research has been done within the building sector. The multi-dimensional nature of analysis in both spatio-temporal dimensions is relevant to facility maintenance. While the emphasis is less on planning and more on maintenance and operations, the complexity of the multi-dimensional visual analytical tasks is similar to GIS research. Andrienko et al. (2010) described the issues associated with focusing too heavily on either spatial or temporal dimensions in visual analysis of spatio-temporal problems. Given the building industries heavily dependence on these multi-dimensional problems, new ways of focusing on both temporal and spatial constraints and patterns can help maintenance and operations of buildings as well as present new ways for all occupants to engage in the data involved in buildings.

Examples of temporal visualization of BMS data. Temporal data visualization is not new in BMS. Some examples of temporal data visualization include: Watt's watt web interface, featuring social networking affordances (Gulbinas et al. 2014); Pulse Energy's Energy Management Software, used by many university campuses; KGS' Clockworks™ software, including an automated analytic and fault detection system; as well as many others. Some of these example applications have the ability to obtain a spatial location of the building, but not of the sensor locations. These systems tend to focus on the energy consumption data in aggregate (building level) and sub metering form.

Examples of spatio-temporal visualization of BIM data. Virtanen et al. (2016) used several open standards to integrate point cloud models in a virtual world with sensor data. The types of data visualized were spatial and temporal, however the integration of the spatial and temporal natures of the various data sources was not explored. The simple prototype was focused on exploring a networked example virtually available on the internet. While an interesting case study in linking point cloud data with sensor data, the prototype didn't address building level, large scale implementation, or trend data display. In another recent example, Shin et al. (2014) developed a mapping system between floorplan data and a sensor grid system. The focus of this implementation was on visualizing temperature grid information in a single room. The example integrated the spatial aspect of temperature data, but did not integrate time into the visualization. Different time points were accessible in the dataset, and visualization occurred of the hourly temperature changes. A limitation of this visualization approach was the static nature of the visual analysis provided by the application. The option to view the data in an exploratory fashion was also not implemented. Both examples explored various aspects of the spatial nature of sensor data in a 3D or semi-3D manner, however the proximal information and analytical information was not present for users to explore in more depth the adjacencies and interactions between similar sensor data. This work tries to address the spatio-temporal nature of proximal interaction and information by integrating a 3D visualization approach.

DEVELOPMENT METHODOLOGY

The methodology started with a review of current practices in building management systems to understand operations visualization of sensor data. Next, the researchers developed scenarios for development purposes in order to understand the end-users (e.g., building occupants) and their system usage requirements. A prototype was then developed to explore 3D visualization of sensor data information. In the development process, several software packages were used to aid the prototype creation.

Prototype development. A case study was identified for prototype development where a BIM model existed and sensor data was available of an operational higher education facility. The building had a mix of uses typical in educational facilities (offices, classrooms, and computer rooms). To develop the visualization system, the use case requirements and scenarios were combined. The target group was the end-users and the target scenario was access to data related to their comfort. End-users were determined to be the focus of the prototype because they present a new user type and have a more varied understand of building maintenance and management. Further development will investigate the linkage between operators and building occupants.

Personas and Scenarios. The use of both personas and scenarios have been shown to be effective initial brainstorming methods for user experience (UX) and interactive design (Pruitt and Grudin 2003; Silva et al. 2011). Two personas and five scenarios were developed as potential users and circumstances of system usage. Of those developed, for the initial prototype, one persona and scenario was the main focus for the current development, with the others left as future development areas. Personas and scenarios were developed with a PACT analysis of the people, activities, context, technology, with a scenario description (Benyon et al. 2005).

Development workflow. The development process started with using the building information model from an open standard and using common engineering software to export schedules and model content for use in the prototype. A video game engine was chosen to be used in development of the prototype for quick mocking up, ease of display features, and ease of adding interaction elements with real-time rendered model content. Schedules of data values were exported for use in the model, with the capability to further make the application workflow easier with use of a database connection. Sensor data was collected for three rooms (one office, one classroom and one computer room) in an occupied higher educational building. For the prototype, building information model data and sensor data was used in CSV format. Previous work had identified space geometry as one of the important elements not easily transferred through commonly used standards and usually is redrawn manually (McCaffrey et al. 2015), thus development focused on automating room information export using IFC standards to utilize room geometry.

Software. The software used in the development process along with usage description is documented in Table 1.

Table 1. Software usage table.

Software(v)	*Input Format(s)*	*Output Format*	*Description*
ArchiCAD (19)	IFC 2x3 STEP	CSV	Building room, home floor, space information
Revit (2016)	IFC 2x3 STEP	FBX	Building geometry with unique identifying name
IFC Convert (0.5.0)	IFC 2x3 STEP	DAE	Export space geometry
3D Studio Max (2016)	FBX	FBX	Address geometry complexity and material texture control
Unity (5.3.5f1)	DAE, FBX, CSV	WebGL	Imported geometry, data, logic, and interaction into web viewable prototype

Output system. From reviewing the literature and developing the personas and scenarios the user interface required the following functional attributes: a menu for filtering options, a 3D view, interactive charts view of data, intuitive interface for usability, and easy access to different degrees of detail.

PROTOTYPE DEVELOPMENT RESULTS

Using the methodology described above, a persona and scenario were selected for prototype development. Two personas were developed; one for the operations management and one for the building occupants (in this case staff and faculty in an educational facility). The building occupants were selected as the focused persona so as to create a new visualization system which is easily understood by occupants who may be unfamiliar with operations systems and data, but who have an interest in the functioning of those systems (e.g. ensuring their office is warm enough, sending work orders if a classroom is constantly cold). The five scenarios developed were (1) general end-user accessing environmental conditions from visualization tool; (2) administrator accessing environmental conditions from visualization tool; (3) end-user exploratory data analysis of spatial and temporal data; (4) maintenance personnel exploratory data analysis of spatial and temporal data; and (5) logging environmental issues with maintenance personnel. The scenario selected for prototype development was the first scenario, with the requirements of the later four scenarios as future directions for prototype development. The data focus for occupants was the sensor data associated with occupant comfort. For the prototype, temperature, air flow, and humidity were available in the building dataset. Other data types for building comfort, such as metabolic rates, user clothing, and surface materials were not added in this prototype because that data was not sensor driven or not available. The prototype was developed to display building, floor, and room level data, with surrounding and detailed building geometry for context.

System building level view. A user, upon entering the system, starts in their building view (Figure 1a). From the building view, a user can select a floor of the building and can toggle building geometry. The space geometry is linked to the temperature of the room and ranges in color between a comfort temperature range. Development occurred in a winter climate with a test set of one week of data from several rooms in a currently operational education facility. The typical comfort temperature range for winter conditions is between 20ºC-25ºC (68ºF-77ºF), depending on the relative humidity (ASHRAE 2010; Canadian Standards Association 2011) and was set as a scaled color value. Red indicates the temperature of the space was outside of the acceptable range.

System floor level view. In order to view the functioning of an entire floor, a floor view of the building was implemented (Figure 1b). In the floor level view, users can investigate the relationship between a specific data type and its proximal relationship to various sensors. For demonstration purposes, temperature was chosen to display the relationship between the various rooms. In the example shown, the third floor is displayed, with four rooms displaying sensor data. One can easily see that only one room is red, or out of range of comfort.

System room level view. A specific room can be explored in more detail. In the room view, the sensors and their locations are shown (Figure 1c). Building geometry can be turned on to view floors, doors, windows, and ceilings (Figure 1d). The room view is where the user can access information about all sensors located in the space of interest. In Figure 1e, the example shows air flow (on or off status), temperature sensor (color of the room), and CO^2 reading (text output of ppm). Using the view graph toggle button, a user can view specific sensor data. A graph of the sensor data over the course of 6 days is shown in Figure 1e. The user can query the dataset to view the most recent day or period of data points (Figure 1f). The red lines indicate 20ºC (68ºF) and 25ºC (77ºF) maximum and minimum temperature settings, where the green line indicated 23ºC (73.4ºF), or the set point for the room. From the graph, a user can explore the temporal nature of the data.

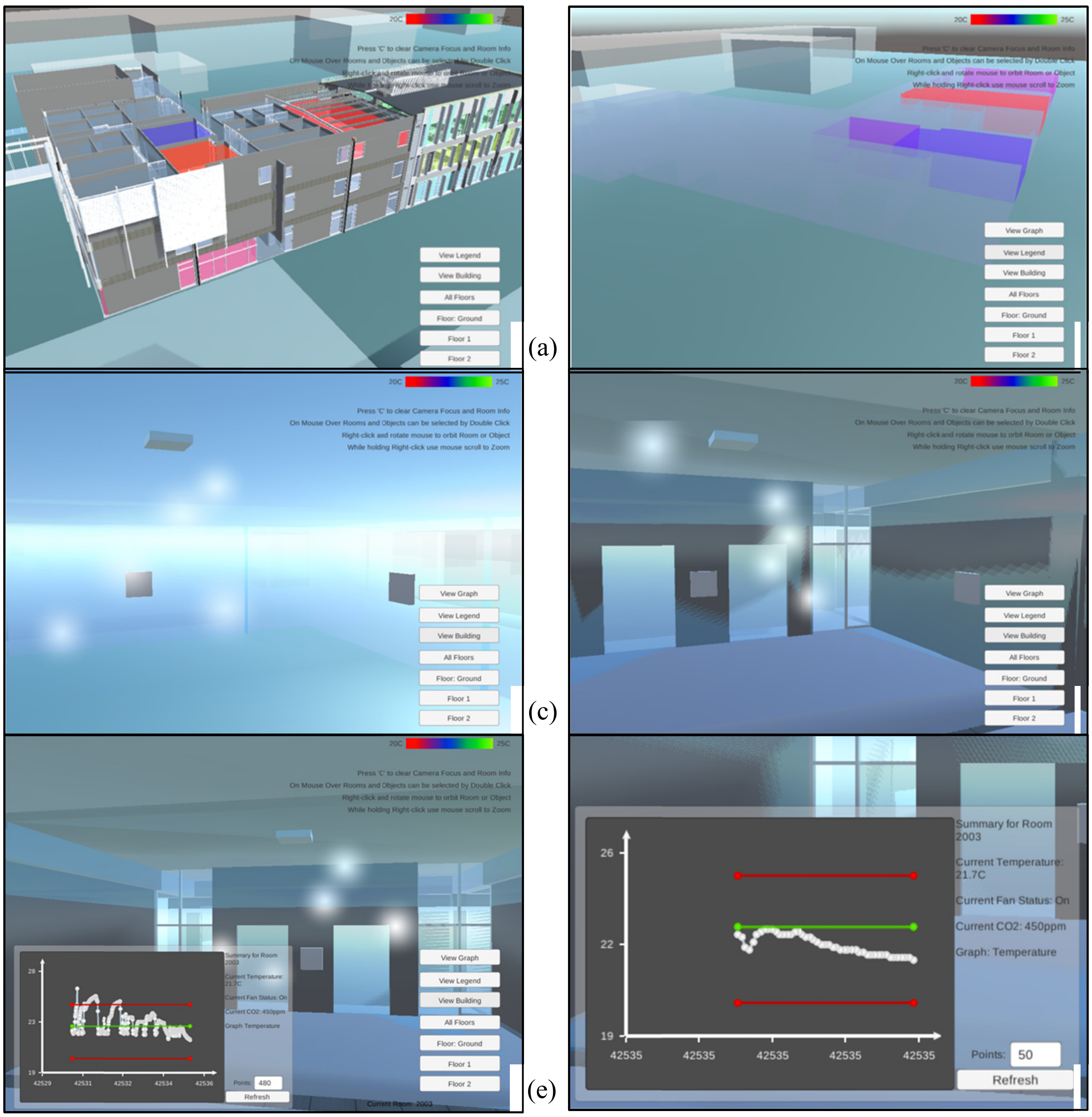

Figure 1 a-f. (a) System building level view; (b) System floor level view; (c) System room level view, without building model; (d) System room level view with building model; (e) System room level view with sensor data view; (f) Close up of changed sensor data chart.

DISCUSSION

The prototype presented shows three views of sensor data in a building at the building, floor, and room level. The types of data presented were temperature, CO^2, fan state, and humidity. Future development will need to explore how to show data in an aggregate form which is understandable by the expected users of the systems. For example, to understand comfort, additional data would be needed from the users (e.g., clothing, activity level) and materials would need to be incorporated into the models.

The prototype shows how data might be made accessible and how proximal relationships between spaces (whether they be rooms or zones) can be explored. Adding an exploratory data visualization system may be useful for both operators and occupants of a building. However, it may have some downfalls for unsophisticated users. Research into metrics for both occupant's and operator's behavior and learning/training will need to be done to understand the types of information which would be the most useful across various building types and uses.

As an initial prototype, the system has various limitations. Currently the system is displaying only three rooms of data, with 6 days at 15 minute intervals. Each room has a different mechanical system and different types of data associated with it. More work is needed to allow for the prototype to work with varying data types and quantities (e.g., it will need to recognize multiple sensors and different sensor types for different spaces). Another area which needs to be explored is the use of rooms and zones, in combination. In this prototype, only rooms were used as zone information was not available in the case study BIM. Zones should be added to aid service tracking and is a layer of information to include in future work.

Future research directions include further development of the afore mentioned features, incorporation of communication between occupants and operations personnel, development of database connections, big data integrations and analytics (e.g., campus level implementation, over several years), research and implement into appropriate aggregate metrics, and evaluation of usability with experts and end users.

CONCLUSIONS

This paper presents the development of a visualization prototype for linked BIM and BMS data for building occupants. It is an initial step into integrating building operators and building occupants with an exploratory data visualization system which can aid both communication between maintenance personnel and occupants as well as providing transparent data access to aid participation of occupants in the energy and comfort of the buildings they inhabit. As it is an initial prototype, the system presented shows an overview of the various functionality of the system. Additional development and testing efforts will need to address extensibility of the system, connection to databases, and data storage requirements.

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An Automated Reconstruction Approach of Mechanical Systems in Building Information Modeling (BIM) Using 2D Drawings

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Abstract
Operation and maintenance of commercial facilities rely on complex building information to locate assets and troubleshoot equipment failures. Although building information models (BIM) provide an integrated information repository for searching for facility information, currently more than 90% of existing buildings in the U.S. were still built with 2D drawings. Manually reconstructing BIM, especially the mechanical systems, has been proven to be very labor-intensive. Hence, previous research studies have investigated automated 3D reconstruction approaches using point clouds data obtained by laser scanner techniques or 2D photos. But due to the needs for a line of sight, these approaches are not applicable for constructed buildings. Researchers have also developed approaches that convert 2D drawings to spatial building models, but the previous studies are limited to generate architectural components such as the wall, doors, and windows. Thus, this paper investigated challenges and approaches to automatically generate models for mechanical systems in buildings using 2D drawings. We analyzed the contents and characteristics of the mechanical components that are represented in drawings and developed a set of classification and algorithms that support the automated recognition of the spatial information and metadata of the mechanical systems. A software framework was proposed to utilize the developed computational approach to recognize 2D drawings for BIM reconstruction. The results of the prototype demonstrated that more than 80% of ducts can be recognized from various drawings in DXF format.

Keywords: 3D Reconstruction, Building information modeling (BIM), Graph Theory

INTRODUCTION

Facility managers need building information to perform tasks such as operations control, corrective maintenance, preventive maintenance, and regular inspections. They use a variety of information sources, including the as-built drawings, equipment specifications, warranty, inspection reports, etc. (Bhatla et al. 2012). But retrieving on-site information using 2D drawings and unstructured documents is challenging because of the complex spatial relationships of the different building components and the huge amount of drawing and documents (Yeh et al. 2012). These issues often cause a time delay and lead to low efficiency in facility management. For example, a time delay occurs if the tradesperson misinterprets the 2D drawings and prepare a wrong type of pipes for fixing leaks. In this case, the tradesperson would need to go back and forth from the field to the shop to get the pipes with the right size. The transit time between places was identified to be one of the non-value adding activities that directly waste time in facility management (Lee and Akin 2009). Since more than 85% of the total costs of a building is spent during the operation and maintenance (O&M) phase (e.g. Lee and Akin 2009; Teicholz 2004), improving the efficiency of the workforce in facility management can directly save the operational budget for organizations.

Among O&M activities, if we exclude the core maintenance activities such as diagnosis, repair, and inspection, most activities were observed to be information-related activities which account for 12% of their total time and these activities could be facilitated by providing computational support (Lee and Akin 2009). Previous studies have investigated the benefits of using BIM to eliminate the non-value adding activities in FM (Teicholz 2013) since BIM is a data repository that enables efficient access to information such as asset specifications and spatial information (Becerik-Gerber et al. 2011).

Although potential benefits exist by using BIM in FM, most of the existing buildings are designed and built based on 2D drawings. In Europe, more than 80% of the residential building were built before 1990 (Volk et al. 2014) and does not have BIM which means that the building owners and facility managers are not benefitting from using BIM during the O&M phase. Possessing BIM could be valuable but the problem is that manually generating a building model is time-consuming (e.g. Santos et al. 2011; Yin et al. 2009). Furthermore, BIM's potential benefits have not yet been perceived by the building owners (Edirisinghe et al. 2016) so that they would not invest in reconstructing BIM for their facility. Therefore, an automatic method that could create BIM is needed to reduce time and error and require less skill to use.

Previously, various studies have attempted to automatically create a 3D building model by using point clouds collected from laser scanners, a raster image of 2D drawings, and photographs as inputs. The limitation of the point cloud based reconstruction method is that laser scanners require line of sight so that they cannot scan the mechanical components that are typically hidden above ceilings or behind walls. In addition, laser scanner equipment is expensive, fragile, lacks portability, and requires trained operators (Bhatla et al. 2012). Using a raster image of the 2D drawings mostly focused on how to reconstruct architectural components such as walls, doors, windows, stairs, and roof (e.g. Riedinger et al. 2014; Santos et al. 2011). Therefore, we propose an automated 3D reconstruction framework that could create mechanical systems in BIM using 2D drawings.

This paper includes the following contents. First, we have identified which information should be retrieved among multiple layers in the 2D mechanical drawings by categorizing the components and classifying the layers. Second, data cleaning process proceeds since there were a great number of draft errors. Third, graph theory was utilized to retrieve the geometric information of the mechanical components. Fourth, a method that could use the symbols and texts information in the 2D drawings for 3D reconstruction is suggested. Lastly, the result of the reconstructed mechanical model using the proposed prototype is shown.

RESEARCH APPROACH

Vision. In order to address the challenge associated with reconstructing 3D mechanical systems using 2D drawings, we proposed an automated framework that use 2D drawings in vector format (e.g. the Drawing Interchange Format, or DXF, is used to develop a prototype in this study) and other documents (e.g. ductwork symbols, piping symbols, sensors, equipment references and schedules, and abbreviations of type and ID of assets). Figure 1 shows the main components and processes of the proposed vision.

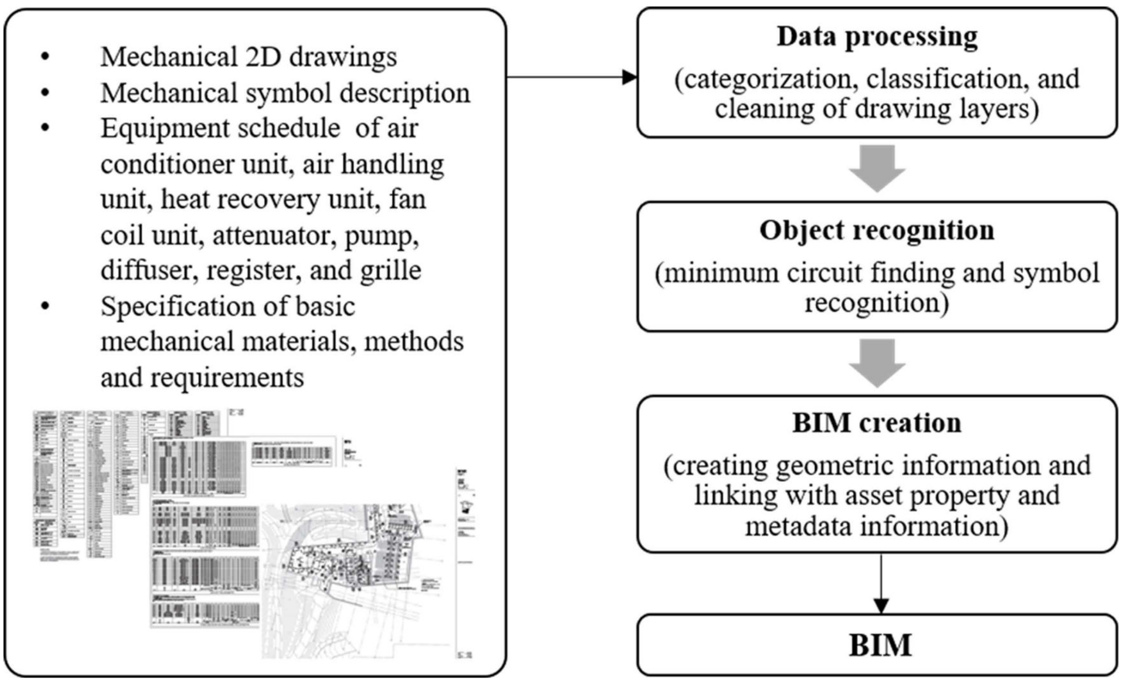

Figure 1. Vision of the proposed framework for BIM reconstruction of mechanical systems

The proposed framework first analyzes 2D drawings for mechanical systems by classifying the CAD layers and cleaning the draft errors. The outputs of these analyses ensure that the 2D drawings are ready for object recognition. Second, we developed algorithms that use the computational approaches, such as minimum circuit search method and computer vision, to recognize various components from the mechanical drawings. These components are categorized into three groups based on their characteristics. The next section discussed the details of the classification and the associated computerized approaches for recognizing the type, dimension, location and metadata of various mechanical components. Finally, the recognized spatial information and metadata are reconstructed into Industry Foundation Classes (IFC) format to create as-is BIM. The following section discussed the details about categorizing the various shapes and symbols in the 2D drawings, classify the layer information, and finally the algorithms that are used to automate the reconstruction process.

Categorization of mechanical components in 2D drawings. Comparing to the architectural and structural drawings of building projects, one main characteristic of the mechanical drawings is that there are a larger number of mechanical components that are represented by unique symbols, text, and shapes. For example, shapes and dimension of components in HVAC (heating, ventilation, and air-conditioning) system are very different from building to building due to various manufacturers and designs of the equipment. Dimension information of mechanical assets is typically represented in a text that is randomly positioned nearby or inside the shapes on the drawings. The reference information of a Variable Air Volume (VAV) unit may be located in a corner of the drawings and pointed to the asset by an arrow. Moreover, some air ducts are drawn with a shared edge (line) although they are separate components. All these variations in representing the mechanical components on 2D drawings make it very challenging to develop computerized approaches that can automatically deduce the different types of information that belong to each component. In order to identify the type of information we could use in the 2D drawings, we analyzed the different ways that these components were represented in the drawings and categorized them into the following groups. Figure 2 shows the hierarchy of the categorization.

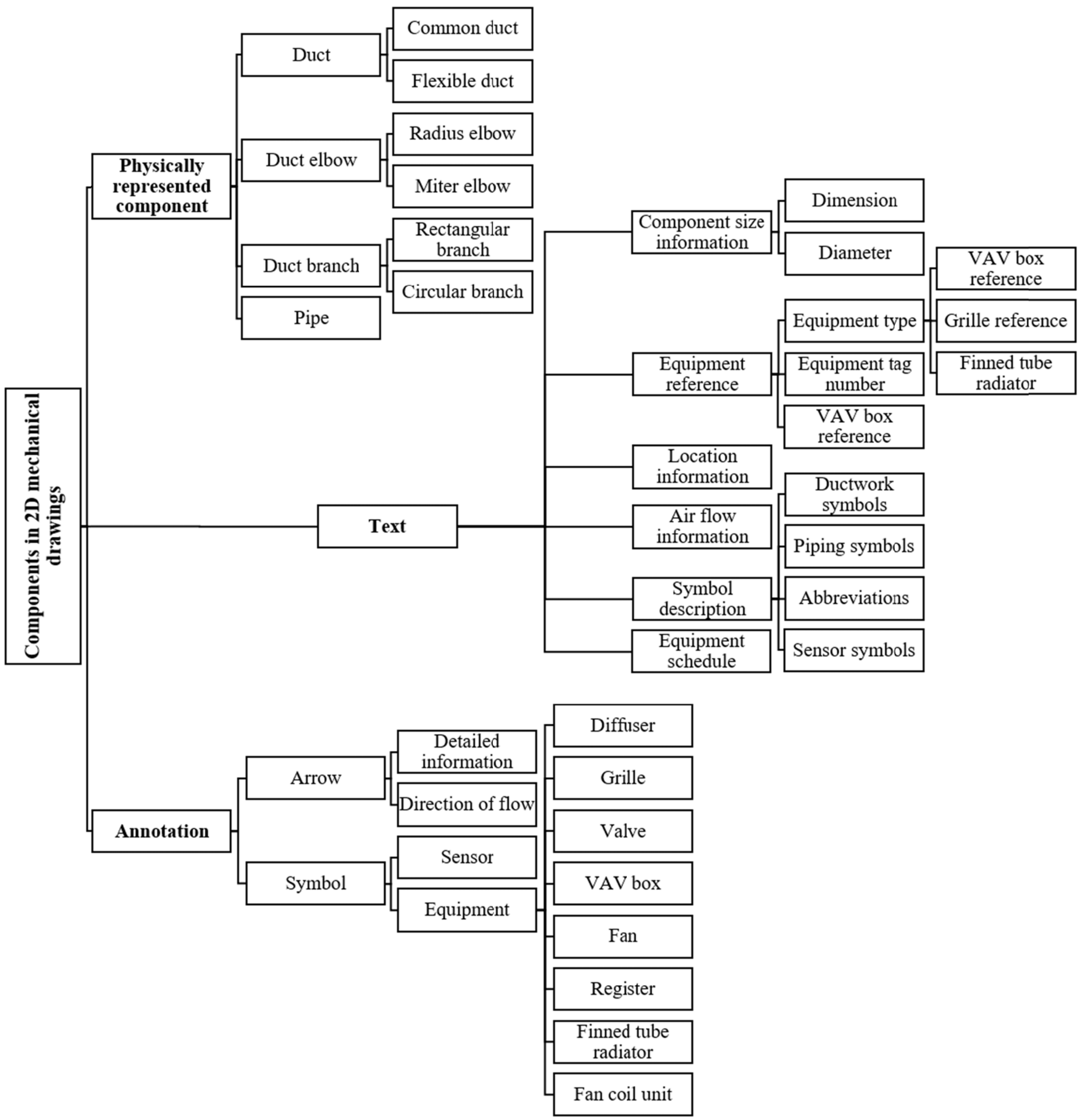

Figure 2. Categorization of components in 2D mechanical drawings