Research on Configuration Item Data Structure in the Frame of Nuclear Power Plant Information Models

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Abstract. The nuclear power engineering information model is a specific type of information model that matches the business model of nuclear power engineering construction. It is a set of related information about the structure, system, and components of nuclear power plants, including a large amount of design data, relationships, and rules, used to integrate, express, and describe the processes and data of various stages of the entire life cycle of nuclear power plants. The information model of nuclear power engineering supports requirement management, configuration management, and physical configuration management of power plants throughout the entire cycle of nuclear power engineering[1]. Among them, configuration management plays a crucial role in the construction of nuclear power projects, connecting demand upwards and regulating the actual physical configuration of power plants downwards. The configuration item structure is generally carried out according to the SSC hierarchical method. Due to certain requirements that cannot be connected to SSC items, dedicated nodes must be added to supplement the configuration item structure. With a large number of configuration items in nuclear power engineering and complex association and constraints, its accurate expression requires strict and multi-dimensional association engineering data structure specifications, and the matching software database must fully adapt to these data structures and association rules in order to meet the management requirements of software on data permission, status and association. This paper mainly discusses the logical structure composition of nuclear power engineering configuration items, describes the data model from the aspects of engineering object type and attribute structure, equipment model, multi-layer function model, etc., and applies this model to construct information model. It will help to meet the data requirements of the nuclear power engineering project for information consistency with configuration items, multi-dimensional deconstruction and separation, and data status control and tracking, improve the efficiency and quality of information flow of nuclear engineering projects, shorten the construction period and reduce the construction cost.

Keywords: Nuclear Power Plant Information Models; Data Specification; Engineering Data Structure

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1 Introduction

Nuclear power engineering construction requires transferring design information from engineering, procurement, and construction to the owner, providing effective data with consistency, multi-dimensional decomposition, and full-cycle traceability for the entire engineering chain. The Engineering Design Information Model (PIM) includes shared information between various disciplines, status markers and control of data permissions, as well as version information of the data. It also undertakes the task of passing valid design data to downstream engineering stages and feeding back data information regarding design change requirements from downstream stages.

Nuclear power engineering information models support requirement management, configuration management, and power plant physical configuration management throughout the entire lifecycle of nuclear power engineering. Requirement management plays a crucial role in the early stages of the lifecycle, with each requirement allocated to specific configuration items based on a framework, ensuring that the power plant configuration is maintained in accordance with the design intent throughout the nuclear facility's lifecycle. Configuration management, on the other hand, plays an important role during the construction and implementation phase of nuclear power engineering, ensuring that the actual physical configuration is implemented in line with the requirements of the configuration items. Nuclear power engineering projects are large in scale, have long construction cycles, and involve numerous participating units (departments) across various downstream sectors of the engineering chain. Currently, each of these units adopts independent management platforms. Due to the lack of rigorous, multi-dimensional information model specifications, it is difficult to meet the downstream sector platforms' requirements for engineering design data consistency, multi-dimensional decomposition, and full-cycle data status control and tracking. This results in poor information interoperability between the software used by various participating units, making it difficult to maintain consistent engineering data, and thus causing inconsistencies in data among the downstream sectors of the engineering project [2].

Nuclear power engineering configuration items have complex associations and constraints. Accurate expression requires a rigorous, multi-dimensional associated engineering data structure specification, which also brings challenges to change control in configuration management. Local modifications often trigger a series of cascading associated changes [3], Some modifications even require the use of attribute-related matrices to express attribute associations between different entities [4]. Engineering changes refer to modifications to the system's functional structure, equipment, layout, etc. which also mean modifications to the configuration structure (engineering data structure tree). Therefore, the definition of the configuration item data structure must also meet the requirements of engineering changes for data relationship traceability definitions.

A data structure refers to a collection of objects with certain relationships or constraints that can be processed by computer programs . Simply put, a data structure is the interrelationships or constraints between data. Data structures include logical structures and physical structures. The physical structure of data refers to the physical storage order of data and the distribution of storage units; the logical structure of data refers to organizing and expressing data information through logical relationships, constructing data structures according to logical relationships [4]. There are many commercial database software available to handle the physical structure of data. When creating a configuration item information model, specific physical data structures are generally not concerned [5], but rather the logical structure of data. This paper mainly explores the composition of the logical structure of nuclear power engineering configuration items. From the perspectives of engineering object types and attribute structures, equipment models, and multi-level functional models, the data model is described. Applying this model for information model construction will help meet the data requirements of various sections and links in nuclear power engineering projects regarding consistency of configuration item information, multi-dimensional decomposition, and data status tracking and control. It can be used to improve the quality and standardization of information flow in nuclear engineering projects and achieve information interoperability among software in various links of the factory chain.

2 Structure of Nuclear Power Plant Configuration Items

Currently, nuclear power plant design is mostly expressed using a document-based design approach. Design data is reflected in a large number of design documents, drawings, and reports, such as system specifications, calculation analysis reports, layout drawings, and equipment detail drawings. Each design document, drawing, and report is independent, but there is a large amount of associated information between them, including association types, specification requirements, association relationships, and connection relationships. The determination of this information depends on the experience of relevant design engineers and cannot be evaluated and determined through computer means.

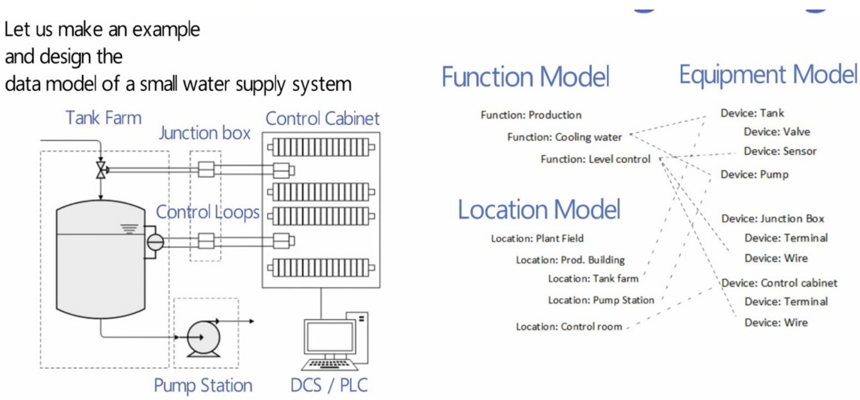

Fig. 1. Sketch of Nuclear Engineering Design Data Model Expression

The configuration item structure of nuclear power engineering is generally carried out according to the SSC hierarchical method. Since some requirements cannot be connected to the SSC items, dedicated nodes must be added to supplement the configuration item structure [1]. That is, it abstracts the connotation and principles of association rules between a large number of object data into structural data of different objects, corresponding image information, and alphanumeric mixed information, which are expanded along four interrelated dimensions. It comprehensively uses equipment structure trees, functional structure trees, location structure trees, document structure trees (traceable image information), and constructs the configuration item data structure as part of the information model through strict object coding specifications (such as KKS). The configuration item structure data model can fully describe the complex associations between a large number of objects (equipment, components, pipelines, cables), as well as their connection and association data expression on various drawings (such as the connection between pipelines and equipment, and the connection relationship between core wires and terminals, etc., as shown in Figure 1). The configuration item structure data is composed of multiple identifiable objects in accordance with the pattern specified by the information model, such as hierarchical relationships between upper and lower levels, and association relationships between surfaces.

2.1 Device Structure Tree

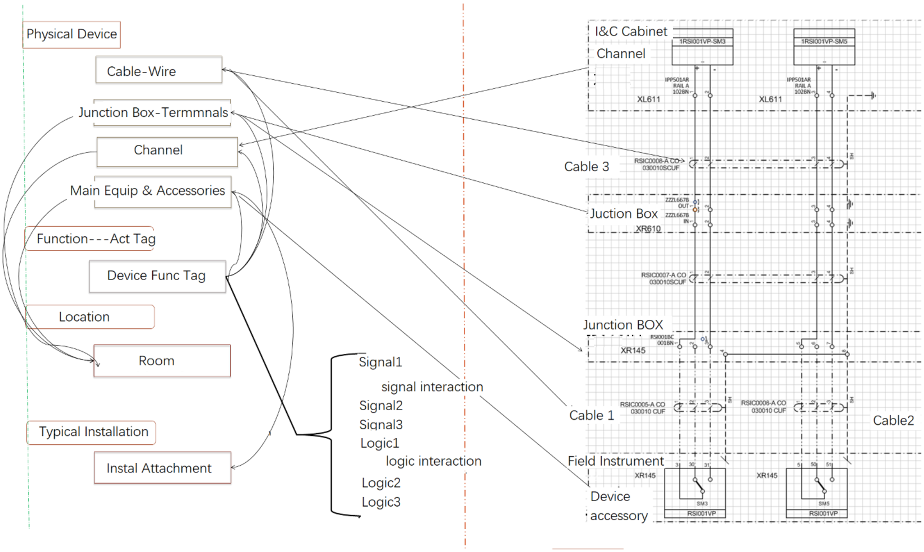

Fig. 2. Sketch of Nuclear Engineering Design Data Association

The SSC model of nuclear power engineering includes equipment structure trees, functional structure trees, location structure trees, and complex association information between them, as well as connection information defined by connections of relevant objects on drawings. The equipment structure model expresses data descriptions of equipment and their accessories and their structural associations in the form of a structure tree, mainly manifested as characteristic attributes of equipment and their accessories, as well as hierarchical relationships between equipment and their accessories. The main associations of equipment include: hierarchical relationship between equipment and storage path; association between equipment and room; association between equipment and function; association between equipment and standard installation method; and association between equipment, pipelines, and connectors generated through drawings (see Figure 2). These associations enable information data to be accurately and quickly transmitted to downstream engineering sectors in the form of multi-dimensional statistical material lists, such as procurement, preliminary budget, and commissioning sectors, through catalogs, detail lists, and various material lists. Equipment models involved in nuclear power plant systems can be designed in accordance with the requirements of data configuration specifications, including controlled equipment, throttling devices, instruments, process equipment and instrument accessories, penetrations, third-party instrument control equipment, local panels, cabinets, terminal blocks, terminals, related cables, and other electrical components, as well as fixed equipment and their accessory hierarchies and attribute structures.

2.2 Functional Structure Tree

The system function model expresses the structural relationships of multiple devices (components), instruments, pipelines, cables, terminals, acquisition channels, and information processing that constitute a system function in the form of a structural tree and object associations. It also adopts a hierarchical expression method to divide the system, making the functional structure of the power plant clear at a glance. For a nuclear power project, a functional model can be structured in a hierarchical manner based on the division of the power plant system, constructing the overall functional model through functional subgroups (standardized functional associations), sub-functional groups, and the functional associations between the two. For example, as shown in Figure 1, the liquid level control of a tank can be considered as a system function, which requires a liquid level gauge, pump, control valve, control cabinet, and various power cables, control cables, signal acquisition channels, terminal blocks, etc., between the devices to form it. The devices involved in the function exist in the tree structure of the function group in the form of function tags and are associated with device objects in the device structure tree (association). The function structure tree provides relevant device combinations and connection methods (such as control loops, power supply loops) in units of function groups/modules. It also provides multi-sectional extraction dimensions for various analysis software and accurate demand data for downstream commissioning and operation and maintenance.

2.3 Location Structure Tree

The location model represents the data structure of the nuclear power plant's physical space and the spatial relationships between entities and equipment by using the room hierarchy of the factory building and the association between equipment and rooms, reflecting the relationship between equipment and buildings. Generally, the construction of the location hierarchy can enable access and lookup of associated equipment according to room/floor/factory/entire unit. Taking the room as the basic unit, it matches with other partitioning methods of the power plant such as installation partitions, fire protection partitions, radiation partitions, and explosion-proof partitions in terms of data structure. It provides various dimensional batch query methods and quick navigation methods, offering accurate data support for downstream tasks such as installation material collection and construction task allocation.

2.4 Document Structure Tree

During the design process of a nuclear power plant, there is a close intrinsic connection between the diagram-document model, the equipment structure model, and the system function model. The equipment structure model and system function model describe the structural relationships between equipment and equipment, systems and equipment, and functions and functions from a topological logic perspective. However, specific geometric shapes and connection relationships are described through diagrams and documents. For example, process flow diagrams express the connection relationships between equipment and pipelines; instrument and control loop diagrams express the core wire termination, signal grouping, and cable connection relationships between on-site equipment (components) in the power plant and control cabinets; control function charts characterize the control calculation logic and monitoring functions of different functional levels. For image information corresponding to equipment, graphical parsing data and associations are provided.

The document structure tree provides a node-based method for classifying drawings. For each system, it includes different types of atlases (functional diagrams, local cabinets, HMI, form documents, etc.). Each atlas (drawing) is associated with floors, equipment, systems, functional subgroups, workshops, and rooms based on the content it expresses, and can be quickly queried and linked through shortcut navigation. In this way, the hierarchical document structure, together with the functional structure, builds a strictly standardized design model hierarchy and an associative data structure.

In general, the organization of the document structure tree is based on the framework of the WBS (Work Breakdown Structure). The generation of the WBS related to construction design drawings relies on the PBS (Product Breakdown Structure), and quality assurance requirements, communication requirements, regulatory requirements, etc., also constitute the WBS (as shown on the left side of the following figure). Design documents describe the operating principles, technical performance of the power plant, analysis of engineering data, or process documents related to management work. According to different document purposes, they are divided into technical documents, graphic documents, technical specifications, and management documents (such as task books, quality assurance outlines) (as shown in Figure 3). All these design documents need to establish a link relationship with the configuration item structure (equipment, function, location). However, due to various regulatory requirements, some design documents need to be submitted to the regulatory authorities in the form of a register, which makes it difficult to link these documents to a specific configuration item, such as safety analysis reports and preliminary design volumes. Therefore, document nodes are added to the configuration items, and dedicated type nodes are set to supplement the configuration item structure, such as the main WBS activities 01 License Application Documents, 21 Preliminary Design Documents shown on the right side of the figure, in order to complete the supplementary configuration item structure for specialized documents related to user requirements and various party requirements.

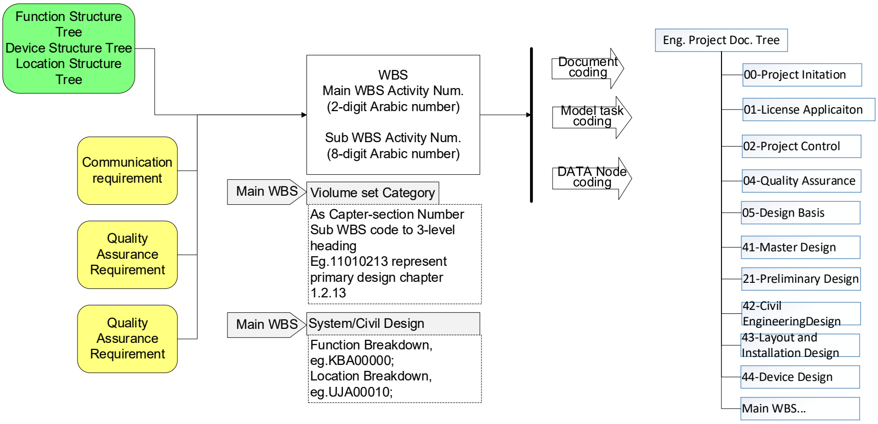

Fig. 3. Document structure tree corresponding with WBS

3 Nuclear Power Engineering Configuration Item Object Type and Attribute Structure

The various object types used in nuclear power engineering configuration items are abstracted based on years of engineering experience. Each entity can be abstracted into different types of objects, and the data structure of an object is generally composed of multiple attributes. Attributes can be divided into data attributes and reference attributes. Data attributes only describe information about the object itself, while reference attributes describe the association between this object and other objects, serving as a way to express relational impacts. This section elaborates on four aspects: object types, types of relationships between objects, attribute types, and attribute status management.

3.1 Object Types

The object types in nuclear power engineering can be classified into four basic categories: equipment/function/location/drawing (as shown in Figure 4). Each category has its own object structure tree, and different types of objects under the structure tree cannot be mixed; instead, they are defined through associations. The complete process of creating equipment data should first define the type, then define the specification, and finally supplement the product model, gradually completing the design deepening.

For complex equipment design, it is a process of continuously adding sub-level components, such as cabinet design (adding electronic components, processors, terminal blocks, etc.).

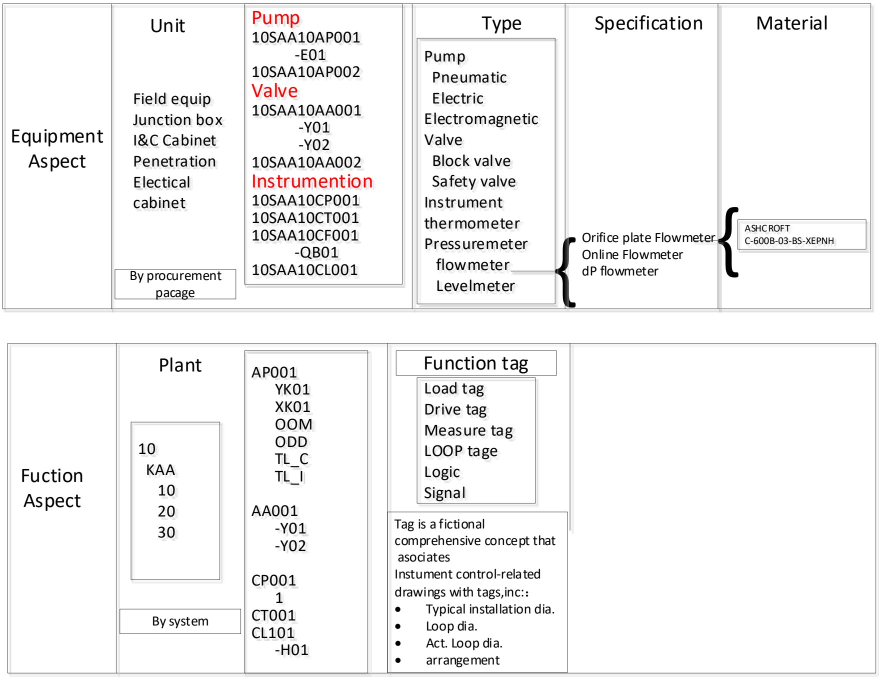

Fig. 4. Sketch of Nuclear Engineering Design Data Object Type

Functional objects generally include types such as interfaces, tags, signals, and logic, with IDs established in a hierarchical abbreviated manner. Functions are typically not categorized by specifications and can directly interface with function groups in upper-level designs to obtain device information associated with the functions. There are fewer types of documents, including atlases, drawings, and reports. The type of location is only rooms, which do not include architectural objects such as doors and windows, but rather an abstract spatial concept. Rooms can define attributes such as fire compartments and radiation zones, thereby establishing data information between equipment and various spatial analysis models.

3.2 Types of Relationships Between Objects

The relationship types between the following 6 kinds of objects can express different information, and through relational definitions, relationships of information can be established.

1) Hierarchical relationships, where (the four major categories in Section 2.1) can be established under the same type of objects;

(2) Associations between equipment and standard installations, used to statistically track the bulk materials consumed by main equipment;

(3) Relationships between equipment and functions (one device can only belong to one function, and one function can be associated with multiple devices);

(4) Associative relationships between functions, reflecting functional interactions between function groups;

(5) Associative relationships between equipment and location (room), reflecting the relationship between physical entities and spatial locations;

(6) Continuations caused by limitations of drawing size, including pipelines, signals, cables, etc. The typical representation objects for this category are special objects such as potential and medium types, and parameters can be transmitted through the form of wiring connections on the drawing.

3.3 Attribute Types and Structure

Attribute configuration is performed on different types of configuration item objects, used to represent device parameters, functional descriptions, functional constraints, and other information. Attributes can be configured as general attributes and reference attributes. General attributes are defined on the object itself and represent the characteristics of the device itself. Reference attributes, on the other hand, obtain attributes from superior objects (at any level), subordinate objects, associated diagrams, associated objects, or object attributes through connection line relationships via the model structure tree, thereby automatically acquiring associated constraints or data traceability information. Attribute types that can be defined in EB software are shown in Table 1. The application of reference attributes can significantly improve data efficiency and is an effective tool to ensure a single data source within and between disciplines. Combined with calculation and experience databases, design specifications and past experience can also be accumulated into object types.

Table 1. Table of Attribute Types

Attributes Type	Application
Unit	Unit conversion
Time	Record time
Date	Record date
Float	Numerical calculation, such as material weight, etc.
	Auxiliary judgment
BOOL	String
text	options
emumration	Cascade-related changes, such as obtaining project properties,
Citation	parent object properties, and drawing information

3.4 Attribute Status and Management

Attribute status is a critical part in data structure definitions, as it stipulates the data source, data validity, and read/write permissions for data. Attribute permission restrictions generally include three types: editable, read-only, and invisible. In contrast, attribute statuses are numerous, as they are adjusted according to different needs due to varying work habits and processes across companies.

4 Nuclear Power Engineering Equipment Model Structure

The device tree model generally creates various entity devices, defined as full ID expressions. As shown in Figure 5, this is a convenient way for the procurement department to obtain data: establishing the model along the path of unit/set/procurement package, with the procurement package serving as a module for data transmission and permission management with procurement. Adjustments to the device path have no impact on device information and are only used as a method for work subcontracting. The hierarchy of devices, as well as the object type and code at each level, must comply with configuration management regulations, which serve as the principle for data validity checks. The standard for classifying device types should remain consistent throughout the entire nuclear power engineering chain to ensure that a set of standard structural model data can be used and exchanged consistently and accurately across any department within the company, as well as with upstream and downstream partners in the industrial chain.

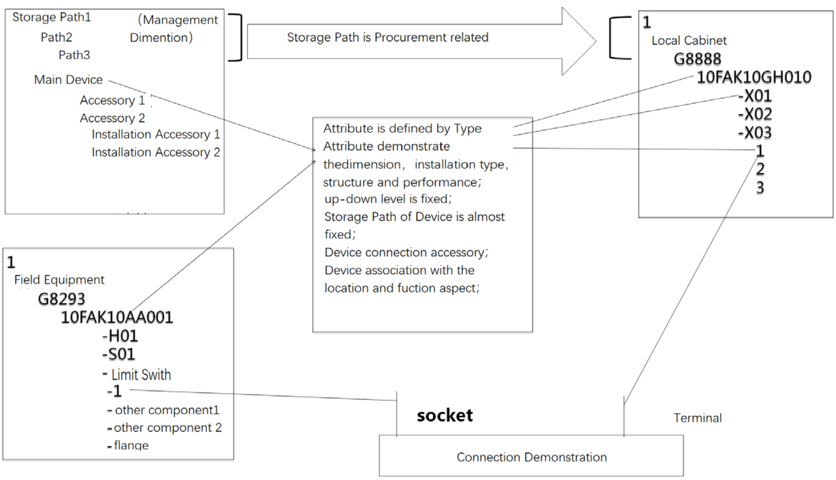

Fig. 5. Sketch of Nuclear Engineering Design Data Equipment Model

5 Conclusion

This paper discusses the logical structure composition of nuclear power engineering design data. It describes the information model from perspectives such as engineering object types and attribute structures, equipment models, and multi-level functional models. By applying this information model construction method, the EB (Engineering Base) software is used to build the configuration item structure. Its data structure can meet the design information expression requirements of complex systems in nuclear power engineering projects, as well as the data needs of various engineering sections for engineering data consistency, multi-dimensional decomposition, and data status control and tracking. Using this structure for information model construction will help meet the data requirements of various engineering sections in nuclear power engineering projects regarding configuration item information consistency, multi-dimensional decomposition, and data status control and tracking. It can be used to improve the quality and standardization of information flow in nuclear engineering projects and achieve information interoperability among software in various links of the factory chain. The company's Instrumentation and Control Department has already adopted this model for the instrumentation and control design of multiple projects, covering control function diagrams, I/O point lists, set values, general equipment specifications, termination tables, cable diagrams, and Hookup diagrams. The accuracy of forms has been greatly improved, and it is also convenient to identify data inconsistencies in the upstream instrumentation and control data submission. The company is also establishing a data management center based on standardized and SSC model principles, making various types of data in the basin more readable and valuable for analysis and application.

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