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Automation of Architectural Design Process and Robotic System in Building Construction using Object-Oriented Design

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ABSTRACT

This paper describes an automation of architectural design processes and the direction between this automation and robotic system in building construction using the concept of the object-oriented design in architecture. The research starts from the premise that many computer-aided design systems are mostly aimed at serving as drawing tools which are used only after a design formal solution has already been established by the architect. If the computer is well applied to the architectural design process, many positive things such as standardization of design detail, increasing productivity and collaboration, minimizing construction costs etc. can be done. To support an early design solution in the computer-based environment, the proposed automation was developed and tested in a real building project, using the object-oriented design concept such as product model. This design automation gives various design alternatives from the early design phase to the final stage of design details, according to musical harmony. This paper shows how architectural design process can be automated and how the data of the applied architectural design can be integrated into product model environment, in relation to robotic system in building construction.

Key words: Automation of Design Process, Object-Oriented Design, IFC, CAAD, Robotic System

1. INTRODUCTION

Construction industries have introduced CAD/CAM systems for the purpose of shortening building-time, maintaining continuous machine capacity, providing greater precision, etc. Advantages of conventional CAD/CAM systems, however, have been limited to the automation and rationalization of individual process. The conventional CAD/CAM systems can mainly transfer shape related information. They can not transfer design intents under transferred shape, functional features, and various product attributes. As far as shape representation is concerned, evolution from wire-frame representation to surface representation and then solid representation shows considerable progress for representing real object. However, these representations are limited to mathematical description of shape after design; design intents of shape are not modeled.

In order to resolve this situation, "Product Model" has been proposed and discussed among research fields and ISO TC184/SC4. Different from conventional systems, various information around geometric shapes, design intents and appropriate building systems can be included in a new CAAD (Computer-Aided Architectural Design) system, which makes it easier to improve communication-

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and coordination-knowledge between the professionals involved. To develop this CAAD-system, it is of importance not only to know CAD/CAM systems applied for individual construction fields well, but also to effectively combine fields of automation in construction which resulted from the application of CAD/CAM systems to each process independently.

Today's industry offers a growing number of rational solutions for constructions, including integrated systems as well as a wide variety of elements or subsystems such as ceiling, façade, installation, wall and interior systems. For example, all elements, including the outer skin, the finishings and services, are standardized and prefabricated, and are delivered from works only when they are actually needed on site, as shown in Fig. 1. It is thus possible to reduce the entire construction period for a house to three months.

However, the lack of design variability has been always seen as a big disadvantage of these systems. Furthermore, a lot of problems arise in their effective interfacing: for example, it arises a number of problems, because the collaboration between construction fields such as design, structure, HVAC etc. is only concentrated on the last design process, although we need necessarily the collaboration and frequent communication in each design process.

Here, this study can propose architectural feedbacks and new ideas through interactive process between architects and engineers; the design computation and object-oriented design process (product model). The research will work on aspects of a computer-aided design system that gives an intelligent advice on aesthetic qualities of a design, will improve rule computation, and will let cooperate with robots through the technology of product model.

Fig. 1. Process of Prefabricated Houses in Vorablberg, Germany

2. PRODUCT MODEL IN BUILDING CONSTRUCTION

2.1 Overview of Product Model

It is widely accepted that the quality and efficiency of the design process in the AEC (Architecture, Engineering and Construction) domain can be improved only through increasing automation of the design and construction process. The key to success in achieving automation is seen as the integration of the information processing required by the various disciplines involved at the various stages of the design process; that is also the basis for collaboration. To do the collaborative work associated with each field, the communication aspect should be understood at least.

In order to enable this communication among actors, for example, in the construction process, the data in each process have to be formally defined and standardized. In general, most of this issue is concerned with the exchange of project data. As there are many different CAD-systems and each CAD-software in each domain has its own internal description, we encounter difficulties when we try to transfer design data from one CAD system to another. In order to solve these problems, studies have been conducted since the beginning of the 1980s. These studies used the neutral-format files, such as IGES (Initial Graphics Exchange Specification) and DXF (Drawing eXchange Format). IGES has been evolving for over twenty years and has become a reliable and widely used format. However, it has serious limitations; it is restricted to partial geometry and annotation but does include structure and relationships. DXF is an Autodesk proprietary format that has been adopted by the construction industry. Similar to the case of IGES, DXF is not suitable for transferring partial geometry because of its lack of precision. As the next generation of IGES, the STEP is the international effort by ISO at trying to combine the different national activities in a single international standard.

2.2 STEP(Standard for the Exchange of Product Model Data)

STEP was born in December of 1983, when the International Standards Organization (ISO) formed the TC184/SC4 committee. STEP is an international effort to produce high-level standards for exchanging product information that support technical information exchange and communication within industries. STEP is targeted at the exchange of data describing a product between Computer Aided X (X = Design, Engineering, Manufacturing, etc.) systems[1]. STEP product models are rich, structured, object-based data models of industrial products. They are generally designed to provide fairly complete, cross-application descriptions of product data, and the modeling methodologies for defining them are extensive and formal. One of the best reasons of the success of STEP is the standardized EXPRESS language, which allows a complete and unambiguous description of information related to different conceptual components of a product. EXPRESS allows the designer to describe the data structure of the objects of his application, especially through the concept of entity describing a class of objects [2]. EXPRESS-G is a graphical notation for schema defined in EXPRESS [3].

2.3 IFC (Industry Foundation Classes)

IFC is an information standard for the building industry, encompassing AEC/FM (Facility Management) domains. This standard is being developed by IAI (International Alliance for Interoperability) [4] whose mission is to define, publish and promote specifications for IFC as a basis for project information sharing in the building industry.

The IFC concept is based on the idea that objects are brought into an integrated model. These objects are defined in order to support the whole lifecycle of facility development from inception through design, documentation and construction, then facility management and finally to demolition and or disposal. The principal benefit of IFC is their object description - not only does the IFC protocol preserve the full geometric description in 3D, but it also knows its location and relationships, as well as all the properties or parameters of each object such as finish, serial number, material description, etc. Part 11 of STEP, and the ISO EXPRESS language (STEP-11) have been adopted by IFC to describe its model. Thus, the IFC data model corresponds with the STEP standard and consequently contributes to the evolution that permits the exchange of building data between different programs. Unlike STEP, evolution is not planned for a norm, but aims at direct application in the

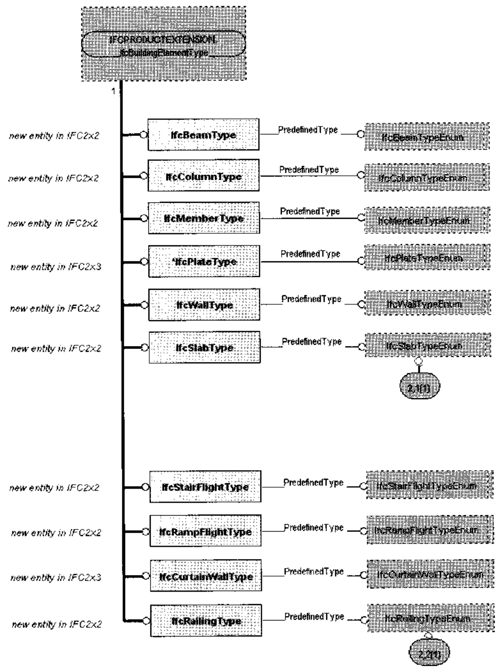

Fig. 2. Subset of IFC R2x3

industry. For example, the IFC has a much broader scope than AP 225 of the STEP. Work on the IFC model development has led to various releases of the model; IFC R1.0, IFC R1.5, IFC R1.5.1, IFC R2.0 and the release of IFC R2x3 at Feb. 2006. A subset of IFC R2x3 is shown in Fig. 2. It illustrates some of the entity definitions and relationships related to building elements, such as the decomposition structure, sub-types and associations with other objects [5].

3. SCHEMA AND DEVELOPMENT OF DESIGN AUTOMATION IN PRODUCT MODEL ENVIRONMENT

3.1 Conceptual Schema

A conceptual schema is a map of concepts and their relationships. This describes the semantics of an organization and represents a series of assertions about its nature. In this section, the conceptual schema describes the relationships between architectural elements such as wall, windows, doors. finishings, etc. in an architectural model. Hence, this conceptual schema can play a basic role to apply to the product model and can be used for applying design rules to product models. The conceptual schema for design automation is shown in Fig. 3.:

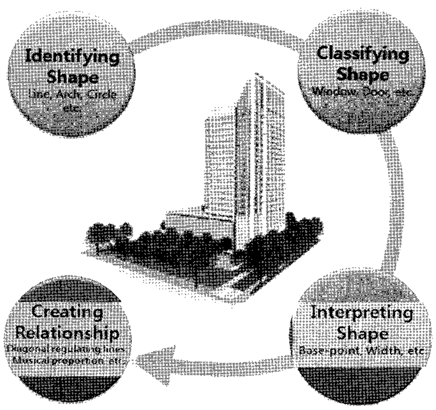

Fig. 3. Conceptual Schema of Architectural Information for Design Automation

Four major sources of the information about the architectural facade are described in Fig. 3. These consist of:

- Identifying shape: line, arch, circle, etc.
- Classifying shape: window, door, column, facade, material of surface, etc.
- Interpreting shape: base-point, position, width, height, etc.
- Creating relationship: diagonal regulating lines, musical proportion, etc.

For implementation in a product model, each shape has to be defined and found in a drawing. In general, a shape consists of a set of lines and curves which are usually connected. When each of the elements of a shape has been identified, it then has to be classified, in order to be recognizable by a computer by its own name, such as a window, a door, a column, etc. The interpretation of a shape is considered as the process that shifts the semantic content of the drawing to a higher level. Normally, this phase is one of main goals of IFC2x3, and is the key to implementation of the application system in an object-orientated CAD-system; here, different aspects of an object are analyzed and stored as parametric values. When all elements of a façade have been recognized, their relationships can be analyzed and proposed by implementation of certain application program. Thus, the design is automated, according to the optimum design rules.

3.2 Scenario of Design Automation

A process model provides a description of tasks needing to be undertaken. It defines all of the required tasks within the process and puts them in a logical sequence. The following process diagram illustrates the required scope of specification development for applying the architectural design rules to CAAD systems in the framework of a product model.

In this diagram, "Information Data" and "Data Contents" can be described with EXPRESS or

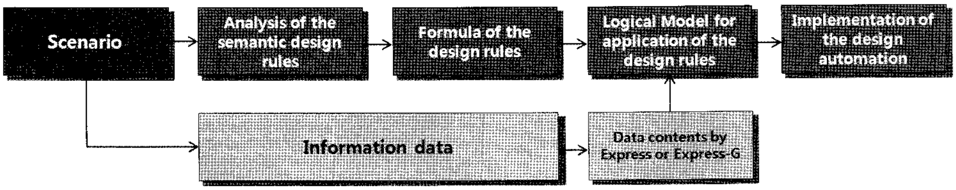

Fig. 4. Scenario for Design Automation

EXPRESS-G, which give the fundamental information about a building. In these phases, general entities, attributes and relationships between a building and its elements are defined. In the case of an architectural façade that will be examined, the hierarchical decomposition can be divided into structural layers, openings, surfaces and columns; the columns are described as optional attributes. These components of the façade can be defined with EXPRESS-G, as the following Fig. 5:

This schema in Fig. 5 contains physical parts of the façade that are related to each other element, which allows input of information about a façade in applications for design rules.

3.3 Programming Language for Applying the Design Automation

The programming language employed in

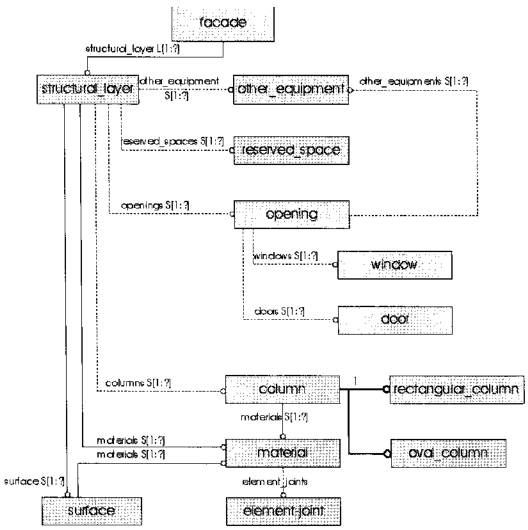

Fig. 5. Overall EXPRESS-G Diagram of the Facade

AutoCAD for customization is AutoLISP. As this language retains most of the general LISP functions, it is a symbolic manipulation-based, interpreted language that provides a simple mechanism for adding commands to AutoCAD. For example, this interactive programming language in AutoCAD allows users to program external applications, using the AutoCAD drawing generation and manipulation functions for 2D geometry, 3D wire-frame structures and 3D curved surfaces. Therefore, customizing AutoCAD into a more useful tool for a particular application for users can be carried out using the AutoLISP program. The system demonstrated in this paper operates in the AutoLISP program of the AutoCAD environment.

4. AUTOMATION OF ARCHITECTURAL DESIGN PROCESS AND ROBOTIC SYSTEM

4.1 Automation of Architectural Design Process

In this section, the above proposed scheme for the design automation is applied in the architectural practice. For the design automation, a music theory was analyzed and the specific music theory for application to architecture was formulated.

The analysis of the music theory is as follows: the first person to make the connection between mathematics and music was Pythagoras. His theory was that pleasing sounds resulted from frequencies with simple ratios, such as 2 to 1, 3 to 2, and 5 to 4, etc., which we now call octaves, perfect fifths, major thirds, etc.

From a technical viewpoint, these ratios correspond to the frequency-relationship. For example, if A note is tuned to a frequency of 440 Hz., then a perfect fifth above that note has a frequency of 660 Hz., because the ratio of 660 Hz. to 440 Hz. is 3 to 2. In this way, musical structure can be demonstrated in the octave starting with C, using Pythagoras' ratios by which most of the notes are tuned to a scale, as shown in the left handed figure of Fig. 6. These ratios can be automated in an architectural design process. For example, each distance of joint-surfaces or each spacing distance of columns on a façade is illustrated as D1:D2:D3:D4, as shown in the right handed figure of Fig. 6. This formula can be calculated automatically with the aid of computer in an architectural design process, according to the musical ratios.

In architectural practice, this design automation of the music theory was tested on a German architectural project, Museum der Moderne in Salzburg, in collaboration with the German architectural office "Friedrich Hoff Zwink Architekten", and on a Korean architectural project, B-Project in Daegu.

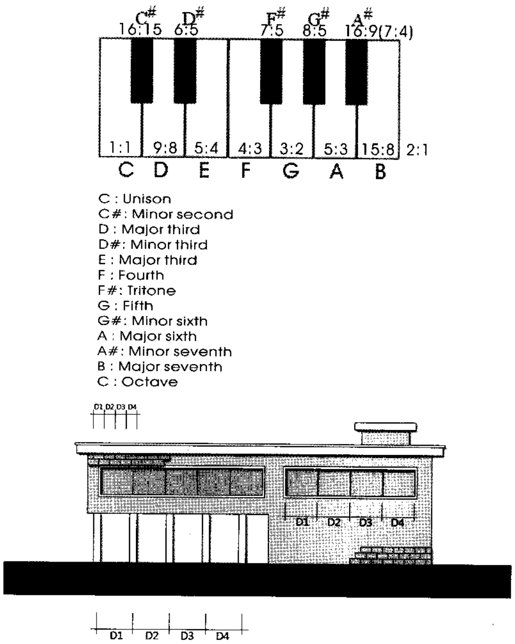

Fig. 6. Musical tones and corresponding Hz. & Basic shape for Design Automation

In the Museum project, this author received a design commission from the German architectural office of that museum to design the façade based on a familiar music piece of the musician Wolfgang Amadeus Mozart. In the B-Project, various design alternatives are studied for avoiding the boring façade design of the long window using Mozart's Clarinet Quintet K581.

The analysis of the music and the application of analyzed music to the façade design were very time- and labour-suspended work. Hence a new methodology such as a design automation was proposed during the design process(Fig. 7, 8). The function of this automation is to change either musical ratios or musical melodies in proportion to the distance between joint-spaces automatically.

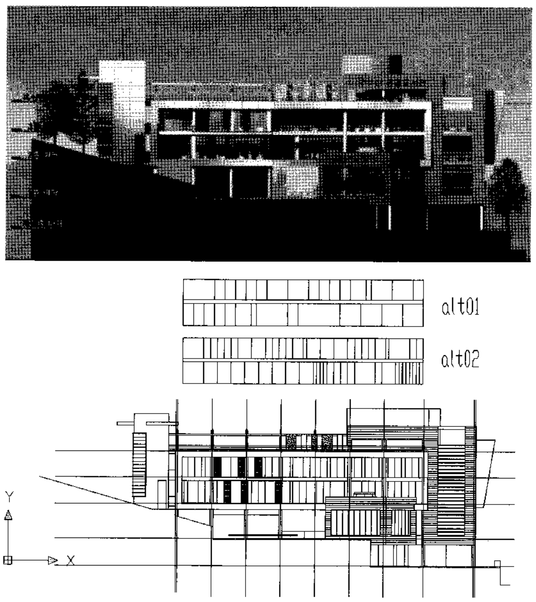

Fig. 7. Alternative Window Design of B-Project Using the Design Automation

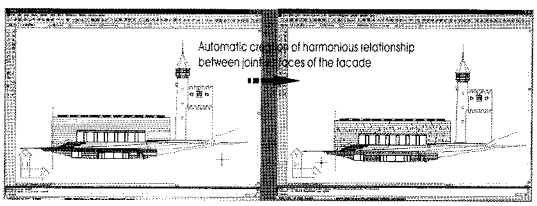

Fig. 8. Design Automation of the Museum Façade

Fig. 9. Photos of the Façade Details

Implementing the design automation, each distance between joint-surfaces of the façade is automatically created in the AutoCAD, according to the inputted music. The designer can select one of the alternative design examples that the computer proposed on the screen(Fig. 8).

In the case of the Museum, musical melodies are decided to be applied to the façade through this design automation, so as that observers of the museum can recognize the pattern of the façade listening to the corresponding music; if the musical ratios were used in the façade, the distance between the joint-spaces would express only the abstract meaning. Through this automation, we can find the fact that it is possible to integrate some design process of architecture into automation system. The following figures show real details of the façade after the design automation:

4.2 Robotic System in the Product Model

During the previous automation example, some requisite architectural information for object-oriented automation of the design process in the product model environment can be derived from the IFC model:

- Total Height of the Building: IfcQuantityLength
- Total Width of the BuildingL it can be measured from IfcQuantityArea
- Distance between Joint-Surfaces: it can be derived from IfcMaterial
- Placement of Elements: IfcObjectPlacement

These architectural information can be connected with robotic system for the interoperability between architectural and robotic system; for example, brick layer masonry robot as shown in Fig. 10.

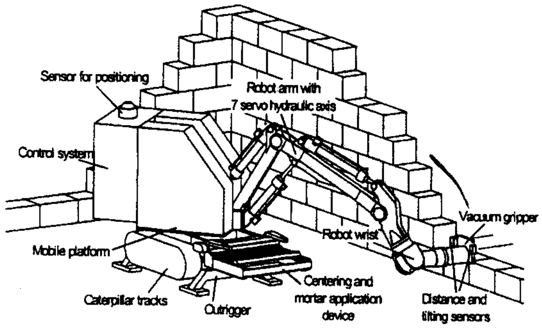

Fig. 10. A robot of Brick Layer Masonry

Several robots for automatic assembly of buildings were developed in the past. For instance, the EU project ROCCO, the brick layer masonry developed a large-range (10m reach) and high payload (up to 500kg) hydraulic 6 DOF robot for brick assembly [6]. This robot performs the assembly sequence obtained by the planning software and needs an initialization process in order to know the bricks pallet position. As architects, we do not need to know all mechanism of the robots in building construction, but we have to obtain basic knowledge about construction robots, such as function, structure, operating principle, etc., in order to consider these robotic systems on site in our architectural design process.

For an efficient working process with automation of design process and robotic system, design information of architecture has to be shared between building system, design rules, product model and robotic system. Fig. 11 shows these relationships. Therefore, the above mentioned automation of architectural design process has to be linked with IFC model for object-oriented automation and exchange of architectural digital data and with robotic system for rational architectural design and reasonable construction cost. Finally, it is strongly recommended that an application oriented design has to be considered by the architects from the preliminary design phase.

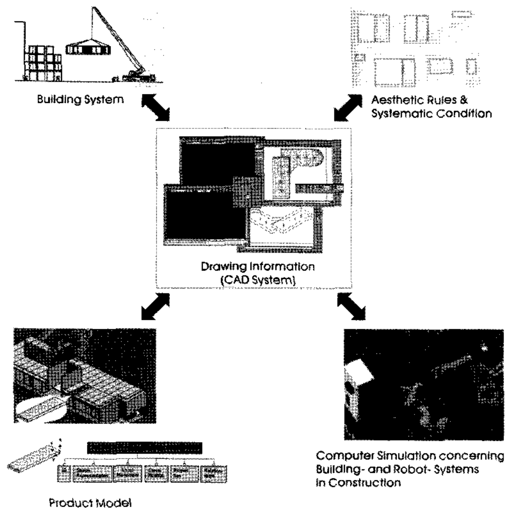

Fig. 11. Scheme of Information Exchange from Electronic Drawings up to Robotic System in Building Construction

5. CONCLUSION

A computer can become a design assistant to architects and engineers, only when it knows not only about drafting objects but also about design objects and their meaning in the architect's professional world. Traditional CAAD systems are the assistants to the draftsman. A new generation of CAAD's should become the architects' assistants. For such a new CAAD environment, it is a prerequisite that the system behave like a design-assistant and not a drafting tool [7].

The proposed design automation is an example of the new CAAD environment. Our application has been implemented on the basis of the concept "computer as design assistant". This automation aims to support architectural design process, based on aesthetic requirements, in particular the harmonious music relationship, and needs specified by architects and engineers.

A significant part of our paper is about product model, in particular IFC model, and robotic system in construction. According to Prof. Bock at the Munich University of Technology(TUM), about 90% of present labor requirements will be replaced by automation. Those workers who remain will probably be highly skilled technicians who can program and maintain the robots [8]. Therefore, we, the architects have to consider robots on construction site during various architectural design phases and keep challenging mind to realize our dream: robot- and aesthetic-suitable architectural design.

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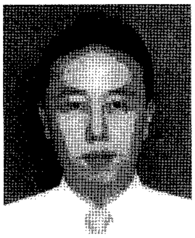

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