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An extended hierarchical graph-based building model for design and engineering problems

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ABSTRACT

This paper deals with research into advanced hierarchical graph structures which have been developed for knowledge representation in computer-aided design and robotics. Complex real-life engineering problems still need useful graph-based models. A new approach to represent models preserving the intrinsic nature of problem structures using graphs with many hierarchies is proposed. Different types of hierarchical dependencies (geometrical, functional, etc.) between design parts can be expressed in one structure. Moreover, the possibility of selecting only problem-related hierarchies reduces the number of data to be analysed in the process of reasoning about considered designs. This approach is illustrated by applying multi-hierarchical graph structures to represent complex data used for robot control algorithms.

1. Introduction

There are many well-known methods of representing knowledge in computer systems. Selection of the appropriate structure for knowledge representation and manipulation is a key issue in constructing knowledge-based systems. On the one hand, such a structure should be hierarchical as hierarchy generating techniques are commonly used for acquiring, analysing and modelling knowledge, in particular to build taxonomies and other complex structures. On the other hand, when the chosen structure has a graph-based form, graph methods make it possible to integrate hierarchical object representations and the process of generating their graph models.

This paper continues research into advanced hierarchical graph structures used for knowledge representation in complex engineering problems. The proposed approach has been inspired by studies on navigating mobile robots inside buildings [1]. Moreover, a graph-based representation of a building design facilitates the communication between different specialists and consultants which turn the project from design to construction. They should adhere to the design specification as usually the construction should be compatible with the previously created design. Changes required during project realization can be introduced to the related graph hierarchy and then knowledge-based reasoning about existing conflicts with elements of other hierarchies can be performed. The considered multi-hierarchical graph representation of designs allows us also to encode information which is not included in their BIM (Building Information Modelling) descriptions [2], like assignment of spaces to different departments. The used graph structures can be saved in the GraphML format and then imported to IFC (Industry Foundation Classes) models [3]. As the IFC format is an interoperable BIM standard for CAD applications, there is a possibility of adding semantic information to extend the BIM visualisation mode. Therefore, the proposed new hierarchical graph model is a useful contribution to representing, understanding and processing information in the domains of computer-aided architectural design, construction industry and robotics.

Up to now, in the process of designing building layouts, the hierarchical hypergraphs have been used to represent design drawings [4]. As these hypergraphs were hierarchical they enabled us to express hierarchical dependencies between different parts of designs, like inclusion of rooms in larger spaces. Additionally, there was the possibility of specifying relations between components represented by hyperedges having different parent hyperedges and nested on different levels of hierarchy. Moreover, the hypergraph hierarchy reflected the top-down way of the design solution development and gave the possibility to consider the design only on the interesting hierarchy levels.

However, in the research towards designing multi-storey buildings [5] it turned out that such a representation is not sufficient to effectively model their layouts. In such a design there exist many different types of relations between design parts, which cannot be expressed with a single hierarchy. For instance, different hierarchies are generally required for geometrical and functional dependencies.

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Similarly, communication paths between floors and elevator shafts cannot be expressed by means of the space hierarchy for single floors.

This paper proposes a new model of building layouts in the form of a graph-based representation with many hierarchies. As many multi-argument relations between components can be expressed by hierarchical arrangement of these components in the graph structure, in order to simplify our considerations, the model is restricted to contain only binary relations between components, which means that graph nodes are connected by simple edges instead of hyperedges.

The robotic domain will be used to exemplify the proposed approach. Multi-hierarchical graph structures encoding knowledge about buildings are useful for robot control algorithms as they facilitate the reasoning process by reducing the number of data to be analysed. The interesting levels of hierarchy can be selected, and only the information related to these levels can be considered.

The paper is organized as follows. Section 2 describes the related work. In Section 3 the proposed graph-based multi-hierarchical representation of design objects, which is the main contribution of this paper, is defined. The new notions related to this structure, like a single view and a view are introduced. Section 4 contains the case study, where the benefits of using the proposed building layout representation by a mail delivery robot operating in a multi-storeyed building are discussed. The paper ends with a conclusion.

2. Related work

Graphs are commonly used to model relations in many systems. They can be used in design systems to model topological relations between components and in databases to model logical relations between objects. Graphs are also used to model data and control flow or specification and analysis of software systems. The research very often concentrates on graphs without hierarchy – graphs, CP-graphs [6], hypergraphs [7]. In many real applications, modelling systems by plain graphs (graphs where edges and nodes are sets without additional structure) is insufficient. The complex systems are very often hierarchical, thus the graphs with hierarchy should be used as the models. Graphs of this kind allow not only for modelling hierarchical relations between components of the system but also for hiding some details of “encapsulated” subgraphs.

During the last years several models based on graphs with hierarchy have been defined [8–19]. The models were used for modelling global computing systems, syntactical structure of agents, mobile systems, design systems, granular computing etc. The global computing system enforces a model with two relevant dimensions: linking and nesting. In the bigraph model, described in [8], these two dimensions are represented by two structures: the link graph and the place graph, which is a tree-like structure. In [9] and [10] the gs-graph model, which is a generalization of the term graph model [11], is introduced. In this model two types of nodes are distinguished: black nodes which represent intermediate places in the tree-like hierarchy, and white nodes which represent communication channels.

The graphs with hierarchy were also defined for programming and system specification. In [12] the hierarchical hypergraph model is introduced, which allows for nesting a hypergraph in a hyperedge. The presented approach allows for modelling a hierarchy, but it does not allow for representing relations between parts of two different components.

The nested graph model described in [13] is an example of another graph model with hierarchy. In this approach a so called hypernode can contain a graph. This model was used for representing and manipulating complex objects in databases. The approach, in which nested conceptual graphs are used, is described in [14–16]. A very similar formalism, based on higraphs, is presented in [17]. A higraph is a graph with hyperedges and nodes. A node (called blob) can contain other nodes. Additionally, a partition (orthogonal) function is introduced in order to create so called orthogonal components. The formalism allows for defining higraph-based languages of statecharts. It can be applied to databases, knowledge representation and behavioural specification of complex systems.

The graphs with hierarchy were also used in granular computing [18,19]. Granular computing exploits structures in terms of so called granules (groups of elements which have similar characteristics), levels, and hierarchies. A granulated graph is called a level, when all the vertices are integrated into granules. A simple granular structure with one hierarchy provides a multilevel representation of the problem being solved. A hierarchy in this model represents one view of the problem with multiple levels of granularity. This approach was extended into a granular structure with a family of hierarchies in order to capture many aspects of the problem. The extended model allows for expressing many points of view of the solved problem (many hierarchies) with different levels of details (many levels of granularity).

It turns out that existing hierarchical graphs are not sufficient to efficiently model objects considered in architectural design and engineering problems. The good representation should allow for expressing multi-argument relations between parts of different components and hierarchical dependencies between different parts of a design. The model should enable modelling many hierarchies of different types, where not all components must belong to the hierarchy. None of the presented models allows for modelling all required features. In the bigraph model, gs-graph model, higraph model, as well as in the nested graph model only one hierarchy can be introduced. The hierarchical hypergraph model introduced in [12] does not allow for representing relations between parts of two different components. The granulated graph model introduces many hierarchies but does not allow components not to belong to any hierarchy.

Therefore this paper proposes an extended hierarchical model. The hierarchical hypergraphs, which were used to represent design drawings in our previous research [4,20], have been modified by introducing multiple hierarchies of various types in a way similar to the one envisioned in [21]. Moreover, hyperedges representing design components have been replaced by nodes, while hyperedges expressing relations between components have been replaced by directed edges.

In complex design situations requirements of different design disciplines lead to different views and representations of the same design object. Modelling multiple views of buildings is considered in various aspects [22]. Multiple views of design objects described in [23] are based on the functional context. Each view is composed of selected functional systems. Our approach can be seen as a new formalization of multiple views expressed in terms of a graph structure. Each functional system corresponds to one graph hierarchy called a single view. Each view corresponds to a subgraph composed of selected hierarchies, which is also called view in this paper. Moreover, this view can be easily limited by taking into consideration only selected levels of hierarchies.

Modelling views explicitly by arranging nodes and edges in many hierarchies is more convenient than using node and edge attributes specifying views. Views can be derived from multi-hierarchical graphs on the basis of hierarchies more efficiently than by filtering graph elements on the basis of attributes. Each single view can be obtained starting from the hierarchy root node without the need of searching for appropriate nodes in the whole graph.

The rapid development of robotics is driven by the need for robots able to perform increasingly complex and important tasks. The autonomous mobile robots are the special group of robots having the ability to move and be self-sufficient [24]. The most important rules, which should be followed by autonomous mobile robots are: ability to gain information about the environment, ability for