design methodology and the proper placement of cabinets and equipment within them. These factors significantly affect the usability, reliability, and efficiency of data centres.

A structured cabling system is designed to organise a single cable infrastructure that can be used by local computer networks, telephony systems, video surveillance, access control, and other systems for the transmission and processing of information.

The cable trays in the data centre serve several functions. They provide protection for cable lines of various systems from external influences. They

also protect cable lines of horizontal and trunk cable systems (subsystems) from electromagnetic interference.

Additionally, they physically separate different systems, such as fibre optic cables and low current cables, in separate trays.

SCS in telecommunication cabinets of data centres are created using functional elements such as copper patch panels, optical patch panels, cable organisers, copper cables, and fibre optic cables.

A variety of tools are available for creating information models. For this research, Autodesk Revit was chosen as the optimal tool for problem-solving and implementation. It allows for the design of architectural, structural, and engineering elements by creating the necessary equipment.

Additionally, it enables several specialists to work simultaneously on one information model, download drawings for documentation, and create custom families, including dynamic ones with a set of changing parameters.

2.1. Designing novel rack family

Recently, the integration of BIM technologies into the design of technically complex objects, such as data centres, has become inevitable. BIM enables rational placement of equipment and communications, simulation of the influence of various factors on equipment operation, and effective organization of joint work among project participants. It also reduces the number of collisions and coordinates their correction in an interactive manner.

To solve the issues of automatic design of structured cabling system equipment inside telecommunication cabinets (copper and optical patch panels, cable organizers) a novel methodology is presented in this section. The methodology defines a new cabinet family with a dynamic set of various elements, including various sub-families of typical active equipment such as switches and UPS. This family was developed based on algorithm level by using as a tool in Revit. This allows for the simulation of the complete equipment of each cabinet. The novel dynamic cabinet family has several distinctive features in comparison with standard methods. The comparison is presented at the flow chart in Figure 2.1.

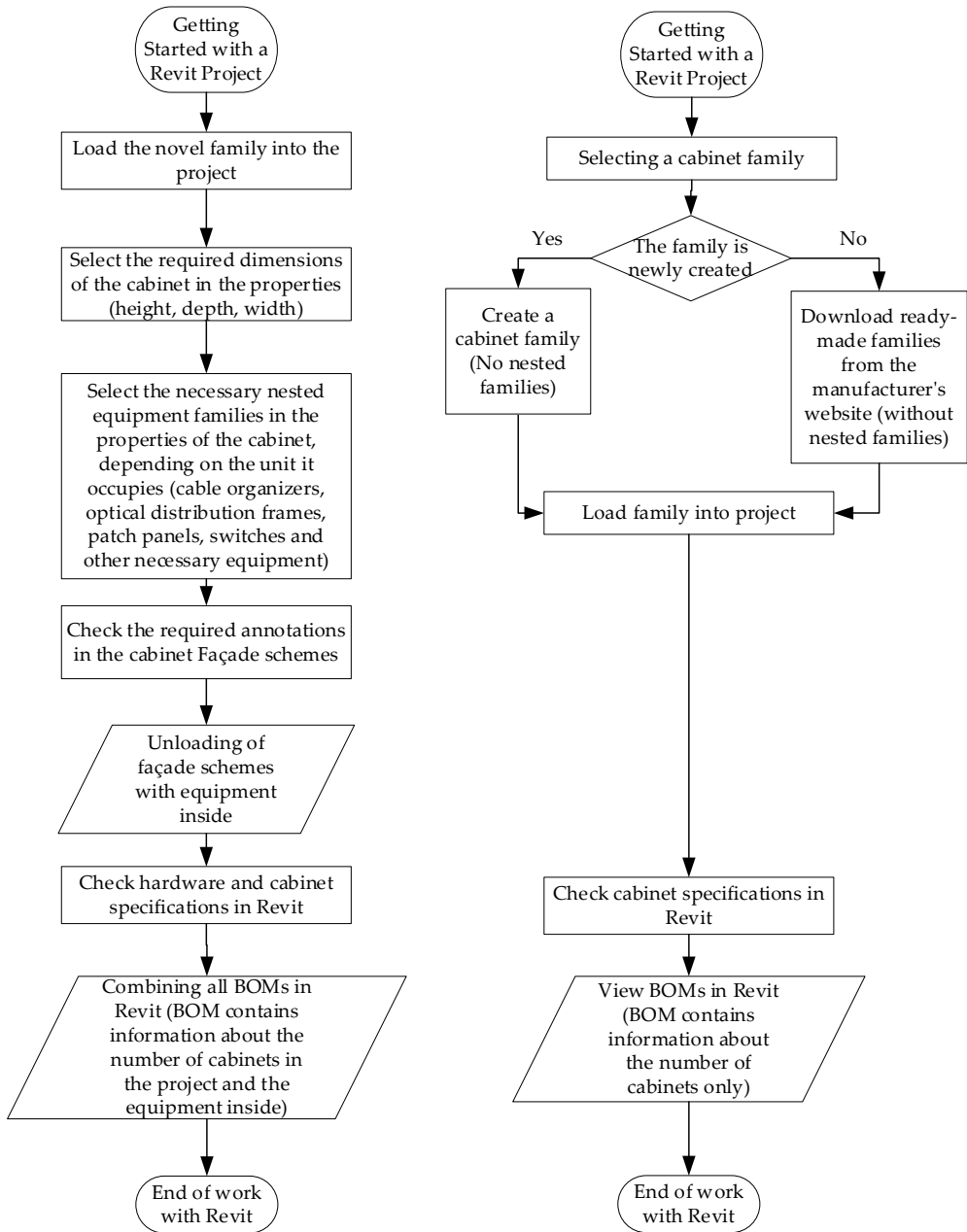


Figure 2.1: Flow chart: Work process with the novel cabinet family and with a simple family.

It also enables the addition and modification of equipment within the cabinet. The system allows for the selection of equipment to be housed in the cabinet and the unit to be occupied. A cabinet façade scheme is

generated based on the equipment housed within it, and a specification is automatically created.

This is necessary due to the potential for several hundred cabinets, each with unique equipment inside. To optimize the design process and FM of data centres, a novel family with changing parameters was created.

2.1.1. Main parameters of the novel cabinet family

A special purpose new dynamic family has been developed with varying sizes and parameters to enhance the efficiency at the design and operation stage. The specific features of this new family are summarised below.

The location of equipment in cabinets is dependent on its type and is determined during the design stage. All elements must be included in the specification phase, and this information is also necessary for the further operation of the data centre.

The user can select equipment to be placed in each unit of the 'properties' section of the new dynamic family within the telecommunication cabinet. This enables the creation of an accurate cabinet façade scheme and specification.

This complex family of equipment is characterised by the presence of numerous subfamilies within the cabinet, each with its own unique parameters that can be adjusted.

The diagrams of the cabinet façades are important for FM as they display the equipment contained within the telecommunication cabinets, including patch panels, crosses, cable organizers, blocks of electric outlets, and active equipment.

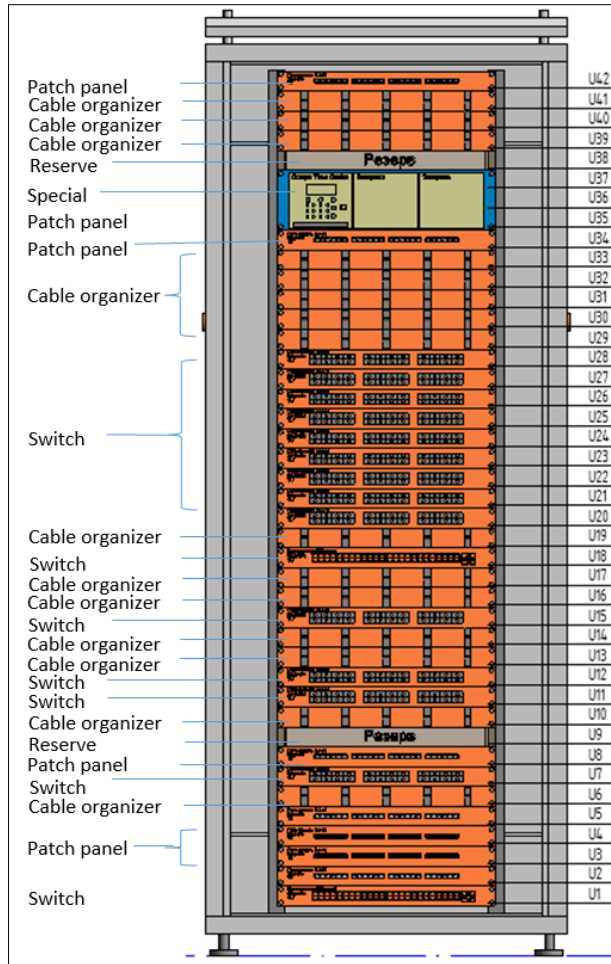


Figure 2.2: Telecommunication cabinet facade drawings [15].

In regard to the data stored within each telecommunications cabinet, it is all contained within the database. To illustrate, each panel is assigned a distinct number, which serves to identify it. Figure 2.3 illustrates part of the database containing information about optical cassettes in the panels in the case study, which include 29921 rows where each row is an optical cassette with specific parameters. The headings of the main database tables are presented in Appendix A.

	Code	Code type	Location	Panel's name	Level	Mark	Position
29001	2917741	1773256	MDA G1 1Tx201	MDA G1.11F.45/B2	389306	178411	113
29002	2917745	1773256	MDA G1 1Tx201	MDA G1.11F.45/C1	389306	178412	113
29003	2917749	1773256	MDA G1 1Tx201	MDA G1.11F.45/C2	389306	178413	113
29004	2917753	1268298	MDA G1 1Tx201	MDA G1.11F.44	389306	178414	112
29005	2917754	1773256	MDA G1 1Tx201	MDA G1.11F.44/A1	389306	178415	113
29006	2917758	1773256	MDA G1 1Tx201	MDA G1.11F.44/A2	389306	178416	113
29007	2917762	1773256	MDA G1 1Tx201	MDA G1.11F.44/B1	389306	178417	113
29008	2917766	1773256	MDA G1 1Tx201	MDA G1.11F.44/B2	389306	178418	113
29009	2917770	1773256	MDA G1 1Tx201	MDA G1.11F.44/C1	389306	178419	113
29010	2917774	1773256	MDA G1 1Tx201	MDA G1.11F.44/C2	389306	178420	113
29011	2917778	1268298	MDA G1 1Tx201	MDA G1.11F.42	389306	178421	112
29012	2917779	1773256	MDA G1 1Tx201	MDA G1.11F.42/A1	389306	178422	113
29013	2917783	1773256	MDA G1 1Tx201	MDA G1.11F.42/A2	389306	178423	113

Figure 2.3: Part of the database containing information about optical cassettes in the panels [15].

In summary, the dynamic cabinet family has several unique features.

These include the ability to choose different sub-families within the cabinet units, the ability to modify and add sub-families within the cabinet, the creation of a cabinet façade scheme based on the equipment inside, and the automatic generation of a specification.

2.2. Automation for cable trays design

The placement of switching equipment inside cabinets is dependent on the cable routes in trays. This section presents a solution that utilizes an automated plugin, specifically the Cable Tray Plugin. This plugin improves and automates the design process in the following areas: placing trays based on the installation method (wall, floor, ceiling) and placing tray elements (hangers, consoles, racks) at user-defined intervals.

Place tray connectors based on the selected connector and tray types at user-selectable spacing. Add a tray cover and partition in the tray properties. Export the list of cable trays and components in XLS or XLSX formats (Microsoft Excel).

Comparison of the new plug-in with the standard features of Revit presented in Figure 2.4.

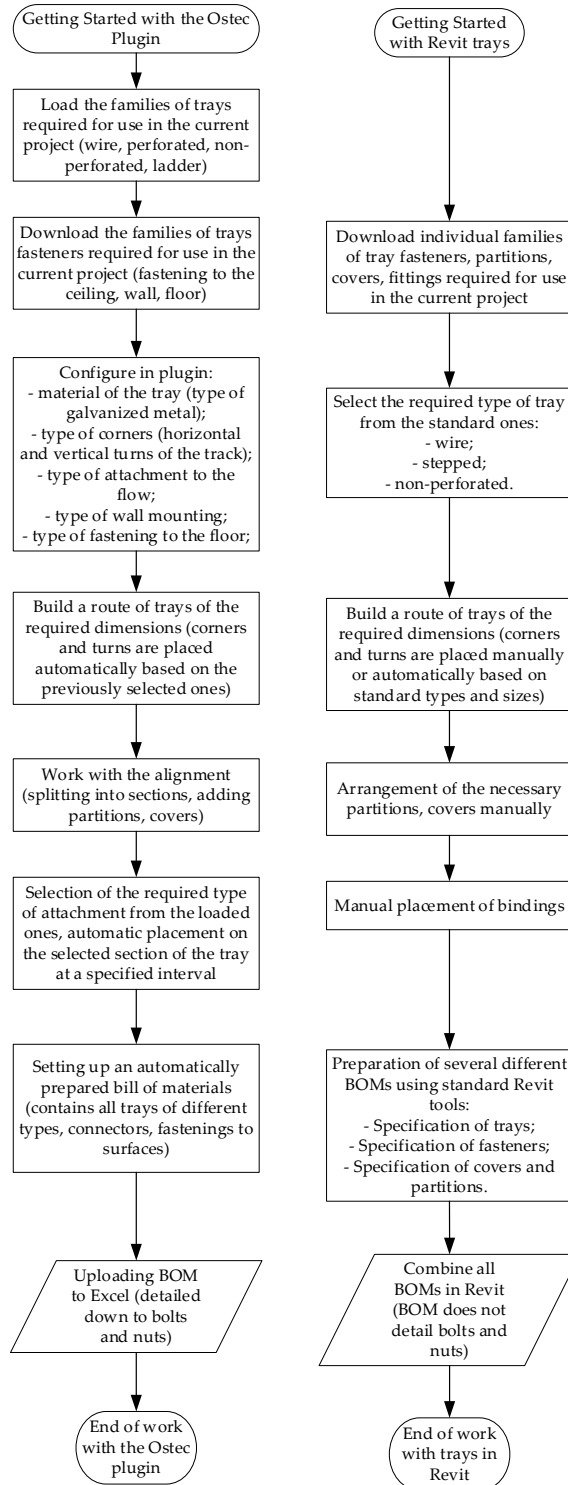


Figure 2.4: Flow chart: Work process with the new method based on an Ostec trays plugin and standard Revit tool.

2.2.1. Cable trays plug-in

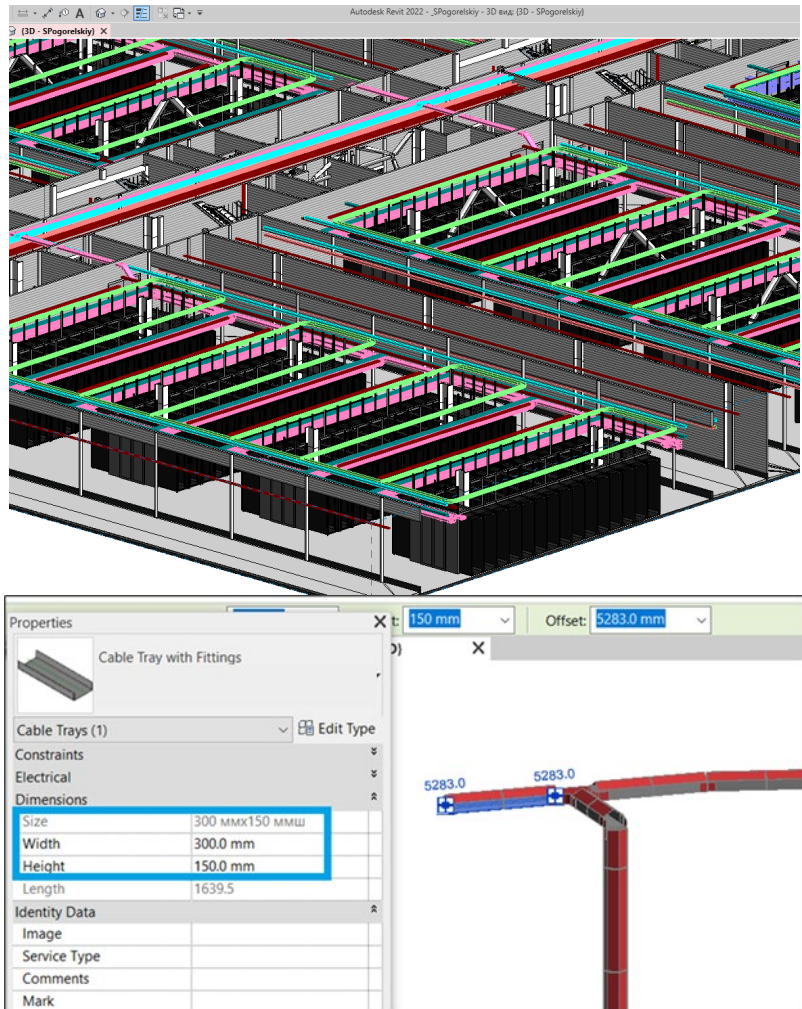


Figure 2.5: Some parameters of cable conduits [15].

Figure 2.5 shows a cable tray section with various elements such as bends, corners and covers. Each element has specific parameters, including size, name, and identifier (ID), which are crucial during the model creation stage. During the modelling process, the tray size may need to be adjusted, and this data is necessary to create an accurate product and material specification.

The aim of the research presented in this section is to improve the design process of SCS in data centres and develop more efficient design methods compared to standard ones. To implement and present the methodology, a plugin is required to provide correct filling of the necessary

parameters and the ability to specify all elements of the tray routes automatically. The Ostec company's plugin is used for this purpose.

The cable tray plugin automates the design process by placing trays based on the installation method (wall, floor, ceiling), elements of the trays (hangers, consoles, racks) at a user-defined interval, connectors of trays based on the selected type of connector and the type of trays with an interval equal to the length of the selected type of tray, and adding a tray cover and a partition inside in the properties of the tray itself.

Export the list of cable trays and components in XLS and XLSX formats (Microsoft Excel) and automatically create a specification.

The specification includes all elements of the cable routes including the necessary connecting elements. An example of cable conduit specification presented in Appendix B.

2.3. Results and discussion

Data centres are complex technical objects that consist of many systems. The cabling system of a data centre is part of a comprehensive engineering and information solution that supports various hardware and software products from multiple vendors.

This section presents a methodology that can improve data centre performance by efficiently designing the placement of trays and cables and managing related information. The method automates the formation of facade schemes and ensures correct specification.

The tray design plugin and dynamic cabinet family introduced in this section simplify the design and specification process and improve FM profitability. Thus, a solution is given to the issues posed in the section.

The plugin automates the construction of cable routes between cabinets. Fastening elements are placed automatically depending on the selected surface (wall, floor, ceiling), and all elements, including bolts and nuts, are included in the specification.

The new family of cabinets enables automatic selection of the required equipment and its location in the 'properties'. Each cabinet can have a unique filling, which eliminates errors in creating facade diagrams. Additionally, all equipment is automatically included in the specification.

The results of this section serve as the basis of the Thesis 1.

In comparison with standard solutions that allow modelling cable routes and equipment in telecommunications cabinets of data centres, the solutions presented in this part of the study allow achieving the following advantages:

- reducing the duration of the design phase by up to 30%. For example, the design processes can be accelerated by 20-30% (due to the use of plugin, novel cabinet families);
- possibility of subsequent identification of each element and work with databases of separately selected elements;
- increasing the quality of the project.

3. BIM based collision tracking at the intersections of different building engineering systems at the design stage

After creating the novel cabinet families and searching for better cable trays design methods, our research focused on collision tracking plug-in creation, due to cabinets and cable trays could give intersections with other engineering system objects.

Each of digital information model elements are three-dimensional, allows for clear tracing of the location (x-y-z position) in space and prevents their intersection.

Collisions can occur due to design rule violations, errors, uncertainties, model inaccuracies and tolerances, according to Chahrour et al [6]. BIM tools can detect two types of collisions: relevant and irrelevant.

Collisions that result in a loss of productivity, interruptions, and rework are considered relevant to the project if they require resolution [7]. Irrelevant collisions, such as a single error repeated multiple times throughout the project or deliberately created collisions, do not require resolution [8].

Accurately identifying collisions, both relevant and irrelevant, and appropriately distributing collision resolution among BIM project teams is crucial in projects where specialised software can capture thousands of collisions [7].

Table 3.1 summarises a systematic review of factors affecting geometric collisions in a BIM model and the impact of collisions on achieving effective design.

Causes of collisions	Authors
Use of incorrect or low level of detail	[73]
Uncertainty in design/use of "fillers"	[74]
Failure to follow design rules	[74]
Accuracy vs. timing	[74]
3D model objects that exceed acceptable clearances	[74]
Designers working in isolation from each other	[75-77]
Complexity of the design	[74,78,79]
Lack of time	[79,80]

Causes of collisions	Authors
Use of 2D rather than 3D models	[73,81,82]
Design errors	[74,83,84]
Use of different file formats	[85]
Lack of experts	[73,79,85-88]

Table 3.1: Summary of causes of collisions [89].

Detecting and preventing collisions at early design stages can reduce the need for extensive revisions to the executive model, which serves as the foundation for the design documentation.

The executive information model is a consolidated model created by engineers from different disciplines who have made changes to their respective sections of the information model.

This section aims to answer the following questions.

What is the optimal engineering design sequence for minimizing collisions?

The algorithm discussed in this section offers several advantages, including consistent design across different engineering systems, elimination of duplicated work, and prevention of unnecessary collisions.

The section also presents a new plug-in for effectively detecting and dealing with collisions, which optimises the work of engineers during the design stage of all modelled systems. The plug-in enables the identification and correction of intersections ten times faster. The plugin enables the exclusion of duplicated intersections and tracks the history of each. Additionally, it optimises the process of generating reports on the intersection of engineering systems.

The method of plug-in development is in the focus of our investigations aiming the improvement of the complex engineering subsystems at the design stage. To show the key ideas in our approach the collision checking procedure is discussed at three levels: code level (plug-in developer), algorithm level (BIM coordinator) and user level (engineers performing the check).

3.1 The implementation of an intersection prevention algorithm at the design stage

The information model is a consolidated model created by engineers from various disciplines who have made changes to their respective sections of the information model.

BIM modelling offers several advantages, as follows. Firstly, it allows for collaboration among specialists of different profiles in a single information environment, regardless of their location. Secondly, specialists from different areas can monitor changes made to the information model and receive notifications about them.

The project includes tools for automatically marking modelled objects and generating specifications for modelled equipment and elements.

These benefits streamline the work of specialists, decrease the probability of design errors, and enhance the quality control of documentation for designed objects.

To identify potential issues that frequently occur during intersection checking, collisions were searched for in the model of the designed data centre.

The model was created using Autodesk Revit, and the collision search was conducted in Autodesk NavisWorks Manage. Several issues were identified.

It should be noted that in this type of project, the number of collisions can reach tens of thousands. Despite the engineers discussing the layout of complex assemblies and designing the systems in a BIM platform, there were still thousands of collisions.

Collision check reports in NavisWorks are presented in an exportable Hypertext markup language (HTML) table. Working with such a large amount of data with the specified number of intersections can be challenging. Unfortunately, the NavisWorks platform only allows for viewing the summary model and does not provide the ability to edit a specific intersection. To address this issue, scheduled weekly checks were implemented from the start of the design process.

The prioritisation of modelling elements was as follows: structural and architectural solutions, ventilation systems, sewerage systems, water supply and heating systems, power supply systems, and communication networks.

The designers work sequentially in predetermined areas of the project, modelling the main volumes of the model within the structural and architectural sections. The designers of the ventilation system then commence their work in this area, as it contains a significant volume of ducts, connectors, and equipment.

The distribution priority order then passes to the designers of sewerage systems. The pipelines in this section are designed at a significant slope, and changing their routing is a labour-intensive process. After these sections, the water supply and heating networks are designed, with power supply and communication networks being designed last. When modelling their part, engineers from each section should take into account the work of their colleagues and make space for the systems of other sections through prior agreement [90].

The BIM coordinator carries out collision checks on the consolidated model with all sections multiple times a week. Reports are then uploaded to Power BI. Initially, engineers were advised to perform daily checks for intersections within their section using tools available in Revit.

A problem with collision checking is that not all intersections in the model necessarily indicate collisions. Quite often, pipe connections with fittings or equipment can be displaced, or elements can be duplicated when working together if the engineer has set the system to follow the change of elements in the adjacent section, or the accounting of equipment service areas can be made in the form of three-dimensional objects. However, hitting model elements in the peripheral part of such an area, which in fact does not carry global problems, is also defined as a collision. When installing flexible ducts, it is more efficient to separate them rather than correcting them during the design stage. A significant number of collisions fall within the specified tolerances, leading to an increase in collisions.

To solve this problem, it is recommended to filter objects before generating a report. In order to address collisions in the report, tolerances can be assigned to account for them. However, it is important to note that Autodesk NavisWorks tools may not allow for these tolerances. To check for intersections, the object can be divided into zones or sections as provided in the project. The decision on which elements to filter should be made on a project-by-project basis.

Note that when generating a report on intersections in NavisWorks, the table should list the results of each collision between objects. This means that the same collision will appear twice in the report, but in different parts of it when it involves two objects. Additionally, when one object intersects with multiple objects, such as a duct intersecting with several pipes, the number of collisions will naturally increase significantly.

Therefore, it is recommended to group intersections by combining lines with identical elements before sending the report to the engineers for collision correction. This will automatically reduce the number of collisions in the report.

Additionally, NavisWorks has a significant drawback when it comes to working on collisions, specifically the correct display of the intersection area of objects. The automatically generated view often lacks the correct trimming area, which can cause inconvenience for further consideration and work on the collision.

In order to eliminate the identified shortcomings, a plug-in was developed (in C#) and tested by BIM experts and engineers of various systems at the design stage.

3.1. The novel collision tracking plug-in

The methodology proposed in the research part for checking collisions is based on several key factors. These include compliance with the sequence of checking systems, exclusion of irrelevant collisions, and setting tolerances when joining system elements.

In our methodology for collision checking, we have introduced three levels: code level (plugin developer), algorithm level (BIM coordinator) and user level (engineers performing the check). At the developer level, forms are developed for data visualization and code for the logic of user interaction with the database. The work of the principal blocks of the plugin at the code level can be visualised by means of the diagram shown in Figure 3.1.

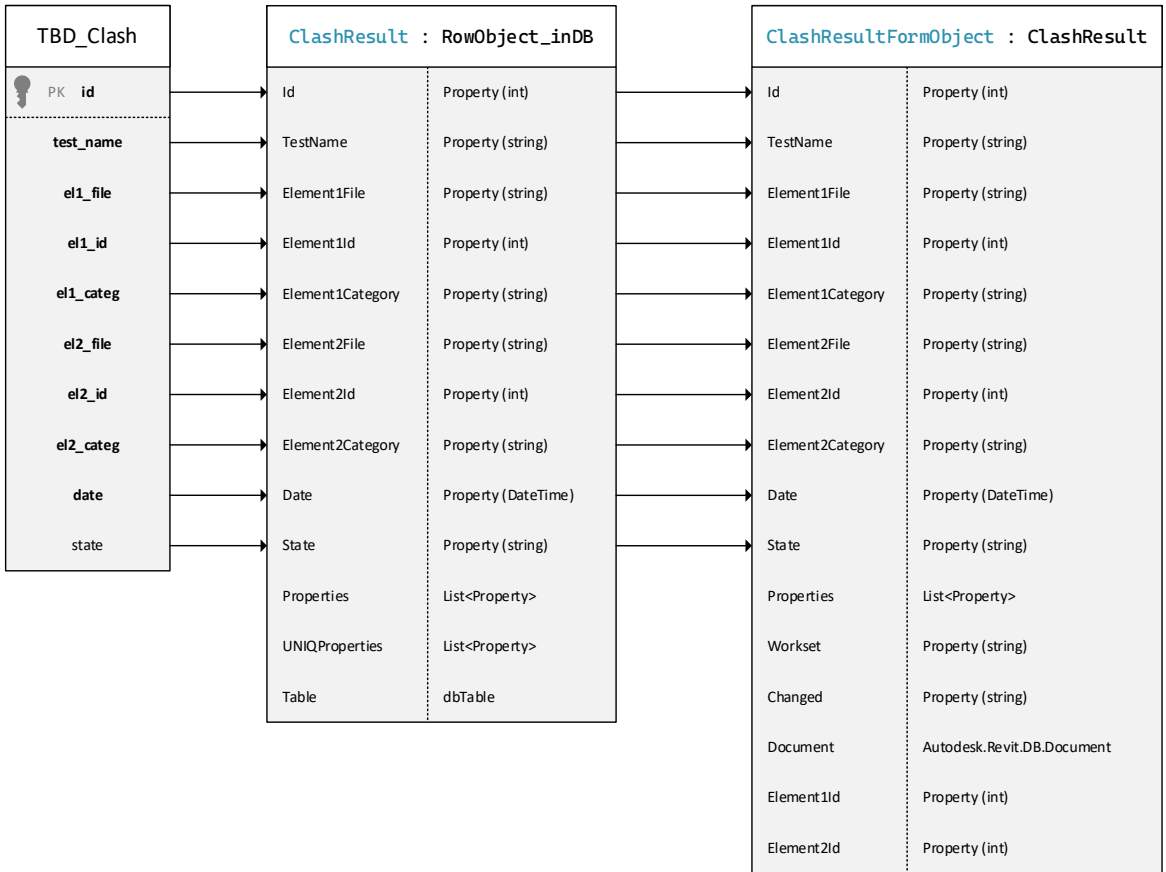


Figure 3.1: Code level, diagram of the principal plug-in blocks [91]

The principal data blocks are the TBD_Clash table in the database, which stores information about all the unique collisions that have ever occurred in the project. A unique collision is defined as the combination of `el1_id`, `el1_file`, `el2_id`, `el2_file` that is unique.

The ClashResult form displays current collisions related to the current open model at the current time. Collisions with the most recent date are considered current. Upon loading the subsequent collision report, the date at which the file was saved is employed as the date. In the event that a collision already exists within the table, the date of the report being read is substituted for that of the collision.

The collision class contains two constructors. The first constructor is used when reading an eXtensible markup language (XML) collision report for subsequent writing to the database. It accepts XAttribute, XElement and date (as a string) as input.

The DataRow object represents the outcome of a database query, and its constructor is employed to generate a set of collision objects for display in a given form.

At the algorithmic level, the function of the plug-in can be represented by the following sequence of actions:

- assignment by the BIM coordinator of the sequence of checking various systems and tolerances for intersection, docking;
- generation of a collision report in XML format;
- loading the report into the plugin.

At the user level, the user directly works with the form for searching and visualising collisions and eliminating single collisions. The user's task is to check collisions in a certain sequence and eliminate them step by step. After elimination, an identifier is placed in the form of a checkmark to enter information into the database that this or that unique collision has been eliminated, information about the date of elimination and the name of the user who last performed the action.

The aforementioned levels (code, algorithm, and user) are inextricably linked and collectively serve as the foundation for the plugin's functionality.

3.2.1. The plug-in information model

The plug-in menu is a panel that is embedded in the Revit window. It consists of buttons that are available to users of different levels. Figure 3.2 displays the block diagram of the plug-in.

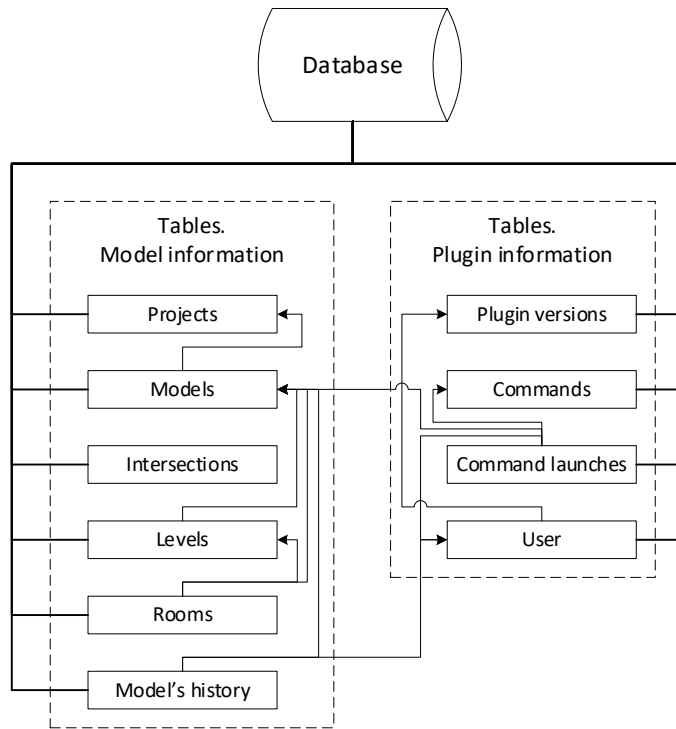


Figure 3.2: Block diagram of the plug-in [91]

The sequence of its use can be broken down into the following steps:

Firstly, the engineer selects the required model/system files for comparison, such as heating, ventilation and air conditioning systems (HVAC) and walls.

Secondly, the plug-in detects all intersections of the previously selected systems within a given accuracy tolerance.

Finally, the engineer sequentially goes through the list of collisions, noting the collision status as checked or unchecked. The plug-in also provides the option to display a 3D view of the required collision.

Each collision is assigned a unique ID, allowing for accurate identification in the database. Additionally, the necessary collision can be displayed on the screen 20 times faster than the standard capabilities of Revit (reducing the time from 20 seconds to 1 second per operation), significantly improving the efficiency of engineers.

3.2.2. Plug-in databases

The information model of the plug-in can be represented as a diagram containing databases and shown in Figure 3.3. The diagram displays several blocks:

TBD_ModelHistory records the history of models, documenting who accessed and modified the information model and when.

TBD_Users contains information about project users and their roles, with the menu presented by the plug-in varying depending on whether the user is a BIM manager or engineer. The BIM manager role has significant functionality, providing statistics on engineers' work with models.

The TBD_UsePlugin section contains statistics on plug-in usage, including user actions.

The TBD_Commands section includes information on all executed commands and their unique IDs.

The TBD_PluginVersion section provides information on plug-in versioning and critical updates.

TBD_Clash_Date contains information about all collisions for the entire duration of the checks. It is linked to the TBD_Clash database, which contains unique IDs for collisions.

Since one system can overlap with many others, TBD_Clash prevents duplication during repeated checks if the collision has been eliminated. If the collision remains, information about it will remain in the database. The provided text contains information about the working set in which the intersecting systems are located.

TBD_Projects also contains service information about the projects in which this plugin is used, along with their short descriptions.

Additionally, TBD_Models provides information about the models checked by the plug-in, including their names and unique IDs.

The TBD_Models_Clash also includes tables of links of collisions of some systems (models) with other systems (models), as well as a TBD_Rooms that contains unique room numbers and their IDs. If needed, it enables tracking of collisions in specific rooms.

TBD_Levels is a service database of floor levels that is directly linked to the previous item and allows for tracking of the floor where the collision occurred.

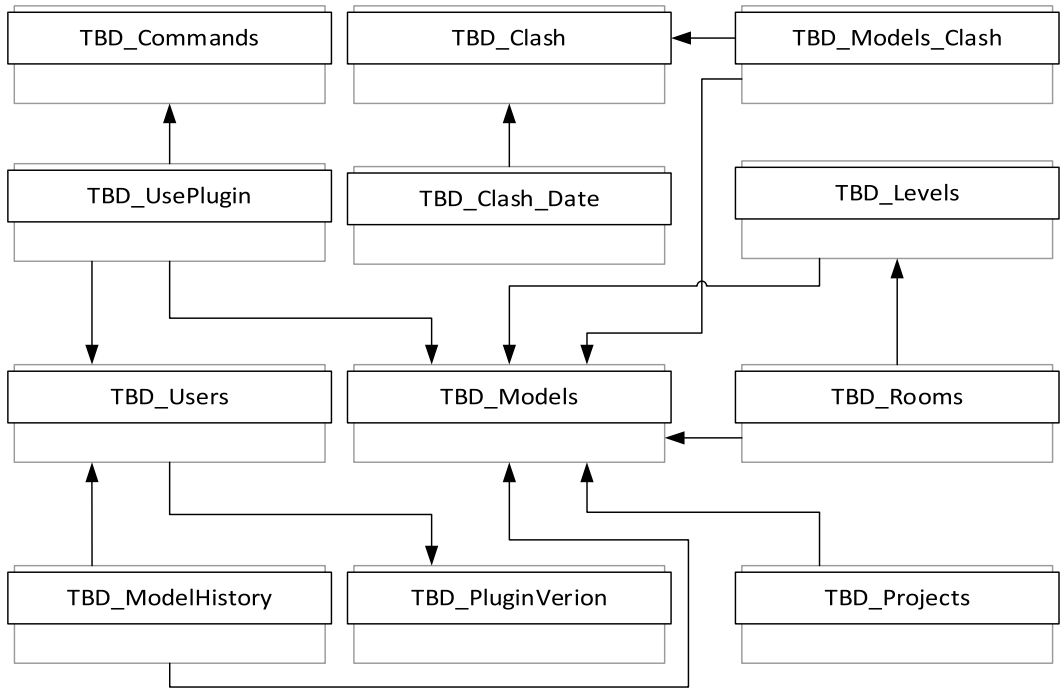


Figure 3.3: Plug-in databases diagram [91]

3.2. Results and discussion

In this section, the methodology for collision checking is based on several key factors. Such factors include adherence to the prescribed sequence of checking systems, the exclusion of irrelevant collisions, and the establishment of tolerances when integrating system components. To facilitate the implementation of the methodology, a novel special-purpose plug-in was developed.

In the context of collision checking, three levels of analysis have been identified. At the code level, forms are created for data visualisation and computer code is developed for the logic that underpins the user interaction with the database. In the context of user-level interaction, users engage directly with the form for the purpose of searching for and visualising collisions, as well as eliminating singular collisions. The objective is to identify and eliminate collisions in a prescribed sequence. Once a collision has been eliminated, an identifier is incorporated into the form in the form of a checkmark. This serves to indicate the successful elimination of the collision, the date of the elimination, and the name of the

user who performed the elimination. The three levels are inextricably linked and collectively constitute the fundamental building blocks of the plugin's functionality.

As collisions can lead to construction errors, it is of paramount importance to remove any remaining collisions between the engineering systems after they have been correctly modelled. With the new approach for the plug-in development, engineers' work in designing all the modelled systems can be improved. It enables the identification and correction of intersections approximately ten times faster, while also excluding duplicated intersections and tracking the history of each one.

The main results achieved with the plug-in are as follows: the plugin's audience coverage refers to the number of engineers who have used it to fix collisions, and it has reduced the time required to search for a single collision. In terms of working hours, the conditional number of clicks required to fix a collision has decreased from dozens to 5000 clicks with the plug-in, compared to 500000 clicks without plug-in. By measuring clicks per second, collision identification speed can increase tenfold.

This allows for the collection of reports in both dynamic and static formats. Without the plugin, creating a single report manually using standard tools would take several hours, but with the plugin, it can be done in just a few minutes. A typical data centre project lasts around one year, during which approximately 150 reports are prepared. This amounts to 450 hours without the plugin or 38 hours with the plugin.

The reports are downloaded from the main databases, TBD_Clash_Date and TBD_Clash, which contain information about all collisions for the entire duration of checks. This includes unique collision identifiers and information about the working sets in which the intersecting systems are located.

Jointly fixing collisions within the same model becomes possible without additional coordination between employees, saving communication time within the project team.

The change histories for each collision are stored in a unified database, enabling easy tracking of each collision as required.

The results of this section serve as the basis of the Thesis 2 and main part of collision case-study results are presented in Appendix C.

4. Efficiency improvement with data centre monitoring based on building information modelling and computational fluid dynamics analysis

BIM can be used to solve data centre design issues. However, some problems arise during the transition to facility operation, such as the correct data export for FM, connecting real sensors with the model, and receiving data. These issues also affect the efficiency of data centre systems management. This section presents a new methodology for interconnecting BIM with real sensors in data centres, based on algorithm level.

The objective of this section is to enhance the operation of data centres during the FM stage. The issue at hand is that data centres are constructed using either computer-aided design (CAD) or BIM, and then a BMS is created separately for facility operation. As a result of this, there is a notable disconnection between the object design and the process of BMS creation. This section recommends designing directly in BIM and then using FM programs to combine the BIM model with BMS. This eliminates duplication of work and reduces the possibility of errors. Also, due to cooling system is affected to data centre efficiency, computational fluid analysis was applied for corridor isolation systems. The lower the load on it, the higher the energy efficiency.

Energy efficiency is improved by constantly controlling the temperature range in data centres. The approach of continuous temperature control is widespread and is a generally accepted standard of data centre operation.

Telecom cabinets housing IT equipment are located in the data centre. Constant cooling is required for this equipment. In order to prevent overheating, it is essential to provide cool air to the cabinet's front door and remove hot air from its rear. However, if there is no barrier between the two zones—cold and hot—the two flows can mix, reducing cooling and increasing the load on the air conditioning units.

To prevent hot and cold air from mixing, it is essential to construct an air containment system. The principle is as follows: the closed container stores the cooled air, preventing it from mixing with hot air and ensuring that high-load cabinets are adequately cooled. The air container should be located between two rows of cabinets or between a row of cabinets and a

room wall. All sides of the container separating the hot and cold zones must be separated by partitions so that cold air only passes through the IT equipment.

The energy consumption of IT equipment is directly related to the power requirements of the cooling fans. One can calculate the cooling power requirements of a data centre as per the rack inlet temperature. When the temperature rises, the IT equipment’s efficiency declines, and power consumption rises.

4.1. Power usage effectiveness of data centres

According to Green Grid, the power usage effectiveness (PUE) of a data centre is the ratio of the total energy used by the data centre to the energy consumed by the computing equipment [92]:

$$PUE = \frac{\text{Total power in the data centre}}{\text{Total power utilized by IT equipment in the data centre}} \tag{1}$$

The PUE ratio always produces a value greater than 1, with larger numbers indicating less efficient data centres. Data centre infrastructure efficiency (DCiE), the inverse of PUE, measures DCiE:

$$DCiE = \frac{1}{PUE} \tag{2}$$

The Table 4.1 shows the levels of efficiency with PUE and DCiE indicators [92].

PUE	Level of Efficiency	DCiE
3	Very inefficient	33%
2.5	Inefficient	40%
2	Average	50%
1.5	Efficient	67%
1.2	Very Efficient	83%

Table 4.1: Efficiency values of data centre [93].

Maintaining a constant control of temperature range and humidity in data centres can improve energy efficiency. The graph in Figure 4.1 shows

that power consumption increases significantly from an average of 27°C, depending on the environmental class of the data centre.

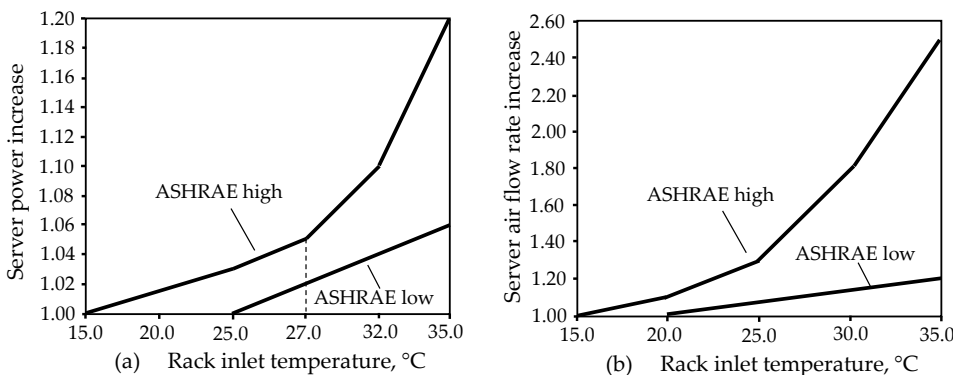


Figure 4.1: (a) ASHRAE Volume Server power increase vs. Inlet temperature and (b) ASHRAE Volume Server air flow rate increase vs. Inlet temperature [94].

The power demand of the fans used for cooling IT equipment is directly related to its energy consumption. The cooling power requirement of a data centre can be calculated based on the rack inlet temperature. When the temperature exceeds 27°C, there is a rapid growth in power consumption and reduced efficiency of IT equipment. In the range of 27-35°C, electricity consumption can increase up to 20%. Therefore, American society of heating, refrigerating and air-conditioning engineers (ASHRAE) recommends a temperature range of 18-27°C to maintain optimal efficiency and reduce energy consumption [95].

In terms of choosing a cooling system, one of the common solutions is a corridor containment system.

There are two basic options for installing a containerisation system in an existing engine room. The first is to isolate the cold aisle, and the second is to isolate the hot aisle. Each of these options has its own set of characteristics, advantages, and disadvantages. Figure 4.2 shows the basic principle of cold-aisle and hot-aisle containment systems (HACS) in a data centre.

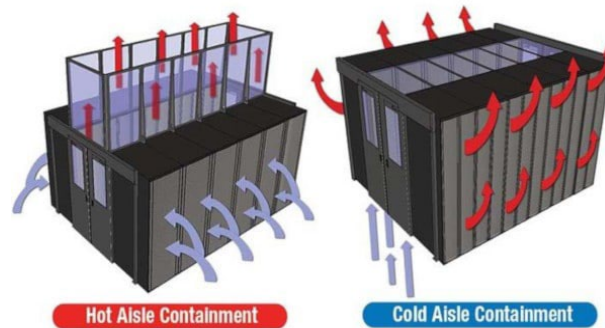


Figure 4.2: Cold-aisle and hot-aisle containment systems in a data centre [96,97].

Air cooling is presently the most widespread cooling system employed in data centres due to its ease of use and maintenance. Cold air is supplied to the data centre by CRAC units. These units have powerful fans that move large volumes of air. Servers are usually located in racks and have built-in fans that funnel air in from the front and hot air out from the rear. Depending on the direction of airflow in the room, various arrangements can be utilised. For instance, one can supply air from the underfloor space (plenum) through perforated tiles or from the ceiling in a suspended format. The assumption is that the hot air generated by the racks will be returned to the CRAC unaltered with the cold air supply to avoid thermodynamic inefficiencies.

Typically, racks are arranged in rows so that the rack inlets of adjacent rows face each other (likewise, the rack outlets of conjoined rows face each other) to create alternating (HACA). While this arrangement partially separates the hot and cold air paths, it is still possible for hot air to be drawn into the cold air stream or bypass the cold air directly. To more effectively reduce hot and cold air mixing, our study suggests a physical separation between the HACA. This separation can be achieved by either insulating the cold aisles or the hot aisles. Additionally, a return air duct configuration can be utilised to segregate the hot air emerging from each telecom cabinet and channel it into the return air duct. However, each approach has its benefits and drawbacks.

Continuous monitoring of data centres can result in significant energy savings by maintaining appropriate temperature and humidity ranges. For instance, to ensure the necessary reliability of data centre equipment,

airflow can be used to control temperature and humidity. As the temperature rises, equipment draws in a greater volume of cool air.

4.1.1. Comparison between HACS and CACS

Regardless of the type of system, there are still people who need to work in the machine room. According to ISO 7243 [98], or the occupational safety and health administration (OSHA), the values must not exceed the wet bulb temperature (WBT). The WBT is an index that measures the thermal stress experienced by people working which is defined in formula (3).

$$WBT=0.7 \times NWB + 0.3 \times GT, \quad (3)$$

where natural wet bulb temperature (NWB) is the natural WBT and GT is the temperature of the globe.

The maximum OSHA suggested WBT is 30°C for continuous work and 32°C for 25% work and 75% rest. Experience shows that most work is carried out in front of the IT racks. According to WBGT, CACS allows staff to work in a work-rest mode (25% work and 75% rest), rather than HACS. This allows equipment to be operated more efficiently within the racks [99].

The ASHRAE standards [95] recommend temperatures in the range of 18–27°C for Intel servers, but in the CACS, the temperature in most of these rooms can be higher than 27°C. It is also necessary to count the leakage. In the case of raised floors, this will be in the range of 25–50%, rather than 3–10% for containment systems. In addition, data centre rooms may contain non-rack-mounted equipment that can be affected by hot air.

In a typical data centre operating at 50% capacity, IT energy is the largest contributor to energy costs, followed by cooling system energy costs. Compared to CACS in a healthy 20°C working environment, HACS consumes 40% less cooling system energy. It is clear that HAC delivers significantly more economiser hours and a lower PUE than CAC under real-world work environment temperature constraints and temperature climates [99].

4.1.2 Cold-aisle containment system (CACS)

To supply cold air to the corridor, perforated plates are installed in front of the front door of the enclosure. The hot air is ‘discharged’ into the total volume of the room. To isolate the cold corridor, enclosure air handling units are positioned around the perimeter of the room, blowing the cold air stream under the raised floor. The enclosures are arranged in a row facing each other.

One disadvantage of CACS is that scaling issues may arise. For instance, uniformity of air supply to different rows may be problematic within several corridors. Furthermore, in the case of highly loaded equipment, it is challenging to increase the local supply of cold flow, as this requires the installation of additional perforated raised floor slabs. Additionally, personnel may find these working conditions less than optimal due to the fact that the entire room is in the hot zone. The specific design tasks are as follows:

- additional height allowance is needed to install the raised floor and additional space is needed to install a ramp at the entrance;
- as the container is insulated along the inner perimeter of the corridor, the racks need front insulation and a blanking plate for the rack at the front.

4.1.3 Hot-aisle containment system (HACS)

In the case of hot corridor insulation, inter-row air conditioners are used, blowing the cold flow into the total volume of the room. The cabinets are installed in rows. The backs of the cabinets face each other. The air handling units are installed in line with the cabinets to minimise the length of the air flow and increase the capacity of the cooling system. The hot air is discharged into a closed container and is then fed back into the air conditioning system. This approach is more practical for operational buildings, small data centres, and retrofits.

Advantages of HACS are that it is a reliable, high-performance solution that can be used with heavy-duty racks as well as in low-ceilinged spaces as it requires neither a raised floor nor an overhead plenum; second, its easy scalability as each aisle is independent; third, the comfortable staff presence in the room. The disadvantages are the high costs, as this option requires more air conditioners, as each container needs its own back-up

air conditioner; second, the inter-row air conditioning takes up space that could be used for server racks; third, the scaling difficulties: adding more air conditioners is only possible if additional connection points are provided in advance.

The design features are as follows:

- the room does not require additional height clearance;
- the enclosure itself is insulated around the perimeter of the corridor;
- the enclosures require front face insulation and a blanking plate as well as the insulation of all enclosure roofs;
- for the end cabinets in the corridor, the cabinet sides and plinth must be insulated along the outer perimeter.

4.1.4 Connection between real sensors and BIM

Temperature and humidity sensors in a data centre have unique parameters, including the temperature inlet and outlet of the rack, sensor identification number, and varying humidity parameters. Digital models of these sensors, complete with necessary parameters, are created and implemented using FM software in a real operating data centre equipped with real sensors. Data was collected from sensors during the operation of the data centres, enabling evaluation of the new methodology.

The process is described in Figure 4.3, which shows the connection between BIM and real sensors. The proposed method solves several problems, including the traditional connection to the BMS and the connection to the BIM operational model, improving the reliability of data exchange. If there is a problem with the connection between the FM program and the BIM model, the traditional BMS will continue to operate normally.

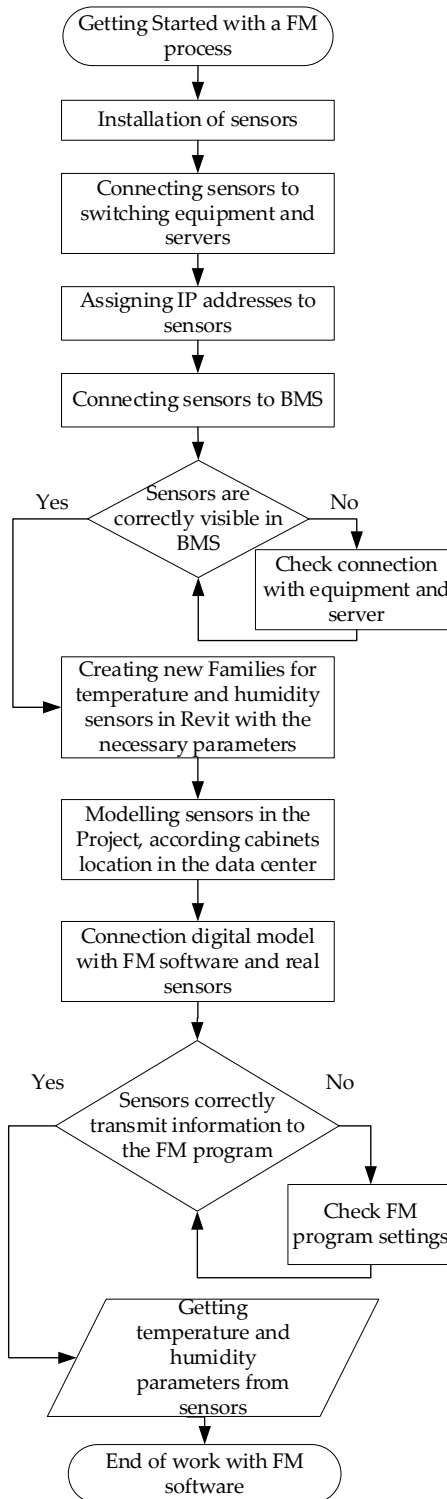


Figure 4.3: Connection process between BIM and real sensors using FM software [19].

4.2 Implementation BIM and CFD analysis for corridor isolation systems

There are many solutions from different manufacturers of corridor isolation systems, in particular, manufacturers are preparing families for building information models. The geometry is of great importance for the possibility of modelling airflow propagation in the future and the subsequent use of the model in the operation phase. Based on this information, we developed a family of corridors that can be conveniently used for various data centres: modular and large data centres with several dozens of machine rooms.

To verify the effectiveness of the corridor isolation system, a CFD model was developed for both cases of isolation: hot and cold corridors. CFD represents a logical and necessary extension of BIM design. BIM incorporates details of the structure including its architectural and engineering systems. This model is subsequently imported into the CFD software, which analyses the room geometry, establishes appropriate boundary and initial conditions, and computes three-dimensional temperature, velocity, pressure and additional physical parameters.

4.2.1 Main parameters of the investigated model and constraints

The numerical model includes a three-dimensional model of the investigated room with the required detail; the boundary conditions that consider the thermal conductivity of enclosures; detailed models of air distributors and heat sources with specified flow and thermal characteristics. As a result of numerical modelling, air temperature values were determined at each point of the room. Visualisation of the results of numerical simulation with the help of gradient distributions on different planes and isosurfaces, provided a complete picture of microclimate formation in the room and allowed us to clearly demonstrate the quality of the selected air distribution scheme as well qualitatively and quantitatively compare different variants of the design solutions.

Cooling of the racks in the server room was performed by the following method: air is blown by inter-row air conditioners into the cold or hot corridor space, moves directly into the IT racks under the pressure of IT equipment fans, and is removed from the isolated hot or cold corridor.

We took the following as the model input data:

- The room contained 15 telecommunication cabinets with IT equipment with dimensions of 600×1200×2000 mm. The heat load in each cabinet was 10 kW.
- Also, in the room, there was one UPS, with dimensions of 600×1200×2000 mm and a heat load of 8.5 kW.
- Cooling was provided by eight inter-row air conditioners with the following dimensions: 300×1200×2000 mm.

The geometric diagram in Figure 4.4 depicts the placement of the equipment.

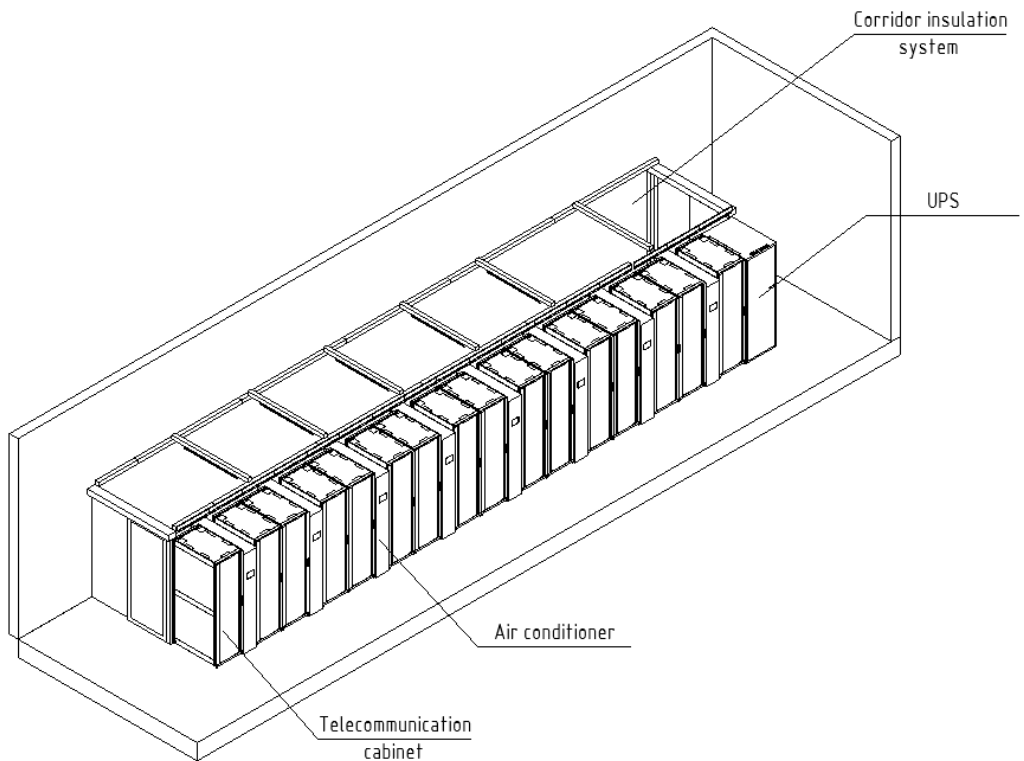


Figure 4.4: Information model of the data centre room [71].

For accurate calculations, it is necessary to set the material properties of the model elements. All architectural solid elements (walls, slabs, columns) will have the physical parameters of concrete material. The casing and plinth of the racks as well as the casing of precision air conditioners will have the properties of steel material. All of the other

geometrical elements were assumed to be air, with the following parameters mentioned in Tables 4.2 and 4.3.

Density	According to the Equation of State for Compressible Gasses
	Gas Constant: 287.05 J/kg·K
Coefficient of volumetric thermal expansion	3400 · 10 ⁻⁶ /°C
Dynamic viscosity	1.817 · 10 ⁻⁵ Pa·s
Specific heat capacity	1004 J/kg·K
Thermal conductivity	0.2563 W/m·K
Intel temperature (HAC)	36 °C
Outlet temperature (HAC)	22.5 °C
Intel temperature (CAC)	23 °C
Outlet temperature (CAC)	37.5 °C
Heat load (each rack)	10 kW
Total air consumption per rack	2150 m3/h

Table 4.2: Boundary conditions [71].

Accordingly, the main elements of the model have the following parameters:

Enclosures of Telecommunication Cabinets and Air Conditioners Made of Steel	
Thermal conductivity	0.55–0.52 W/cm·K (temperature range –0.15 °C to 99.85 °C)
Density	7833 kg/m3
Specific heat capacity	465 J/kg·K
Architectural elements of the server room made of concrete	
Thermal conductivity	1.1 W/m·K
Density	2306 kg/m3
Specific heat capacity	837 J/kg·K

Table 4.3: Main elements of the model parameters [71].

The minimum size of the tetrahedral element of the volume mesh was taken as 1 mm for the main elements of the model, which can provide the required accuracy in this research. Our study confirmed the findings of relevant sources on the choice of methods and settings for isolating corridors within a data centre, and we chose an automatic grid definition

using Autodesk CFD. Figure 4.5 demonstrates the meshing for the main elements of the model.

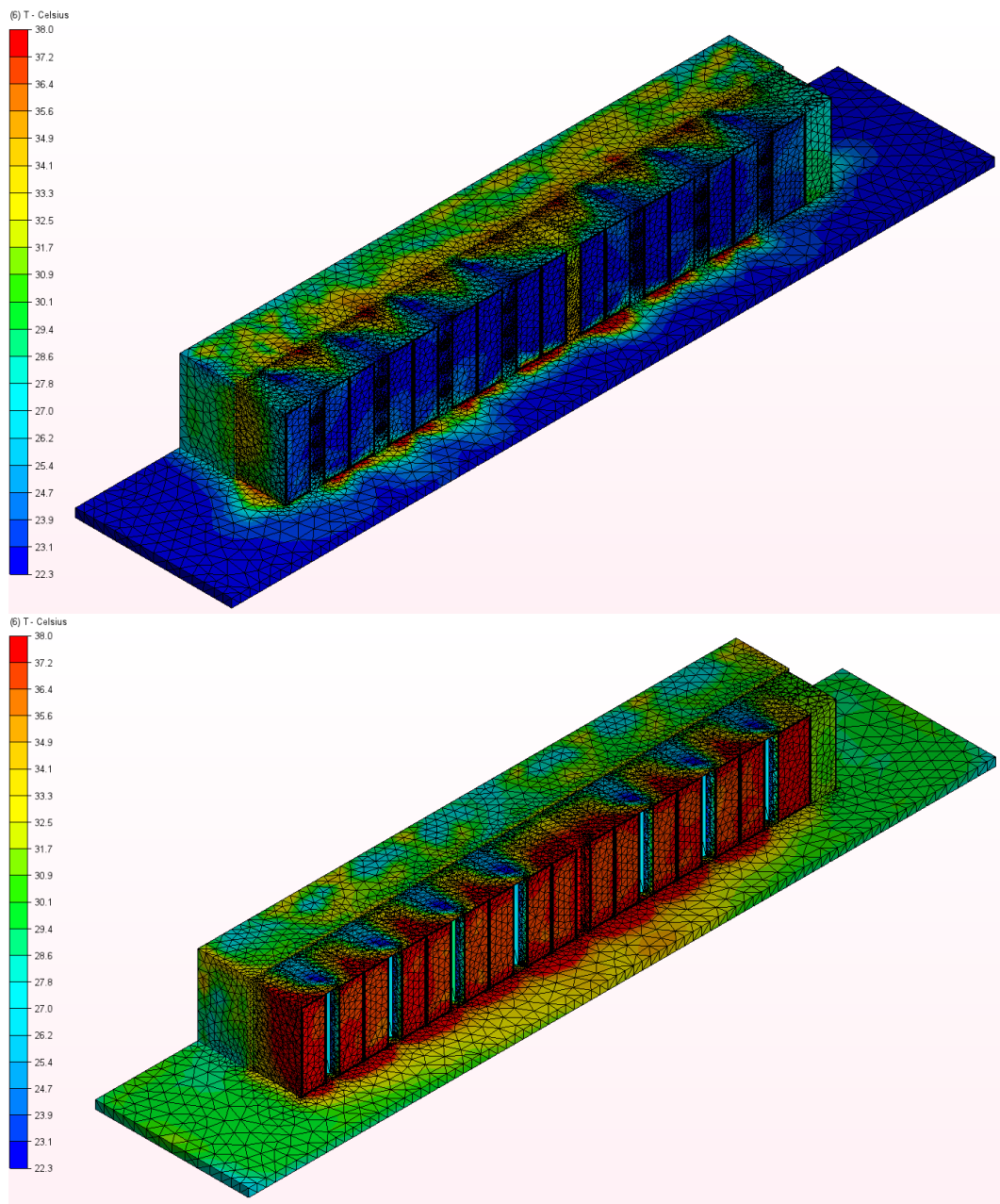


Figure 4.5: Meshing for the main elements of the model. Hot corridor is insulated on top, cold corridor on the bottom [71].

4.2.2 CFD modelling results

As a demonstration of the distinction between hot aisle insulation and cold aisle insulation, we illustrated the temperature analysis across various vertical and horizontal cross sections of a server room hall. Modelling was performed using AutoDesk CFD 2019.

To compare the temperature flows, vertical sections of the server room in the area of the second and ninth telecommunication cabinet were made, which are shown in Figures 4.6 and 4.7. The vertical section demonstrates that if the hot corridor is isolated, the area in the non-isolated zone will be in the region of 22.3–23.9°C. This temperature range is comfortable for the constant maintenance of equipment in the racks. In the case of cold corridor isolation, however, the temperature outside the isolated area could be as high as 38°C in some locations, which according to OSHA would cause engineers to pause their work.

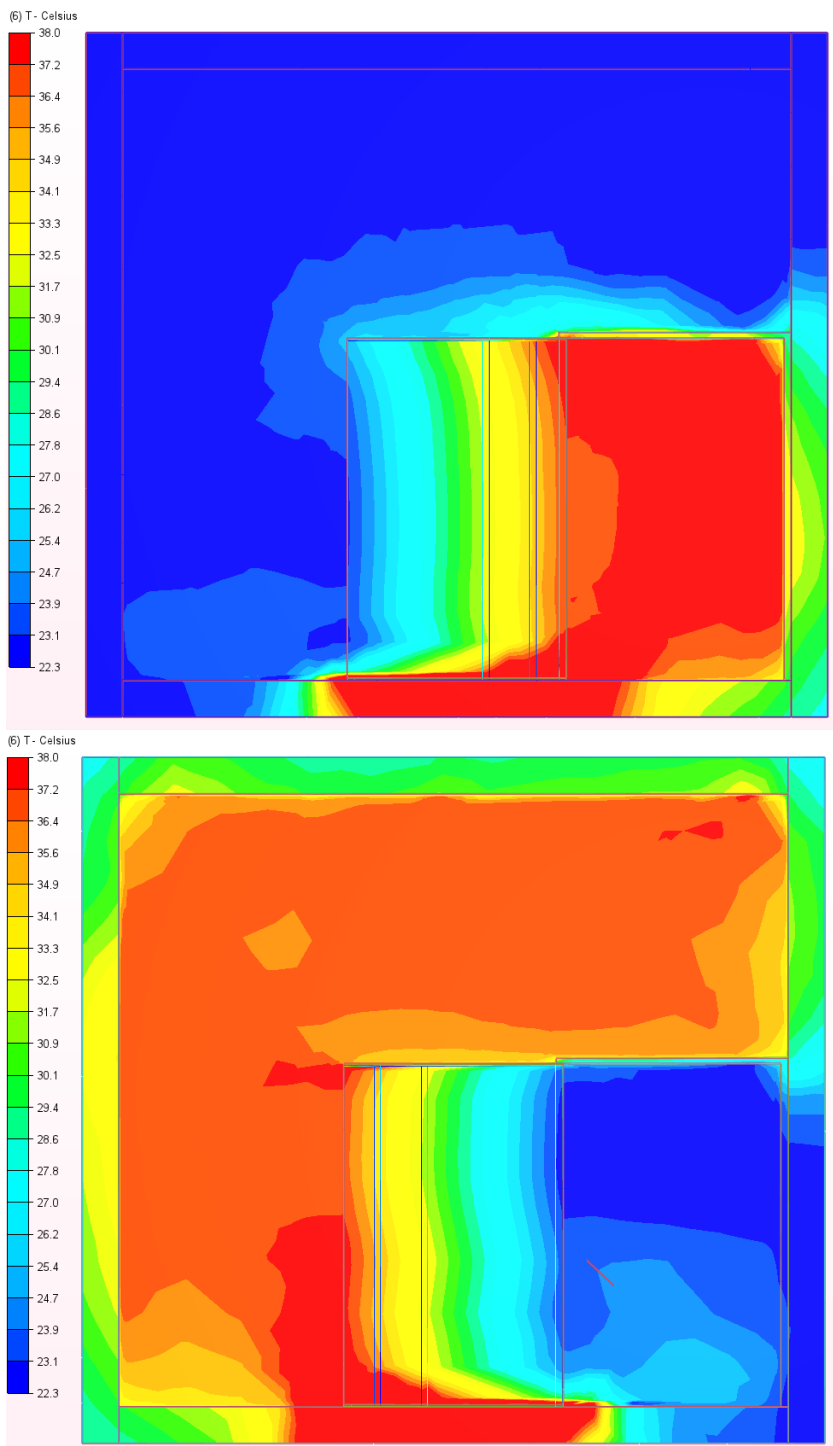


Figure 4.6: Temperature field of the cross section on the second rack. Hot corridor is insulated on top, cold corridor on the bottom [71].

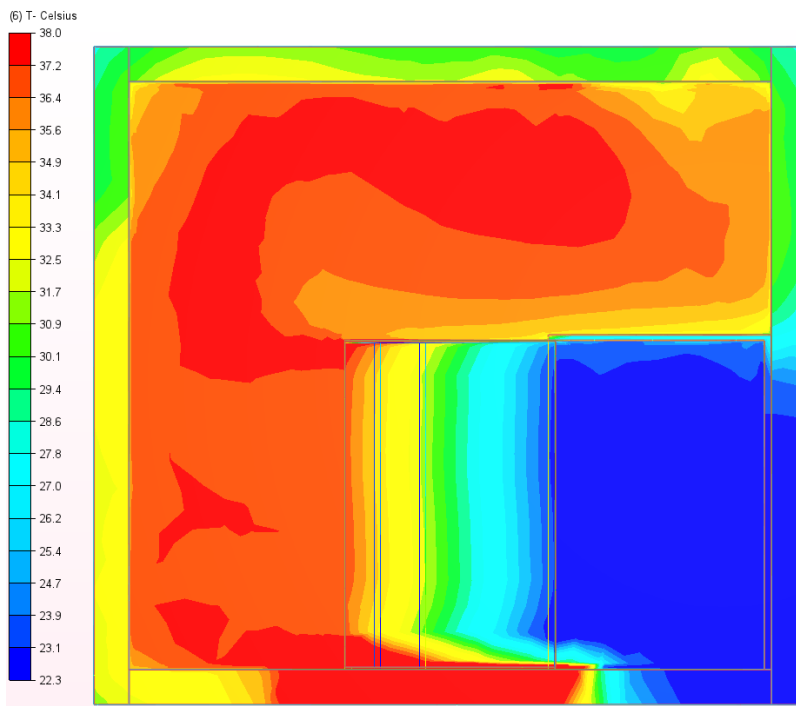
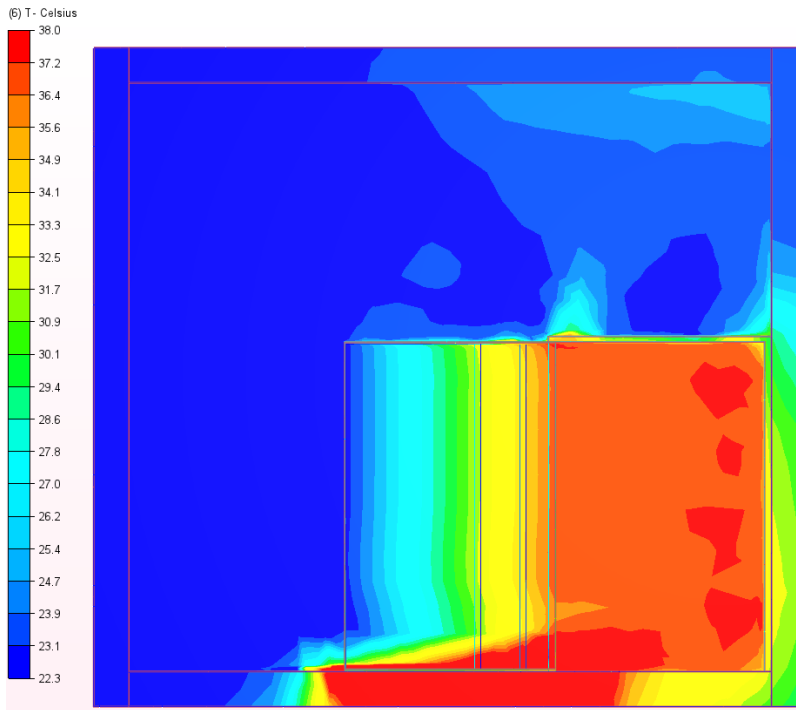


Figure 4.7: Temperature field of the cross section on the ninth rack. Hot corridor is insulated on top, cold corridor on the bottom [71].

In addition to the vertical sections, horizontal sections of the server room around the 21 Unit and 42 Unit telecom cabinets were made and are shown in Figures 4.8 and 4.9. Horizontal cross sections of the server room demonstrated that with hot corridor insulation, the temperature outside the insulated area was uniformly distributed in the range of 22.3–26.2°C. Alternatively, with cold corridor insulation, the highest temperatures outside the isolated area were concentrated in the rack area and reached up to 38°C.

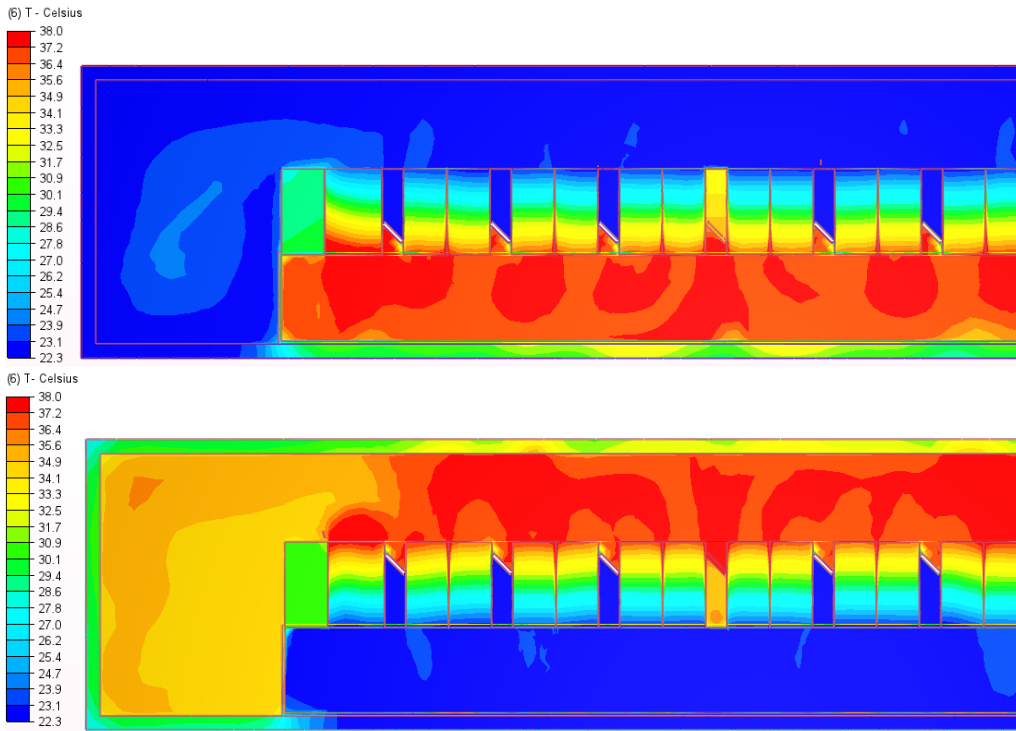


Figure 4.8: Temperature field of the cross section at the 21 Unit line. Hot corridor is insulated on top, cold corridor on the bottom [71].

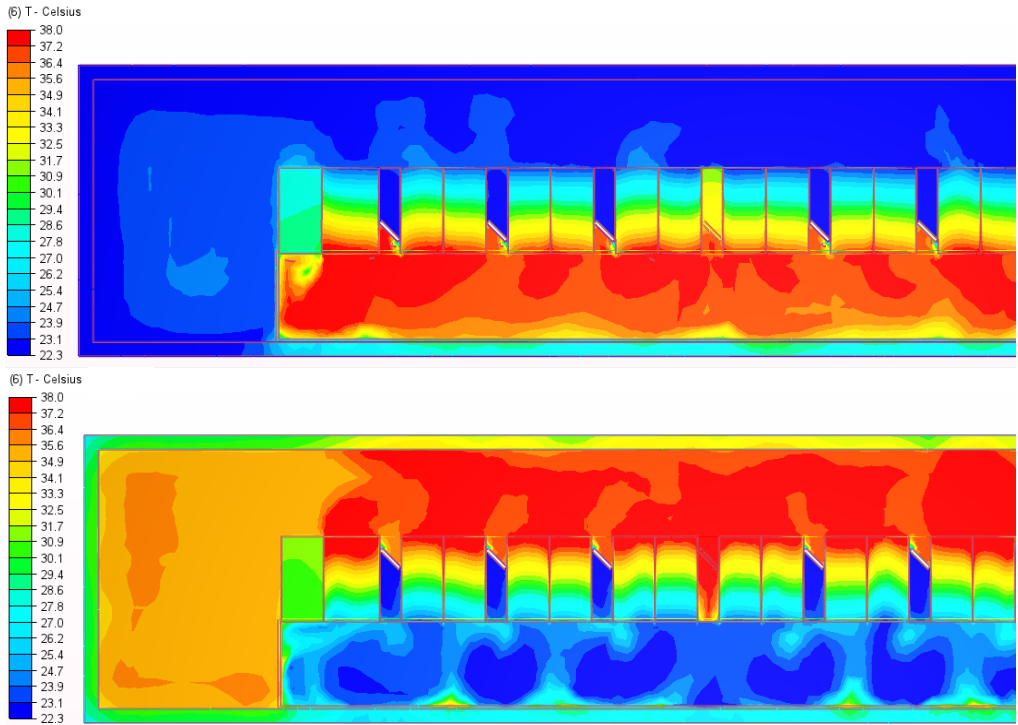


Figure 4.9: Temperature field of the cross section at the 42 Unit line. Hot corridor is insulated on top, cold corridor on the bottom [71].

The simulated outcome of the parametric experiments in CAC and HAC is presented in Figure 4.10, demonstrating the airflow velocity distribution passing through the rack while displaying the temperature and motion dynamics.

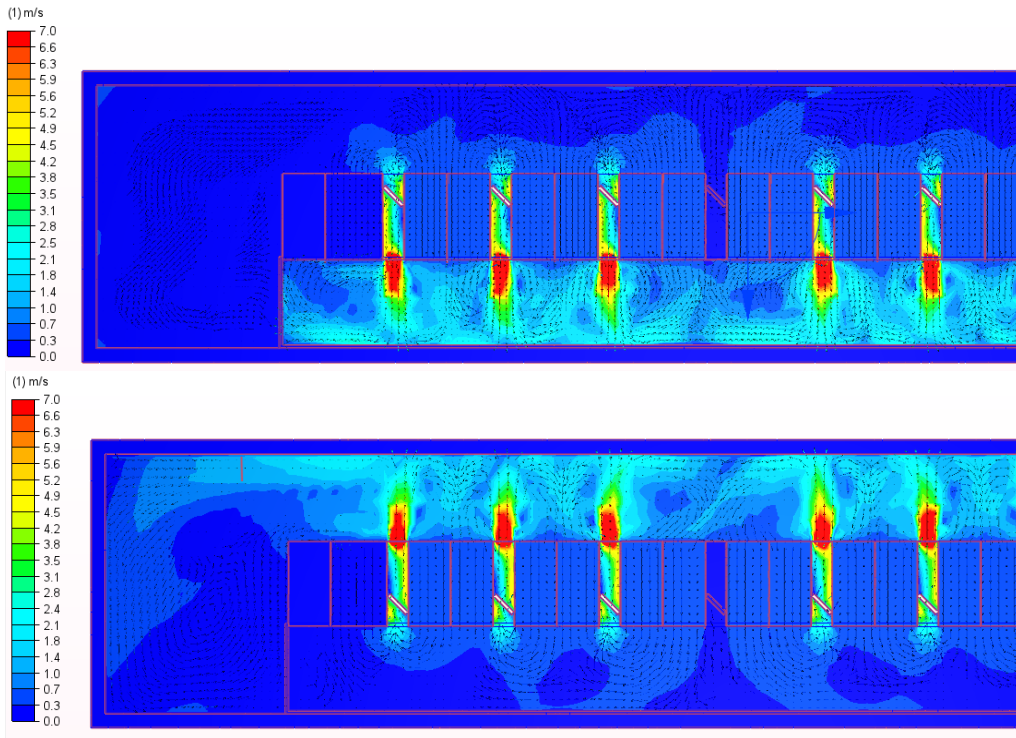


Figure 4.10: Parametric tests of the cross section at the 21 Unit line. Hot corridor is insulated on top, cold corridor on the bottom [71].

The current system parameters show the permissible numerical temperature values from the point of view of being able to provide the required temperature conditions for the operation of computing and engineering equipment.

Based on the above diagrams of temperature fields, we can conclude that when the hot corridor was isolated, the temperature inside the isolated area reached 38°C in some areas. At the same time, the temperature in the non-insulated area corresponded to a range of 22.3–27.8°C. In contrast, cold corridor insulation provided temperatures inside the insulated area of 22.3–23.9°C and outside the corridor in the range of 33 to 38°C.

The visual data presented in this section verifies that the temperature range within the racks at the air inlet does not exceed 27°C. This is significant as the temperature influences energy efficiency, as per [92]. As the air inlet temperature rises, the energy consumption increases, subsequently negatively impacting the energy efficiency.

According to TIA-942 [100], clause 5.3.5, there are recommended requirements of the machine room environment affecting the operation of the equipment in the data centre. These requirements are as follows:

- Psychrometer dry-bulb temperature: 20°C (68°F) to 25°C (68°F);
- relative humidity: 40% to 50%;
- dew point: not more than 21° C (69.8°F);
- rate of change: not more than 5°C (9°F) per hour;
- depending on local environmental conditions, dehumidification and humidification equipment may be required.

Ambient air temperature and humidity should be measured after the equipment has been started. Measurements should be taken 1.5m (5ft) above floor level at intervals of 3m to 6m (10ft to 30ft) along the axis of cold aisles and at any location where air is drawn by the operating equipment.

Temperature measurements should be taken at several locations near the air intake of any equipment with possible cooling problems.

4.3 Building management systems

A BMS in a data centre is usually linked to several installations, including the power supply, with equipment to monitor the condition of the distribution section, diesel generators and UPS; the air conditioning of the technical rooms; the automatic installation of gas firefighting equipment; and the general ventilation control. The BMS is a fully autonomous and functionally complete solution. The system comprises technological equipment, measuring and control instruments, and automation equipment.

A BMS consists of primary measuring sensors and actuators, with data collection modules located in local automation cabinets. The modules and sensors are connected by communication and data transmission channels. The BMS server collects data for further control using the operator's workstation.

4.3.1 Description of the main automation equipment

The main automation equipment comprises humidity and temperature sensors.

These sensors reflect the temperature and humidity indicators in the data centre premises. The recommended humidity parameters are in the range of 40-60%. Typically, data centre room temperature sensors are

mounted in potentially hot areas near each HVAC unit to monitor their operating status.

A network switch is a device that connects equipment to a computer network within one or more network segments. It operates at the link layer of the Open System Interconnection (OSI) network model.

A BMS server has been installed in the cabinets and data centre to collect data from sensor equipment. It has been integrated into the BMS data exchange network following the Ethernet standard.

The operator panel software is designed to organize local control and output information from sensors. In the event of a failure, the software provides control and visualization functions for presenting data.

4.3.2 Connecting sensors to the BMS

Temperature and humidity sensors are located alongside a digital-to-analogue converter and are connected to the controller using RJ-45 connectors. The controllers can communicate using Transmission control protocol (TCP)/Internet protocol (IP), Simple network management protocol (SNMP), and other protocols. The signals from the sensors are processed in the controller, recorded in the memory, and transferred to the server software via the IP network. Moreover, the BMS program's web application enables us to access data and establish thresholds.

Figure 4.11 illustrates the process of connecting sensors to the BMS system.

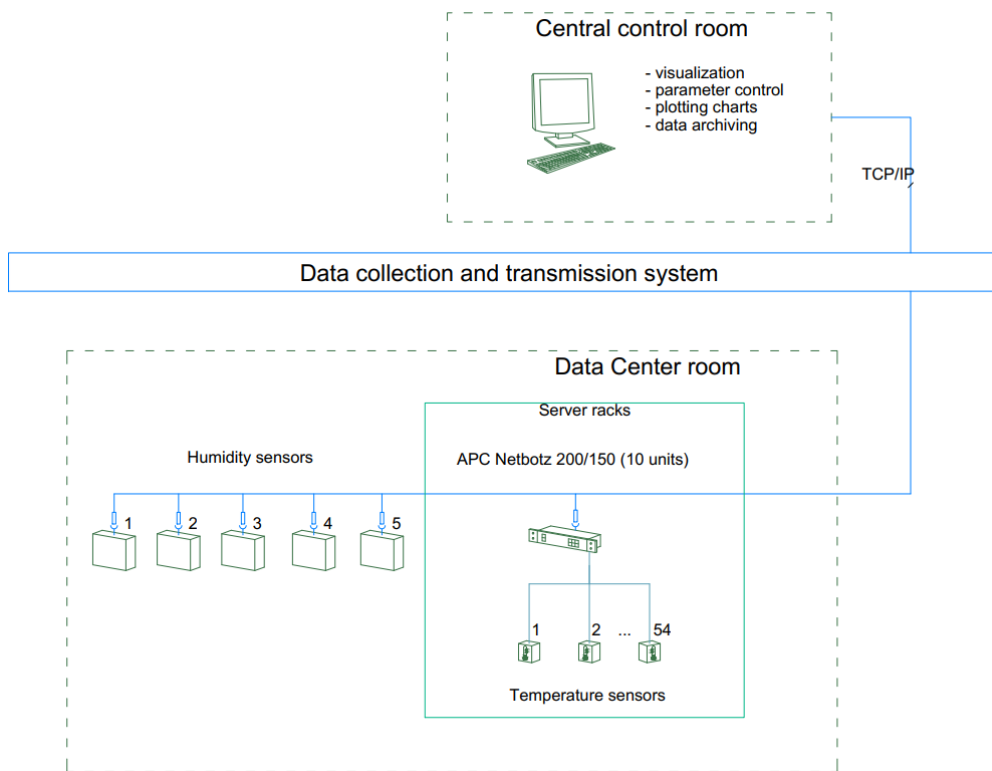


Figure 4.11: Connection of sensors to the BMS system [19].

Temperature and humidity sensors located in a data centre provided the data analysed in this study. These sensors were connected to controllers and expansion boards provided by article processing charges (APC). These sensors were connected to controllers and expansion boards provided by APC. In this study, we used a total of 10 controllers and expansion boards. Each controller or expansion board can accommodate up to 6 sensors.

4.4 Implementation BIM for FM

From the perspective of the BIM model, it is essential to include humidity and temperature sensors to accurately monitor the environment where the servers are located in real-time.

Using internal thermometers of equipment for data acquisition, which is common practice, has several disadvantages. The main disadvantage is that the temperature data only reflect the sensor installation point and do not show the real condition of the cabinet as a whole. Additionally, servers do not have humidity sensors, which are also crucial for the normal operation of a data centre.

Therefore, to ensure optimal data centre operation, a specific number of temperature and humidity sensors must be installed at designated locations. This leads to an optimisation problem for the sensor system, which can be studied using the proposed model.

It is recommended to use sensors with a cable connection to eliminate potential electromagnetic signal interference. For example, the use of Wi-Fi sensors is not recommended [16].

To link physical sensors to the model, it is essential to generate families of these sensors in Revit and choose the FM software.

4.4.1 Preparing new families according to the requirements of the proposed model and data export

To create the model families, temperature and humidity sensors were designed with the following parameters: Name, Manufacturer, Equipment code, Type, Brand, Unit of measurement, Inlet and outlet temperature or humidity, ID, Note, and sensor size. All of these characteristics are necessary during the operational stage. Additionally, they are automatically included in the specifications of new sensors created in Revit and exported to the FM model.

The proper organization of communication with BIM is crucial for the framework used in FM. Practical examples of using BIM for FM are provided in the following sections. [17].

The primary methods for exchanging information include transferring the model through IFC files and using XML or Construction operations building information exchange (COBie) properties of the model elements.

Another option is to manually create an FM model or use specialized software for direct data transfer.

In addition to the graphical component, the information component is a crucial element of families in Revit for FM. The transfer of data to the FM model remains an open issue, as it is dependent on the specific data exchange requirements of each facility.

Consequently, it is more efficient to directly transfer data to the program for FM. This method allows the transfer of both graphical information about objects and their properties. Furthermore, in the proposed methodology, the following functions from FM software have an important role:

1. Transfer the 3D model with all the necessary parameters to the software for FM.
2. Supplement the model with the necessary information: scans of drawings, datasheets.
3. Connecting of real sensors and elements of engineering systems to the program.
4. Indication and display of emergency situations, with the ability to identify the object in 3D.
5. Creation of scheduled maintenance schedules and assignment of responsible persons.

When implementing our model, EcoDomus software for our study purpose [101] was used, which provides the abovementioned functions. Communication between EcoDomus and BMS also allows us to display graphics from the equipment's sensors, providing access to relevant information to all building engineers. Communication between BMS and EcoDomus is facilitated through a web interface. EcoDomus receives the same data as the BMS system.

The location of temperature sensors in the data centre room illustrated in Figure 4.12.

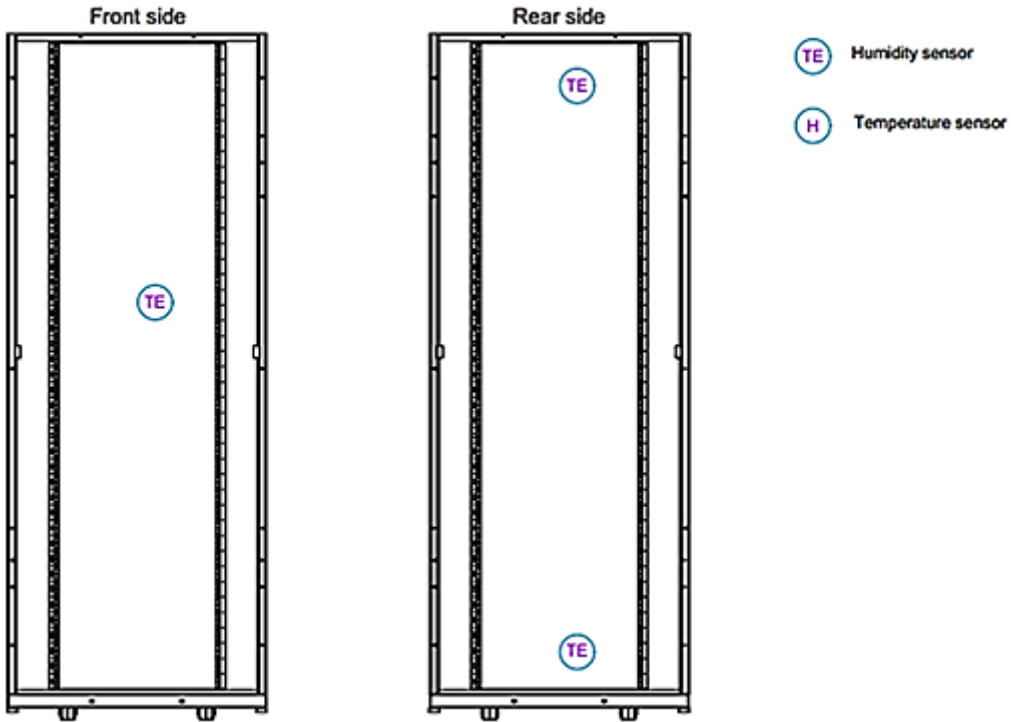


Figure 4.12: Location of temperature sensors in the data centre room in the racks [19].

4.5 Results and discussion

Improving the design and operation stages of data centres leads to increased facility efficiency. Crucial to operational efficiency is controlling the temperature and humidity distribution within data centres. Therefore, determining the optimal parameters of the temperature and humidity sensor system, including the number and position of sensors, is essential for improving efficiency. Optimization requires an appropriate data model, such as the one proposed in this section.

Our experience in implementing a data model in the 'CROC project' demonstrates significant time savings from the data centre's design stage to its operation. Compared to working with classical CAD and BMS systems, we achieve efficiency improvements in the design stage.

The following improvements were achieved in the case study: a 25% reduction in engineers' work time (from 80 to 60 man-hours), a 50% reduction in approval time with related systems (from 24 to 12 man-

hours), and a two-fold reduction in time for checking intersections during the design stage with other systems (from 32 to 16 man-hours).

The method presented in this section enables the detection of deviations from the required sensor parameters and immediate notification of the operator. Additionally, unlike the traditional BMS, changes in sensor position or the addition of new sensors are automatically replicated in the information model.

The results obtained during the monitoring of the sensors are reflected in Appendix D. From the obtained data, it can be said that the real data differs from the CFD analysis, this is due, among other things, to the use of different architecture and geometry of the corridors themselves. But the most significant factor is that there are leaks at the real facility, and it is not possible to completely isolate the corridor. In this regard, hot and cold air mixes. Another important aspect is that the sensors were installed only inside telecommunications cabinets.

The results of this section serve as the basis of the Thesis 3.

5 Application of the research results

As described in Section 1, the main components of a data centre include technical systems such as telecommunications cabinets and air conditioning units, systems for routing various cables, pipelines and air ducts, a temperature monitoring system, a system for cooling equipment and an UPS system.

The racks, the equipment inside them and the cables connecting the equipment are the key elements from an information systems point of view. To ensure correct operation, it is necessary to design the object without unnecessary intersections with other engineering systems, taking into account and correcting any emerging intersections. Effective cooling and monitoring of these parameters are also necessary. This creates the need to select the equipment cooling system correctly and simulate temperature parameters accurately.

As second part of research into optimising the design of cable routes and equipment inside telecommunication cabinets, the results were used to model the data centre of 'Compressor', CROC's company. The data centre is certified by the Uptime Institute at Tier III level, which corresponds to a fault tolerance ratio of 99.982%. The 'Compressor' data centre has a total area of 5000 square metres and can accommodate 800 racks, each with an average electric power of 6 kW. The total power supply capacity of the data centre is 8 MW.

The research on a new plugin for identifying and eliminating collisions between engineering systems was applied at a large private data centre. The data centre comprises several floors with telecommunication rooms and over 1000 racks. The research in cable routes and new families of racks from the previous part were also utilised in the design of this data centre.

The climate monitoring portion of the study was also tested in a private data centre. Models were created for 54 temperature sensors and 5 humidity sensors that were uniformly distributed throughout the room. The digital copies of the sensors were connected to real sensors located in 18 cabinets and zones in the actual data centre using FM software. This section of the study also pertains to CFD modelling. The input data for the model consisted of a room containing 15 telecommunication cabinets measuring 600×1200×2000 mm and a heat load of 10 kW in each cabinet.

The room contained one UPS measuring 600×1200×2000 mm and a heat load of 8.5 kW. Cooling was provided by eight inter-row air conditioners measuring 300×1200×2000 mm.

As demonstrated by the materials provided, our research has practical applications and are still utilized for designing and modelling tangible objects.

6 Summary

In this dissertation, we presented our research about the improvement methods for design and maintenance of data centres, based on BIM concept. We highlight the main contributions of this dissertation using four theses. First, we introduced our research and the theoretical background of the Structured cabling system in the Section 1. Also novel cabinets family and cable trays design methods was introduced in Section 2.

The new special purpose cabinet family enables automatic selection of required equipment and its location in the 'properties' section. This allows for unique filling of each cabinet, eliminating errors in facade diagram creation. All equipment is automatically included in the specification.

Thesis 1

Introduction of a novel systematic approach for design and identification of cable channels for a unified data centre cable infrastructure, allowing all cable channels elements to be automatically considered and specified.

I have developed a new-dynamic family of telecoms cabinets for server rooms and data centres, allowing for different internal equipment configurations and optimising documentation for subsequent operation.

The equipment location design inside cabinets and the element specification in the model of SCS was optimized with a new specific dynamic cabinet family based on algorithm level.

As a result, the novel family that was created and implemented in Revit, reduces the duration of the design phase and creates schemes up to three times faster in comparison with traditional CAD design.

The key features are the following: by adjusting the family parameters different sub-families can be selected within cabinet units, sub-families can be modified and added within the cabinet, the creation of a cabinet facade scheme is facilitated on the basis of the equipment inside, specifications are generated automatically.

The improved solution for organising cable ducts was found based on user level, making it possible to automate the process of modelling and accounting for all elements of cable trays.

Related publications:

Pogorelskiy S.; Kocsis I., Designing structured cabling systems documentation and model by using Building Information Modelling – Literature review, Annales Mathematicae et Informaticae (2024). DOI:

10.33039/ami.2024.02.005

Pogorelskiy S.; Kocsis I., Automation for structured cabling system in data centres using Building Information Modelling. International Review of Applied Sciences and Engineering 13.3 (2022), pp. 335–345. URL:<https://doi.org/10.1556/1848.2022.00424>

In Section 3, we described the plugin enables engineers from different systems to use it simultaneously, reduces the time required to search and display collisions by a factor of ten, speeds up the process of generating reports on system intersections, and allows tracking of the history of changes to each individual collision.

The aim of this section was to identify the main issues that arise when working on the intersections of engineering systems in the BIM model and developing a plugin.

Thesis 2

I developed a solution that allows to effectively track and visualise collisions based on BIM where different engineering systems intersect during the design phase, also allowing to reduce irrelevant collisions.

The efficiency of the collision reduction process was improved using a new approach in plug-in design.

The C#-based novel plug-in was developed based on code level, and has been tested in a real-life project eliminates intersections with engineering systems in data centre models. It has significantly reduced the time needed to search for a single collision, as the conditional number of clicks needed to fix a collision has been reduced by 100 times. Collaborative fixing of collisions is enabled within the same model that saves extra work and communication. At the algorithm level, a unified database allows for easy tracking and reporting of each collision.

Related publications:

Pogorelskiy S.; Kocsis I., BIM based collision tracking at the intersections of different building engineering systems at the design stage, International Review of Applied Sciences and Engineering 1-11 (2024). URL:<https://doi.org/10.1556/1848.2024.00833>

In Section 4, we to demonstrate the concept of a direct connection of BIM from design to operation of a data centre providing a practical example of a temperature and humidity monitoring system.

Improving the design and operation stages of data centres leads to increased efficiency and significant cost savings. Crucial to operational efficiency is controlling the temperature and humidity distribution inside data centres. Therefore, finding the better parameters for the temperature and humidity sensor system, including the number and position of sensors, is essential for efficiency improvement.

In this case we introduced a solution through the utilization of both CFD analysis and BIM during the design and CFD stages. The conclusions drawn support the necessity of investigating BIM and CFD in tandem.

The objective of this research part was to undertake a comprehensive literature review of corridor isolation systems and analysed the use of corridor isolation and identified the optimal method.

To determine the method, I carried out BIM of the server room and analysed the required elements, materials, and geometry. Also was used hydrodynamic modelling to identify the distribution of temperature flows. The CFD provides a reliable model that simulates real data centre scenarios.

As a demonstration of the differences between hot- and cold-aisle insulation, was analysed the temperature in various vertical and horizontal segments of the server room hall.

Thesis 3

I combined a BMS in a data centre with a real-time BIM model to improve its operability. The utilisation of CFD modelling and the identification of an enhanced cooling methodology for data centre equipment has facilitated the optimisation of cooling efficiency for equipment within cabinets, thereby enhancing their operational efficacy.

The communication between real sensors and BIM was improved with a new approach, based on algorithm level.

The direct connection and communication between BMS and EcoDomus were facilitated through a web interface.

As a part of the new solution, relevant information is visualized through graphics about the equipment's sensors to support all building engineers.

The methodology was tested with 54 temperature sensors and 5 humidity sensors where the digital copies of the sensors were connected to the facility management software.

The proposed method enables the detection of deviations from sensor parameters and immediate notification of the operator. In contrast to the classical BMS, changes in the position of the sensors or the addition of new sensors are automatically duplicated in the information model.

Also, CFD model was established to simulate real data centre scenarios, by analysing the required elements, materials, and geometry of a BIM model of a server room and conducting hydrodynamic modelling to identify temperature flows. The contrast between hot-aisle and cold-aisle insulation was analysed through a temperature analysis of various vertical and horizontal cross-sections of a server room.

Related publications:

Pogorelskiy S.; Kocsis I., Efficiency improvement with data centre monitoring based on building information modelling on the facility management stage, *Designs* 7 (2023) 3:1–3:15. URL: <https://doi.org/10.3390/designs7010003>.

Pogorelskiy S.; Kocsis I., BIM and Computational Fluid Dynamics Analysis for Thermal Management Improvement in Data Centres, *Buildings* 13(10) (2023). DOI: 10.3390/buildings13102636.doi:10.3390/designs7010003.

Finally, in Section 5 we presented possible applications of our main research results. The creation of various add-ons and plug-ins for BIM modelling of technically complex objects such as data centres is an important scientific and engineering experience on the basis of which the

performance at all stages of the model's life can be significantly optimised. Also, an important feature of our research is that it was tested on real objects and in case of additional real requests from engineers, we made the necessary adjustments and additions.

Abbreviations

3D	3-dimensional
4D	4-dimensional
ACCA	The Association of Chartered Certified Accountants
AECO	Architecture, engineering, construction and owner-operated
AHP	Analytic hierarchy process
APC	Article processing charges
ASHRAE	American society of heating, refrigerating and air-conditioning engineers
BIM	Building information modelling
BMS	Building management system
BVH	Boundary volume hierarchy
CAC	Cold-aisle containment
CACS	Cold-aisle containment system
CAD	Computer-aided design
CFD	Computational fluid dynamic
COBie	Construction operations building information exchange
CRAC	Computer room air conditioning
DCiE	Data centre infrastructure efficiency
FM	Facility management
HAC	Hot-aisle containment
HACA	Hot and cold aisles
HACS	Hot-aisle containment system
HTML	Hypertext markup language
HVAC	Heating, ventilation and air conditioning systems
ICT	Information and communication technology
IFC	Industry foundation classes
IP	Internet protocol
ID	Identifier
IT	Information technology
ML	Machine learning
MEP	Mechanical, electrical and plumbing
NWB	Natural wet bulb temperature
OSHA	Occupational safety and health administration
OSI	Open System Interconnection
PDU	Power distribution units
PIM	Performance indication model
PUE	Power usage effectiveness
SNMP	Simple network management protocol

SCS	Structured cabling systems
TCP	Transmission control protocol
UPS	Uninterruptible power supply
XML	eXtensible markup language
WBT	Wet bulb temperature
WSN	Wireless sensor networks

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A. List of relevant publications

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B. Appendixes

Appendix A

Table A1. Headings of the main database tables for télécommunication cabinets [15]

Component	Patch panel (Optical cassettes/adapters or cooper cassettes/adapters); Cable organizer; Switch; Reserve panel; Blank panel; Special telecommunication equipment
Code	A unique number identifying a specific family or object in a model
Code type	Identification number of the family type, for example, all optical panels in which cassettes are built have their own number, those in which optical adapters are built have a different number
Location	Closely related to cabinet marking and identifies the location of equipment in the cabinet.
Unit	Identifies a specific unit in the cabinet
Panel's name	Unique identifier of the panel name
Level	Relative elevation of a floor or building in a model
Mark	Unique marking of an element in a model
Position	Characterizes the type of object, closely related to the type code

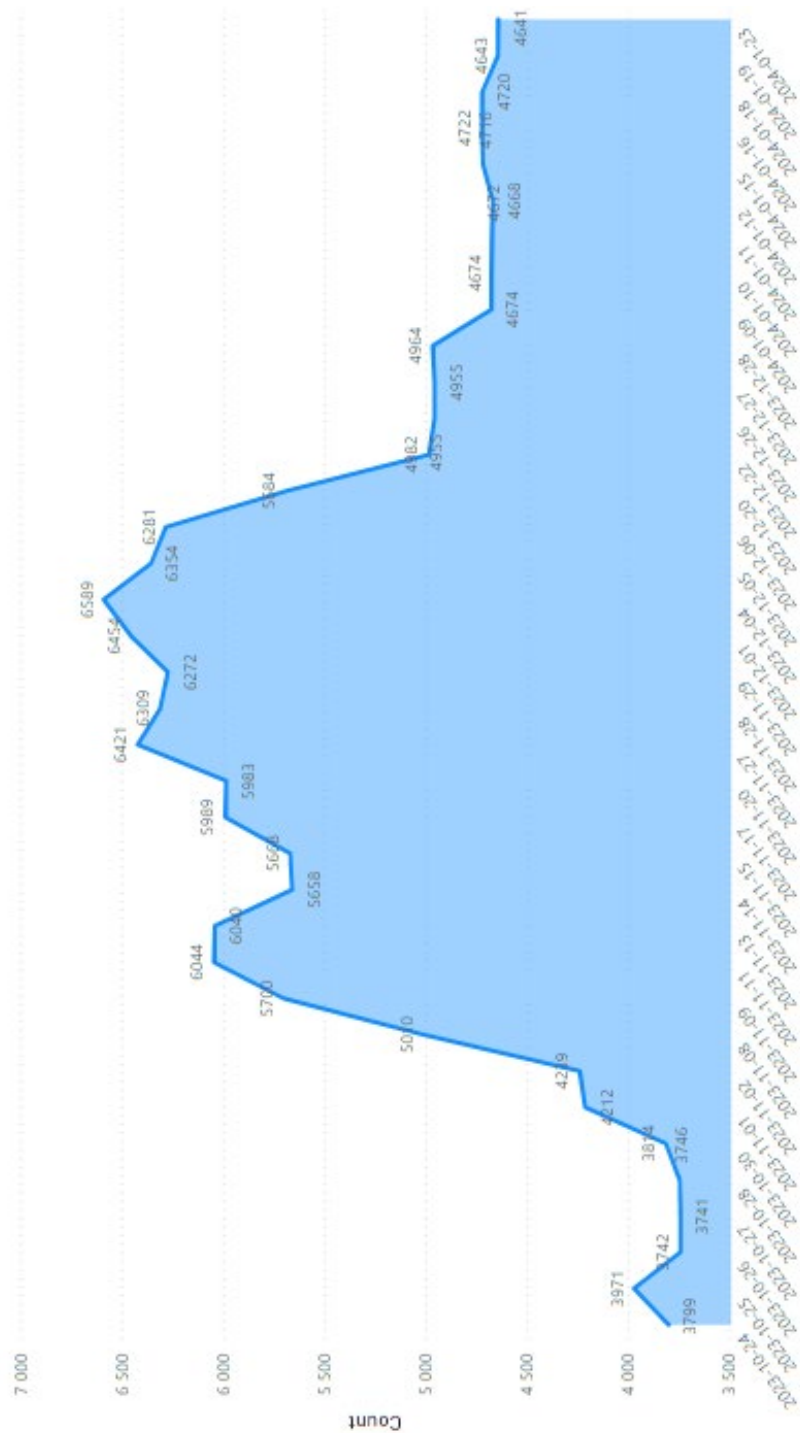
Appendix B

Table B1. Example of cable conduits specification [15]

№	Name	Type, brand	Item code	Manufacturer	Unit rev.	Number	Weight, kg	Packaging
	Cable trays							
1	Non-perforated tray LN series 50x50x2500	ЛНМТЗ(М)-50x50пп	012551	OSTEC	Meter	97,5	0,77	30
	Details							
2	Mounting profile PP100	ПП100	051901	OSTEC	meter	16	0,5	60
3	Swivel bar for tray height 50	ППС	040351	OSTEC	unit	8	0,04	100
4	Changeable universal tray connector for a tray with a height of 50	СЛУИ-50	032851	OSTEC	unit	6	0,06	150
	Fasteners							
5	Split anchor M8x30 (brass)	А3М830А	063089	OSTEC	unit	186	0,013	100
6	Semi-cylindrical head screw DIN 7985 M6x10	ВМ6x10	066109	OSTEC	unit	56	0,005	500
7	Nut with lock collar DIN 6923 M6	ГМ6СВ	067609	OSTEC	unit	56	0,003	500
8	Nut with lock collar DIN 6923 M8	ГМ8СВ	067809	OSTEC	unit	372	0,007	250
9	Connecting nut DIN 6334 M8x28	ГСМ8	069089	OSTEC	unit	54	0,04	100
10	Threaded rod DIN 975 M8x2000	ШП8-2	064829	OSTEC	unit	213	0,6	25

Appendix C

Figure C1. Clashes for engineering systems [91]



Appendix D

Table D1. Average temperature data from the sensors used in the case study [19].

Temperature Sensors			
	Rear Side	Rear Side	Front Side
Cabinet 1	TS 1.1	TS 1.2	TS 1.3
	23.18 °C	23.60 °C	18.54 °C
Cabinet 2	TS 2.1	TS 2.2	TS 2.3
	22.99 °C	23.33 °C	19.00 °C
Cabinet 3	TS 3.1	TS 3.2	TS 3.3
	22.53 °C	23.18 °C	19.04 °C
Cabinet 4	TS 4.1	TS 4.2	TS 4.3
	22.76 °C	23.72 °C	19.31 °C
Cabinet 5	TS 5.1	TS 5.2	TS 5.3
	22.68 °C	22.38 °C	18.93 °C
Cabinet 6	TS 6.1	TS 6.2	TS 6.3
	22.95 °C	23.75 °C	19.04 °C
Cabinet 7	TS 7.1	TS 7.2	TS 7.3
	23.68 °C	22.72 °C	19.50 °C
Cabinet 8	TS 8.1	TS 8.2	TS 8.3
	23.45 °C	22.41 °C	19.16 °C
Cabinet 9	TS 9.1	TS 9.2	TS 9.3
	23.45 °C	22.91 °C	19.20 °C
Cabinet 10	TS 10.1	TS 10.2	TS 10.3
	23.72 °C	23.37 °C	19.50 °C
Cabinet 11	TS 11.1	TS 11.2	TS 11.3
	23.07 °C	23.22 °C	19.31 °C
Cabinet 12	TS 12.1	TS 12.2	TS 12.3
	22.53 °C	23.83 °C	19.31 °C
Cabinet 13	TS 13.1	TS 13.2	TS 13.3
	23.49 °C	23.33 °C	19.27 °C
Cabinet 14	TS 14.1	TS 14.2	TS 14.3
	21.72 °C	23.26 °C	19.04 °C
Cabinet 15	TS 15.1	TS 15.2	TS 15.3
	22.22 °C	22.64 °C	19.08 °C
Cabinet 16	TS 16.1	TS 16.2	TS 16.3
	21.84 °C	24.64 °C	19.16 °C
Cabinet 17	TS 17.1	TS 17.2	TS 17.3
	23.49 °C	22.61 °C	19.04 °C
Cabinet 18	TS 18.1	TS 18.2	TS 18.3
	22.57 °C	22.91 °C	18.93 °C

Table D2. Average humidity data from the sensors used in the case study [19].

Humidity Sensors				
HS 1	HS 2	HS 3	HS 4	HS 5
35.19%	34.70%	36.89%	35.15%	35.36%