KNOWLEDGE REUSE IN THE DESIGN OF STEEL CONNECTIONS USING 2D-CAD DRAWINGS

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SUMMARY: *Design knowledge reuse is the most common design method in structural engineering and dominates completely in the design of steel connections. This paper describes a case study and a prototype with the objective of gaining knowledge on how to create computer support for knowledge reuse in the design of steel connections. The case study identified the key characteristics of the design knowledge reuse process in the form of subprocesses. It also showed that the most commonly used documents in these processes are drawings and that these contain most of the information needed for reuse. The prototype was implemented using the Case-Based Design approach. Evaluation of this prototype confirmed the findings of the case study and suggested that information about the geometry and topology of the members connected was sufficient for indexing previous steel connections. The prototype significantly facilitated the process of finding the documentation of recalled previous connections and thus most of the information necessary for reuse. A method of capturing the required information automatically during the process of the designer creating the drawings was implemented and evaluated.*

KEYWORDS: *knowledge reuse, case-based design, structural engineering, live capture.*

1. INTRODUCTION

1.1 Background

Over 50% of the work of structural engineers consists of reusing knowledge about previous design solutions (Moore 1994) – i.e., *the most common design method* is to search for, copy, and modify information and knowledge about previous solutions.

In using the design method of knowledge reuse, a number of advantages have been cited:

- A faster and cheaper design process (Barton and Love 2002, Carballo et al. 2003),
- A product with higher quality (Frakes and Succi 2001) and
- Faster and cheaper production. (Johnson and Broms 2000).

Information technology is increasingly used in the design process, and more and more of the information created during the design process is documented digitally. This should create new opportunities to support and aid the design method of knowledge reuse; however, there is a lack of tools supporting this method.

1.2 Aim and objective

The aim of this research, of which the studies in this paper form a part, is to facilitate the design method of knowledge reuse, focusing on structural engineering.

The case study will describe the design of steel connections. This is an area where knowledge reuse is the most common design method, and the most frequently used documents in this process are drawings. For these reasons, the design process of steel connections was chosen as the main target for the project. The *objective* was to gain knowledge on how to create computer support for knowledge reuse in the design of steel connections, focusing on the information in 2D-CAD drawings.

To achieve the objective, the following central research questions are addressed:

1. What are the key characteristics of the knowledge reuse process in the design of steel connections?
2. What information is used in this process?
3. How can this information be captured in the course of the ordinary design process?
4. What approach should be used for implementing computer support for knowledge reuse in the design of steel connections?

1.3 Method

Apart from studying relevant research and approaches used in practice, two research methods will be used:

- Case study and
- Prototyping

A case study is conducted mainly to find answers to the first two research questions. The case study is presented in part 3.

A prototype is implemented and evaluated. The purpose is to confirm the findings of the case study and to gain more knowledge concerning the third research question. The prototype and its evaluation are discussed in Section 4.

2. RELATED RESEARCH AND AVAILABLE APPROACHES IN PRACTICE

To answer the question 4, we describe related research below together with approaches available in practice.

2.1 Related research

There has been a great deal of research in the area of design knowledge reuse in structural engineering, with most of the approaches previously tested originating from Artificial Intelligence (AI). In the 1970s and ’80s a large number of rule-based expert systems were developed for the purpose of knowledge reuse – see for instance Löfquist (1994) for an overview. However, these systems were not entirely successful because of the difficulties in producing a formal representation of the knowledge (Brandon 1990, Pu 1993, Davenport et al., 1998). The knowledge had first to be acquired from experienced designers and then generalized and transformed into rules.

To overcome these problems, researchers started to study whether *cases* (information about specific problem-solving experiences) could be used as a representation of design knowledge. Using cases for design knowledge reuse is commonly termed Case-Based Design (CBD), see Pu (1993), Maher and Pu (1997), Johansson (2000) for an overview of CBD systems. Although many of these systems are useful in solving the specific problem they are intended for, CBD systems are seldom used in practice. One of the main reasons is that the representations used in these systems are system specific and differ considerably from representations used by the ordinary designer when documenting design information. This makes it difficult to achieve an automatic translation, and it usually requires manual structuring and indexing of the design knowledge. For this reason an increasing amount of research is concerned with using the information that can be automatically captured during the ordinary design process (Maher and Simoff 1998, Fruchter and Demian 2002, Johansson and Popova 2002).

Although there has been much research in the area of design knowledge reuse, very little has focused on the reuse of details. One exception is the steel design environment SteelTeam (Ernst and Roddis 1994)**,** implemented using the rule-based technique. The research team behind SteelTeam also implemented two other systems, concerning bridge fabrication errors. The BFX system was implemented using the rule-based technique (Melhem et al. 1996) and the CB-BFX system was implemented using the case-based approach (Roddis and Bocox 1997). Roddis and Bocox (1997) compared these two systems, concluding that CB-BFX performed better. However, in both the knowledge systems the knowledge had to be gathered manually.

2.2 Available approaches in practice

Many structural engineering companies have attempted to create aids for design knowledge reuse concerning details modeled using 2D-CAD drawings. In most cases the codification strategy (Hansen et al. 1999) has been used, meaning that the details have been structured, coded, and stored in a database. A search tool has been implemented which makes it possible to search for a detail using free text or some kind of classification standard, in Sweden mostly the BASB standard (Berg von Linde 2003). Examples of typical indexes used are "Beam-to-beam connection" and "Beam-to-column connection." Although these systems have been a major investment for companies, many problems have been reported and they are seldom used in design work (Berg von Linde 2003, Sverlinger 2000). The implementation of the systems themselves is seldom a problem: standard IT tools are used in a well-tried manner. However, the problem is to fill the system with useful details (Berg von Linde 2003): finding details, coding them, and storing them in the database takes a great deal of time and requires staff with good knowledge of both IT and structural engineering. Furthermore, maintaining such a system also demands substantial effort. This work is also regarded as tedious by most designers. Because of the substantial investment, in terms of both time and money, needed for such systems only large companies can afford them. And because all offices in the company have to bear the investment, the system has to contain details approved at company level. The problem with this is that the design of details differs between offices (Fenves 1998), and because "local details" are not included the usability of the system is limited.

Modern product-model-based CAD systems such as Tekla structures (www.tekla.com) and StruCad (www.acecad.co.uk) have functions that aim to facilitate the reuse of steel connections. These functions are based on the rule-based technique. For the designer to make a connection reusable, s/he should design rules describing when it is suitable to use that connection together with the behavior of the connection. However, as described above, it has been shown that it is very time consuming to gather all the necessary knowledge and to generalize this knowledge into rules.

Comparing the research above with the available approaches in practice, it is interesting to observe that although there has been much research in the area of design knowledge reuse, very little focuses on the reuse of details. If, on the other hand, one examines the work done in practice the opposite is the case: the majority of the work focuses on reusing details.

We may also conclude that the rule-based approach is currently tested in practice but with similar disadvantages as found in the research prototypes using this approach. To overcome these problems, researchers have tried the Case-Based Design approach applied to the information that can be captured in the course of the ordinary design process.

3. CASE STUDY

After a description of the case study, we describe and discuss our observations from the case. To explain why the project described here focused on steel connections, we first describe the observations on design knowledge reuse at different levels of granularity. To find answers to the first two research questions, we then describe and discuss our observations on the knowledge reuse process and the information used in this process:

1. What are the key characteristics of the knowledge reuse process in the design of steel connections?
2. What information is used in this process?

3.1 Case study description

Structural engineers in Sweden are also responsible for the detailing. For this reason, a structural design office was the natural choice to study knowledge reuse in the design of connections.

The case study was conducted at a structural design office in Gothenburg, Sweden. The first author was employed by the structural engineering company as a part-time consultant structural engineer over a two-year period (2001-2002). This made it possible to adapt the action research method (Gummesson 2000). This method is used mainly in management research with the aim of facilitating the process of designing organizations. Knowledge is generated using case studies, where the researcher actively participates in the design of an organization in a company, preferably as a consultant. The main data-gathering methods in such case studies are participant observation and informal interviews. The benefits of the method, compared to other case study methods, are said to be better access to data (Hult and Lennung 1978, Gummesson 2000) and a better understanding of the design process and the designers' situation (Alloway 1977, Gummesson 2000). As this study had a similar aim, namely facilitating the design process, although the type of design objects is different, the action research method was adopted.

The firm had about twenty offices in Sweden at the time of the case study. The office in Gothenburg employed about twenty engineers with a good mix of age and experience. The author was a novice at the start of the period of employment. This often made it necessary to discuss design problems with the more experienced engineers. These discussions created, in turn, good opportunities to observe the knowledge reuse process employed by the experienced engineers and the information that was used in this process. The author was involved in a wide range of projects and all kinds of engineering. The projects concerned most types of building assessments with slightly over half concerning steel structures situated in workshops.

3.2 Observations and discussions about design knowledge reuse at different levels of granularity

The method of knowledge reuse was used through the whole design process, from the conceptual design to the detailed design. In simple terms, we can state that the structural engineer reused solutions at two different levels:

- The system/subsystem level, and
- The detail level.

For reuse at the *system/subsystem level*, we observed that experienced designers in most cases quickly mentally recalled reusable previous solutions. Finding the documentation on the previous solutions was often more laborious, however. Fruchter and Demian (2002) make similar observations.

For the *detail level*, we observed that knowledge reuse was by far the most dominant design method. We also observed that experienced designers did not recall previous reusable solutions to the same degree as at the system/subsystem level. This is probably due to the fact that the amount of details are much greater than the amount of systems/subsystems. For the detailed level it was also observed that inexperienced engineers had to design many details on their own because it is not practically possible for an experienced engineer to be involved in the design of every detail. It was also observed that finding the documentation on previous solutions was even more laborious at the detail level. For the most frequently used materials (steel, timber, and concrete), it seemed that finding reusable steel details was more time consuming than finding reusable details for timber and concrete structures. This may be influenced by the type of projects carried out, but it seemed that the variation of steel details was greater than that of timber or concrete structures. These last observations were the reasons why the design process of steel details, and in particular *steel connections*, was chosen as the main subject of the project described here.

3.3 Observations and discussion about the reuse process and the information used in this process

3.3.1 Recalling previous connections

When asking an experienced designer for advice – how to solve a connection – documentation showing the *geometry and topology of members involved* was of greatest importance. The documentation most commonly used was the drawing of the structure containing the connection. In addition, the experienced designer also wanted more general information about the project. It was observed that the designer used this information to understand *the activity the structure should serve*. The example in Fruchter and Demian (2002) indicates that the index “*Hotel*” was used to give information about the activity. In our case study, we observed that this kind of classification of the activity was seldom sufficient: experienced designers preferred instead to know the client or company where the structure was to be situated as s/he often had detailed knowledge about the activity of the client/company gained from previous projects. Although it was clear that experienced engineers wanted this information, we observed that they seldom needed to ask for it – they could obtain the information by looking at the title block of the drawing, which in most cases includes the name of the client/company. If the client/company was unknown, the drawing containing the plan of the structure (or the plan created by the architect) could be useful in gaining an understanding of the activity.

Experienced designers also wished to know the more precise *function of the structure* where the connection was to be sited, for example “support for cooling aggregate” or “pipe support.” To some degree this is given by the drawing of the structure containing the connection. However, here too information can be found in the title block of the drawing.

We observed that the numerical values of the internal forces were not taken into consideration when recalling previous solutions, though of course indeed in the adaptation of the solution. The profile of the members, the activity around the structure, and the function of the structure all indicate the magnitude of the internal forces, however. The *degree of fixity* (whether the connection should be fixed, pinned, or semi-rigid) was always taken into consideration. In most cases this can be understood by examining the drawing of the structure containing the connection.

3.3.2 Finding information about a previous similar connection

When the experienced designer had recalled a reusable previous connection, the *information describing the connection* had to be found. A connection is mainly documented by one or more *details* (see Section 4.1). In order to find these details, the drawings of the project containing the previous connection had to be found and the details of that project browsed. As stated earlier, finding this documentation was a laborious task and we observed that the first detail recalled in most cases was the one selected. It was rare that information about several previous connections was considered before selecting one for re-use.

3.3.3 Understanding previous similar connections

We observed in the case study that reusing a connection does not mean simply copying part of a drawing. To be able to reuse a previous connection, the designer must have an understanding not only of the structural behavior of the connection but also how it should be produced and erected – i.e., the information found on the previous similar connection has to be transformed into knowledge. Dixon (1992) describes this process as "Information is put into context where it can be understood and become knowledge**."** It can be stated that the immediate context of a connection is *the structure where the connection is situated*. Information about the structure can be found in other drawings (sections and plans) of the same project. We observed in the case study that studying the drawings describing the context was vital, and Fruchter and Demian (2002) make the same observations. In some cases, this was not sufficient to gather the knowledge needed. For the reuse of connections designed at the office of the case study, we noted that the knowledge required could be gathered by informal contacts with colleagues (Sverlinger 2000). The *information about the designer***,** contained in the title block of the drawing, was useful in this process. A number of researchers have stated that this mix of computer system and a system of people (a social context) is a requirement for successful reuse (Daft and Huber 1987, Ponelis and Fairer-Wessel 1998, Hansen et al. 1999, Brown and Duguid 2000). If it was not possible to gather the necessary knowledge from colleagues, the next document examined was the design calculation document. This also gave an opportunity to reuse the design calculation process when adapting the previous connection (Johansson and Popova 2002).

For connections designed at other offices, the necessary knowledge is more difficult to obtain and the design has in many cases to be changed and adapted to fit the culture of the office and to obtain the expected behavior of the structure. We observed in the case study that the steel connections used in two offices of the same design firm, but in different cities, were designed using completely different approaches. Designing a structure mixing connections from these offices could easily lead to a structure that was difficult to erect. From this it can be concluded that it is preferable to reuse connections from the office of the designer (Fenves 1998), and *information about the office where the connection was designed* is useful in this process. This information can also in most cases be found in the title block of the drawing.

We observed that knowledge about the behavior of a connection in the production phase came from lessons learned (failures and successes) from previous projects. The feedback from the production phase is of great importance for successful reuse (Bartezzaghi et al., 1997). Fruchter and Demian (2002a) suggest that intermediate versions of a design solution should be captured for the purpose of reuse. However, we observed in the case study that reusing intermediate versions is rare in practice. One reason for this was that the intermediate solutions are seldom documented properly. A further and more important reason is that an intermediate version has not been tested in the production phase and has not been in use. In our view, this "testing cycle" is one of the main reasons why a designer should reuse previous design solutions.

3.3.4 Copying and adapting information about a previous connection

When the necessary knowledge was gathered, the information about the previous connection could be copied and revised to fit the new situation. We observed that finding the digital documentation – *in a format that could be used by the designer in the CAD system* – greatly facilitated re-use.

The same kind of work as the adaptation of previous details is needed each time changes are introduced into the project. The structure has to be adapted as a result of the new situation produced by the changes. It was observed in the case study that changes are very common and a great deal of the structural engineer's work involves adapting the structure as a result of changes. For this reason, the structural engineer uses both tools and a working method that facilitate adaptation. Using 2D-CAD tools, the flexible functions for copy and change, such as delete, move, are used and working methods that avoid errors in the adaptation process have been developed. Three of the most common working methods found in the case study for the adaptation of steel details were as follows

1. Redraw each detail that needs to be adapted from scratch looking at the previous detail.
2. Redraw the members that are going to be connected and then copy the rest of the detail from the previous detail and revise the copied information.
3. Revise the previous detail directly.

It is well known among structural engineers that the lack of sufficient adaptation is the cause of many design errors. It is the opinion, and experience, of the authors that most of these errors are due to using the third method above.

Product-model-based CAD tools like Tekla structures (www.tekla.com) and StruCad (www.acecad.co.uk) have functions that adapt steel details automatically if the geometry or topology of the members to be connected is changed. In this way, most of the errors caused by insufficient adaptation are omitted. These functions are based on the rule-based technique and setting these rules for a detail is somewhat time consuming as described above.

3.4 Conclusions from the case study

The key characteristics of the knowledge reuse process in the design of steel connections have been described and four subprocesses identified:

- Recalling previous connections,
- Finding information about the previous connection,
- Understanding the previous connections and
- Copying and adapting information about a previous connection.

When recalling previous connections, we observed that the following information was used:

- Geometry and topology of the members to be connected,
- Activity that the structure will serve,
- Function of the structure where the connection will be situated and
- Degree of fixity of the new connection.

When recalled, we observed that information about the following topics was needed in order to be able to reuse a previous connection successfully:

- The recalled previous connections (details),
- The structure where the previous connection was situated (sections and plans),
- The designer of the previous connection (title block), and
- The office where the previous connection was designed (title block).

The parentheses show where the information is found.

According to the observations and discussions above, we can conclude that drawings are the most common documents in design knowledge reuse relating to steel connections and that they contain most of the information necessary (if complemented by a social context). Having the digital documentation, in a format that can be used in the CAD system used by the designer, greatly facilitates the subprocess of copying and adapting.

We stated above that it is preferable to reuse connections from the office at hand. This does not mean that only connections from that office should be stored in a computer system for reuse. The more connections that are stored in the case-base, the greater the possibility of finding a usable previous connection. Comparing designs from other offices is also a good way of learning and developing the connections used at one's own office. To be most useful, however, a computer-based system for reuse should be based mainly on connections from a single office.

4. THE PROTOTYPE

A prototype was implemented and evaluated. The purpose of this prototype was both to confirm the findings of the case study and to gain knowledge on how the information needed could be captured in the course of the ordinary design process (research question 3).

In "Related research and available approaches in practice" (Section 2), we argued that the Case-Based Design approach applied to the information that can be captured in the course of the ordinary design process should be chosen for computer support of knowledge reuse in the design of steel connections.

A number of models describing Case-Based Reasoning have been developed, e.g., Kolodner (1993), Maher and Zhang (1993), and Aamodt and Plaza (1994). Comparing the subprocesses in these models with the subprocesses retrieved in the case study, we can state that the CBR models contain two subprocesses not found in the case study. These are:

- *Capture* information about previous cases and the new case and
- *Select* one or more cases for reuse.

Information has to be captured and translated to a format usable for the case-based design system. The system must capture information both about previous cases and about the new case. The capture of information about previous cases is termed acquisition by Kolodner (1993) and Maher and Zhang (1993) and retainment by Aamodt and Plaza (1994). The capture of information on the new case is labeled indexing in Kolodner (1993) and Maher and Zhang (1993) and identifying features in Aamodt and Plaza (1994).

It was observed in the case study that the first connection recalled in most cases was the one selected for reuse, as the process of finding information about previous connections was laborious. Using computer support that facilitates the locating of information enables the evaluation of more than one previous connection before the "best one" is selected for reuse. It is not surprising that all three models (Kolodner 1993, Maher and Zhang 1993, and Aamodt and Plaza 1994) contain the subprocess select.

The subprocess "understanding the previous connections" is not included in the three models (Kolodner 1993, Maher and Zhang 1993, and Aamodt and Plaza 1994). A similar subprocess can, however, be found in models of knowledge transfer processes (Dixon 1992, Sverlinger 2000). It can be concluded that it is difficult for a computer system to support the subprocess of understanding more than finding the information needed for this process. It can also be concluded that the subprocesses of finding, understanding, and selecting are interrelated.

From the discussion above we decided that the prototype should support the following subprocesses:

- *Capture* information about previous connections and the new connection,
- *Recall* previous connections,
- *Find, understand, and select* information about previous connections and
- *Copy and adapt* information about a previous connection

4.1 Capturing information about previous connections and the new connection

Barton and Love (2002) indicate that geometry and topology are the most important indexing features in the retrieval of previous parts in the field of mechanical engineering design. The same observation was made in the case study concerning the recall process of previous connections.

Information about the activity the structure should serve and the function of the structure where the connection is to be situated can be found in the text of the title block and in the sections and plans describing the context of the detail. Demain and Fruchter (2005) have created a match procedure using text analysis techniques. The terms used in this procedure classified the activity and the function. It was observed in the case study that this kind of classification was rarely sufficient. For this reason we decided not to include this information in the indexing of the new details but instead make it available for the designer in the finding, understanding, and selecting subprocess. The degree of fixity is seldom explicitly available in the drawing and it is therefore very difficult to capture this information automatically. The designer, on the other hand, can capture this information from the drawings describing the context of the detail. As stated above, this information should be made available for the designer in the finding, understanding, and selection subprocess.

The information needed in order to be able to reuse a previous connection successfully was listed in Section 3.4. It is quite clear that the details describing the recalled previous connection are the most essential in the process of reuse. Having found the drawing containing the detail, it is not particularly difficult to find the other required information.

4.1.1 Capture information contained in 2D-CAD drawings

As observed in the case study, most of the necessary information can be found in drawings. Design information has been communicated in drawings since the Renaissance, and the language of drawing is an accepted standard representation for building design (Mitchell, 1990). 2D-CAD systems have been the most common geometry modeling tool for more then a decade, and it is in the format of 2D-CAD drawings that most of the experience of a design office is documented and saved. Because of these facts, the 2D-drawings modeled using AutoCAD were chosen as the foundation for the system described here.

A structure, for example of steel, is documented in a number of drawings. In this way the designer subdivides the information into, for him or her, natural subparts. Many drawings are in turn subdivided into a number of views. This subdivision is also done in such a way that each view is a natural subpart for the designer. It has been argued that this natural subdivision is also a good subdivision for a CBD system (Johansson 2000). For steel structures, the views are mainly of three types: plans, sections, and details. Each view is uniquely defined by the project, the drawing, and the title of the view. A view of a steel connection is often termed a *detail*.

As stated above, a CBD system has to acquire the information needed automatically to be of practical use. Gathering information from drawings automatically – the machine interpretation of drawings – has been the goal of a number of research projects: Langrana et al. (1997) and Devaux et al. (1995) in the field of mechanical design and Cherneff et al. (1992), Noack (2001), and Berkhahn and Esch (2003) in architecture and civil engineering. Most of this research focuses on converting lines to objects. This is not a trivial process and more work is needed before the systems are sufficiently robust to be of practical use (Noack 2001, Berkhahn and Esch 2003).

It was noticed in the case study that in the process of creating a drawing, the designer gave the CAD program the information that needed to be captured. Some of this information is then transformed to vector-based lines and text, while some is lost. As stated above, it is difficult to transfer the vector-based lines and text back to the information given by the designer. For this reason, it was decided to try to capture the information during the process of creating the drawing.

To implement this, AutoCAD Architectural Desktop (ADT) Release 2 was used, in particular the tool AEC Details which is part of ADT. AEC Details is a supplementary tool for civil, electrical, and HVAC engineers. It consists of a number of commands written in AutoLisp. The fact that the AutoLisp code is available and editable enabled the capture of the relevant information in the course of the design process.

The implementation of the capture was termed the *indexing processor* and comprised two procedures:

- Acquisition of the name of the detail, and
- Acquisition of the geometrical topology of the members.

Each detail is uniquely defined by the project, the name of the drawing, and the title of the detail. When a detail is to be created the designer indicates this by creating a title. This is done using the command “Create title” in the tool AEC Details, cf. Fig. 4. The AutoLisp file implementing this command was edited so that the title and name of the drawing could be captured and stored in a variable. In this project the name of the drawing was assumed to be the same as the name of the file (this was the custom for small projects at the case study office).

The capturing of the geometry and topology of members was implemented by editing the part of the Material Compose command that is used by the designer to draw views of steel members, cf. Fig. 5.

There are six variables that are defined by the designer when drawing a steel member using the Material Compose command:

1. *View* – shape view, i.e., if the member is seen in section, top view, or elevation,
2. *Material* – since we focus only on metal shapes, the material is always steel,
3. *Profile* – profile name, i.e., IPE330,
4. *Hatch* – states if the member is hatched, e.g., if the view shows a cut through a member,

5. *Hidden* – states if the member is hidden and
6. *Gradient* – inclination angle of the member.

All these variables give information about the geometry and topology of a member.

The acquired information was structured and stored using Extensible Markup Language (XML). Usually there are a number of details contained in one drawing, with each detail consisting of one or more members. One XML file was created for each detail. As an example take a detail entitled A-A in a drawing named K101 with three members – steel profiles HE220A, IPE330, and IPN180 in different views. The AutoCAD drawing window with the three profiles composed and XML file produced during the process is illustrated in Fig. 1.

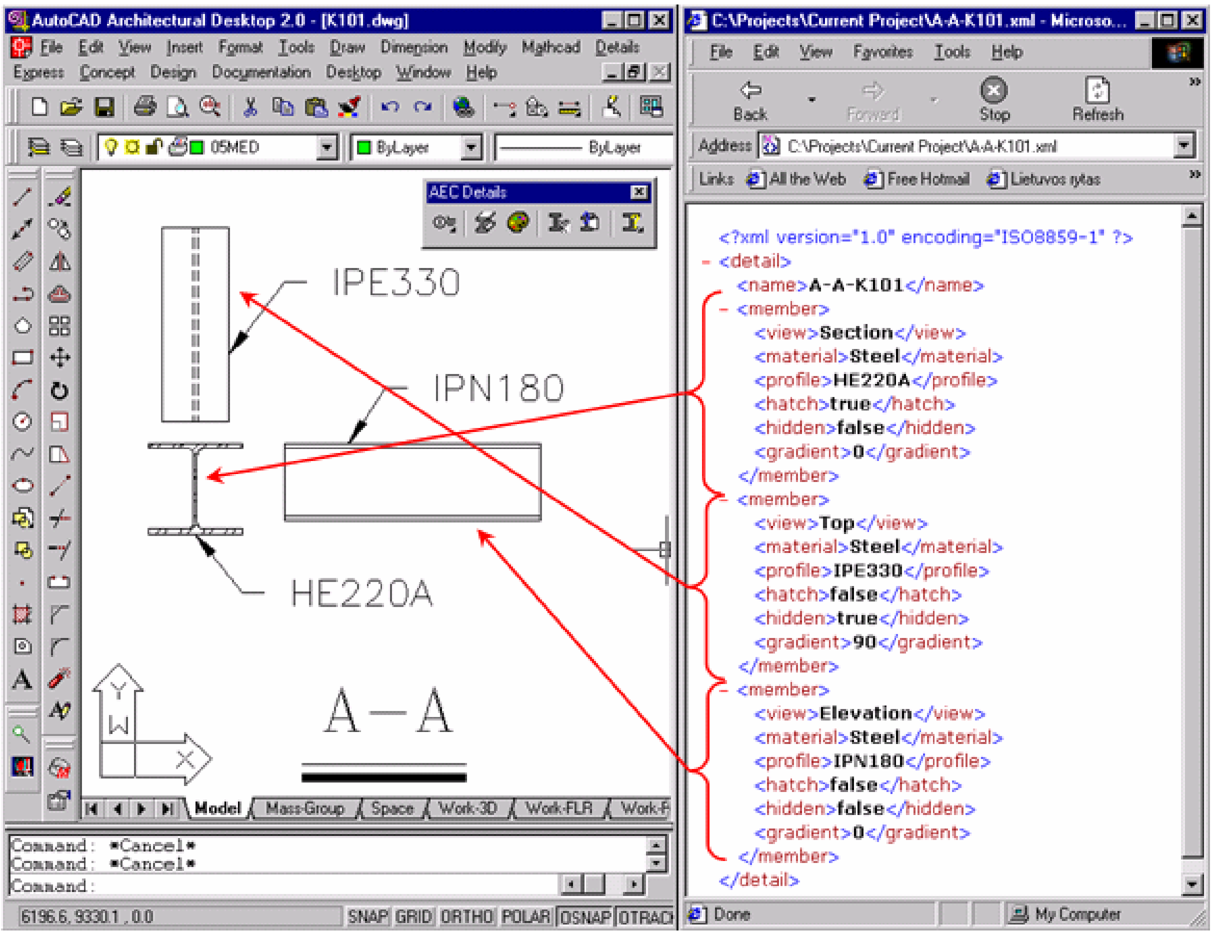

FIG. 1: Sample drawing and XML file

The name of the XML file is the same as the unique name of the detail and consists of the title of the detail and the drawing name in the syntax: TITLE-DRAWING_NAME.xml. For the example above with the title of the detail A-A and drawing name K101, the corresponding XML file will be *A-A-K101.xml.* Most structural engineers organize their project information in a directory specific to each project. Storing this file, together with the drawing, in the directory of the project makes it possible to find both the XML file and the drawing when required.

4.2 Recalling previous connections

To be able to recall the most useful previous connections, the usefulness has to be calculated. The usefulness of a case depends on real world circumstances, which are not completely known at retrieval time (Burkhard, 1998). For this reason usefulness here, as in most cases, is reduced to a similarity problem with the assumption that similar problems have similar solutions. Calculating the similarity was made by comparing the XML file of the detail the designer was currently working on, the *new detail*, with the *previous details* in the case base, and then calculating a match score.

The similarity between members was calculated using Nearest Neighbor matching (Kolodner 1993), where each XML element was matched in a rather straightforward manner (for further information see Johansson, 2000).

Because a detail could contain more than one member, we had to decide which member in the new detail corresponded to which member in the previous detail. As a result, each member in the new detail was compared to all the members in the previous detail. Then the match score for each possible configuration was calculated and the highest score was taken as the match score between the details.

The matching procedure between details became somewhat more complicated as the number of members is not fixed. If, for instance, the previous detail had more members than the new detail and each member in the new detail was fully matched by one member in the previous detail, this resulted in a full match – see Fig. 2. This problem was solved by conducting two matches when comparing the new detail with a previous one. First, it was investigated how the members in the previous detail matched those in the new one. Then it was investigated how the members in the new detail matched those in the previous one.

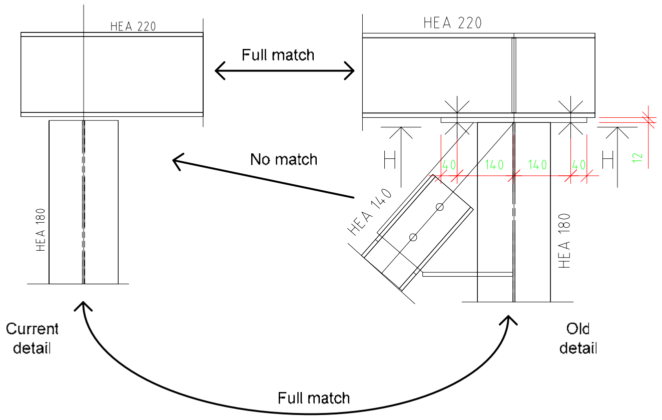

FIG. 2: Matching procedure

The match process, as described above, was implemented using Java. The output from this implementation was termed the *Recall processor*.

When the designer decides to start a retrieval session, the *Recall processor* reads the XML file of the new detail and compares it with the XML files of previous details. When all previous details are compared with the new detail, the *Recall processor* produces another XML file, termed the *result file*, with data related to the results found. It includes the match score, the name of the XML file of the previous detail, the project name, and the path to the drawing file containing the detail.

4.3 Finding, understanding, and selecting information about the previous connection

As stated above, we noticed in the case study that the designer had more problems finding information about previous connections than recalling them. To help the designer find the information about the previous connections needed, a small program called the *Selection processor* was implemented in AutoLisp. The detailed example below shows its function in more detail.

4.4 Copy and adapt information about a previous connection

We observed in the case study that finding the documentation digitally, in a format that could be used in the CAD system used by the designer, greatly facilitated reuse. Using the CAD system, familiar to the designer, as a base for the CBD system makes it possible for the structural engineer to use the ordinary working methods to adapt the previous detail to the new situation.

4.5 Detailed Example

In the course of the evaluation of the prototype a detailed example was created. The purpose of this was to show how the prototype could be used in practice.

4.5.1 Capturing information about previous details

To create a realistic situation, a directory structure was copied from a structure engineering firm. The directory structure contained information from two projects named Siloarea Rörgata and Siloarea 600-700, see Fig. 3. The drawings in the two projects contained 105 details in total.

FIG. 3: Project folder window.

The details were of course not modeled using the prototype described in this paper. For this reason, the previous details had to be retained. This was performed by using the commands in the *Indexing processor* to draw new profiles on top of existing ones in order to produce XML files of the previous details. Storing these files, together with the drawing in the project directory made it possible to find both the XML file and the drawing, when needed, even if the project directory was moved.

4.5.2 Capturing information about the new detail

In our example, the designer is about to compose a detail: three standard steel profiles IPE5000, HE200A, and IPE330 need to be connected into an assembly unit. The detail describing the connection should be entitled A-A. The designer starts by creating the detail title using the manipulated command *Create Titles*, see Fig. 4.

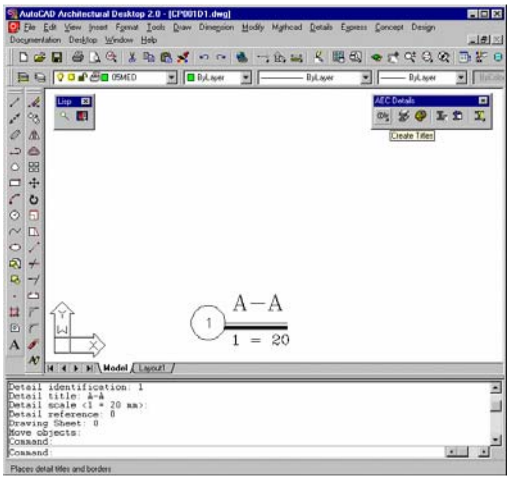

FIG. 4: Detail title created using a command from the Details program

The designer now draws the three different profiles: IPE500 in elevation view, HE200A in section view, and IPE330 again in elevation view. This is performed using the manipulated command *Material Compose*. The AutoCAD window with the modeled profiles and corresponding XML file are shown in Fig. 5.

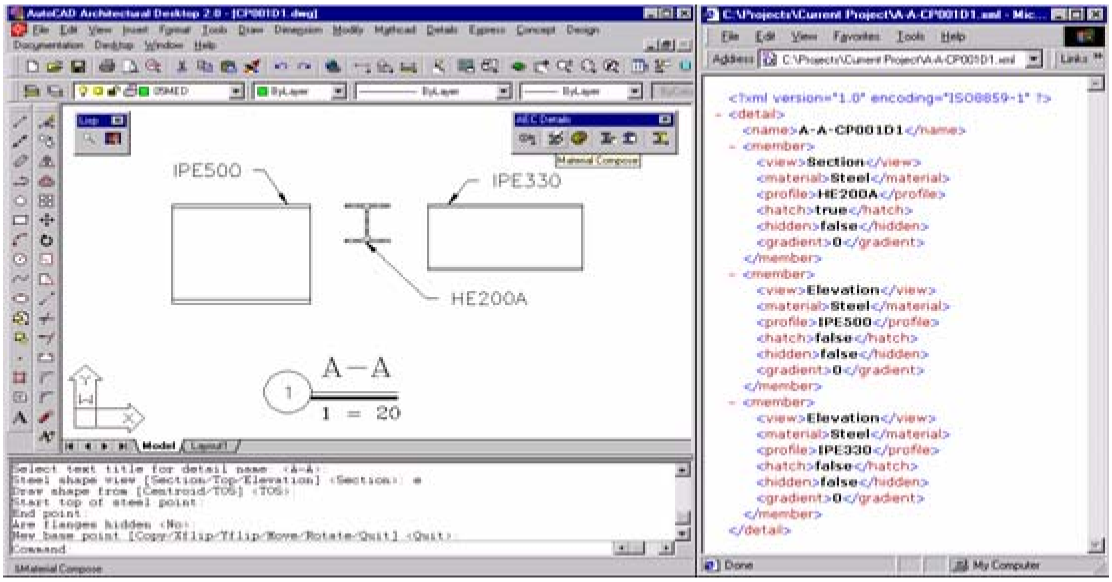

FIG. 5: AutoCAD window and XML file after insertion of the three profiles

In this way, the designer describes the new detail so that the relevant information can be captured in the course of the ordinary design process.

4.5.3 Recalling previous details

Having the XML file of the new *detail***,** the designer can start the *Recall processor* to find information about similar previous details. When the search is completed, the information about the five previous details with the highest match scores is stored in the result file.

After the recall session has been completed**,** the designer can start the *Selection processor*.. The *Selection processor* opens a dialog box and displays the search results from the result file, see Fig. 6.

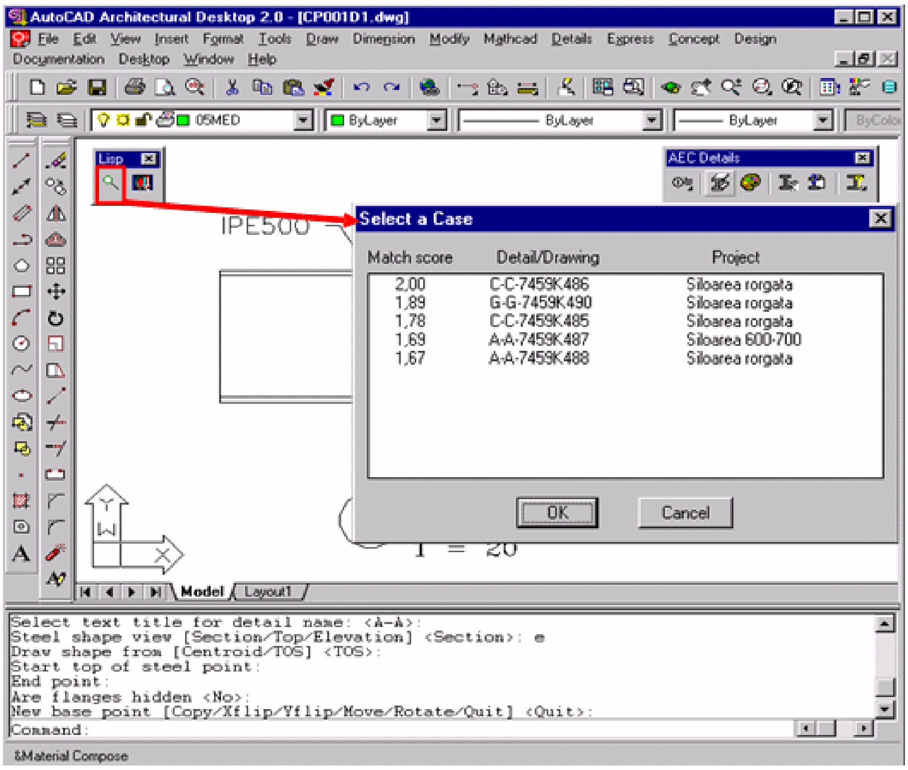

FIG. 6: The Selection processor

4.5.4 Finding, understanding, and selecting information about the previous details

As can be seen from the results displayed, there are five details with different match scores. The more similar the previous detail to the new detail, the higher the match score. The highest possible value is 2.00. In this example, we have one previous detail that corresponds perfectly to the new detail, i.e., its match score is 2.00. As the designer is obviously interested in those previous details with members that have the same shape and profiles, it is most likely he/she will start to evaluate the previous detail with the highest match score. When a detail is selected the designer can press the OK button, which makes the selection processor open the drawing containing the selected detail and the part of the drawing where the detail is situated will be zoomed in on automatically, see Fig. 7.

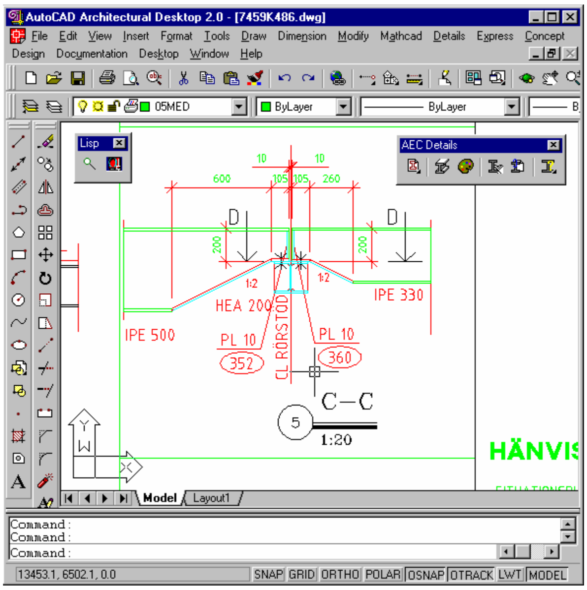

FIG. 7: Zoom-in of a previous detail

When the detail has been found**,** it is easy to find the other information needed to evaluate and understand the previous connection, e.g., the title block of the drawing of the detail, sections**,** and plans describing the context of the connection, see Fig. 8.

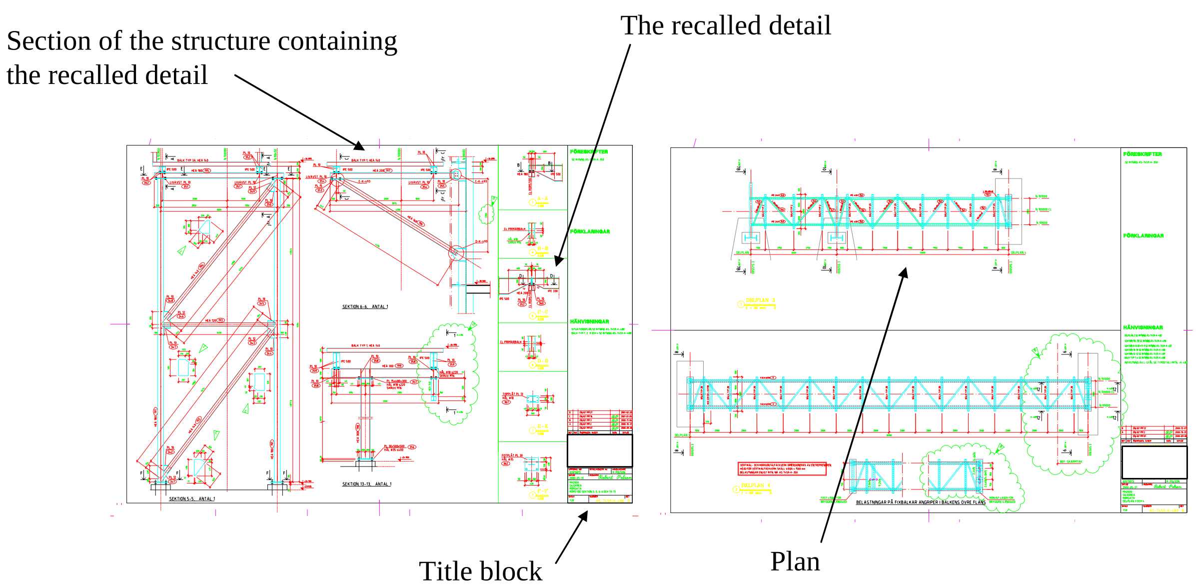

FIG. 8: Finding the information in the title block and in the sections and plans describing the context of the previous connection

Using the selection processor, it is also easy to investigate more that one previous connection and to evaluate and compare these connections before selecting one for reuse.

4.5.5 Copy and adapt

The details documenting the selected previous connection can now be copied and adapted using standard commands available in AutoCAD and the normal working methods used by the designer. Because the structural engineer draws the members that are going to be connected, to index the design problem (see Fig 5), this can be used when using working method 2 (or 1) described in Section 3.3.4. As can be seen when comparing the members in the previous detail with the ones in the new detail, the member with the HEA200 profile differs in terms of vertical placement. The members in the new detail were placed in this way so that a horizontal surface could be created, on top of the steel, for grating. The previous detail shows another way of resolving this. It is now up to the structural engineer to decide whether he/she is going to adopt the previous detail and lower the HEA 200 member. This shows that adaptation can be a fairly complicated process and that the re-use of a detail can cause changes to the other parts of the structure.

For more information about the function of the prototype see Kulikauskas (2002).

4.6 Evaluation of the prototype

According to Clayton et al. (1996), a prototype can be evaluated on four distinct levels: theoretical evidence, worked example, demonstration, and trial.

The two first levels, theoretical evidence and worked example, have been used above to justify the chosen approach.

The prototype and the working example was demonstrated to structural engineers on several occasions. In this way the description of the subprocesses and the information used in these processes was confirmed. The view of the structural engineers was that the prototype would be of great use and should result in time savings. The designers first pointed out the need for quality control, but after a discussion it was concluded that having a more structured reuse process also creates an opportunity to find problems and defects, which in turn could result in details with fewer errors.

Several trials, the fourth evaluation level, were conducted to evaluate the prototype, both in the course of the development of the prototype and in the course of ordinary design work at the case study structural engineering office. The trials were performed in an ad hoc manner to test different features of the prototype, and the number of trials was not counted. However, it was observed in the course of these trails that relevant previous details were recalled by the system in most cases and that it was easy to find the drawing of the previous detail using the features of the prototype. Despite the ad hoc manner of the trails, it is the authors’ conclusion that the information that was used for indexing the details was sufficient. It can also be concluded that the prototype considerably facilitated the process of finding the required information. This in turn made it possible to investigate a number of alternatives, which is currently not common practice.

In the course of ordinary design work it is often necessary to change the profile and/or the topology of members, for example because of changes in the project that influence their geometry and topology. When changing a member, it was observed that the XML file of the connections was not updated correctly. When a member was deleted and replaced, the information about the new member was added to the XML file but the information about the old member was not deleted. The indexing of the connection thus became corrupt. As not all the information about the member is stored in the representation of the CAD program, it is impossible to trace which member was deleted/changed so that the right information could be deleted from the XML file. To overcome this problem, the XML file of the new detail had to be deleted and new members drawn on top of existing ones each time a recall session was performed or a detail was to be retained. Even though this was not a great deal of extra work, it made it difficult to incorporate the prototype in the ordinary design work at the case study design office, i.e., capturing the required information automatically is necessary for a knowledge reuse system to be usable in practice (Flemming and Woodbury 1995, Fruchter and Demian 2002, and Kamara et al. 2003).

5. SUMMARY AND FINAL REMARKS

This paper describes findings from a case study together with an implementation and evaluation of a prototype for design knowledge reuse. Using the case study we have argued that the design of details, especially steel connections, is the area where the design method of knowledge reuse is most frequently applied. The subprocesses of knowledge reuse in the design of steel connections were identified during the case study together with the information used in these subprocesses. It has been argued that the Case-Based Design approach applied to the information that can be captured in the course of the ordinary design process should be chosen for computer support for design knowledge reuse. Combining the subprocesses of the knowledge reuse process found in the case study with the subprocesses from known case-based reasoning models gave a process model containing the following four subprocesses**:** *capture; recall; find, understand and select*; and *copy and adapt*. Observations during the case study showed that drawings are the document type most used in design knowledge reuse for steel connections and that they contain most of the information needed.

The evaluation of the prototype confirmed the findings of the case study. The evaluation also indicated that indexing details using the geometry and topology of the members involved was sufficient and that the prototype facilitated the process of finding information about recalled previous details.

We noticed in the case study that in the process of creating a drawing, the designer gave the CAD program the information that needed to be captured. We therefore decided to try to capture this information during the process of the designer creating the drawings. Although successful in capturing the information required, it was observed in the evaluation of the prototype that changing a member could result in incorrect indexing of a detail. The fact that the entities used in the CAD system are not the same as those used for indexing made it hard to avoid extra work for the designer, in addition to the ordinary design work. Even though the extra work was not substantial, it made it difficult to incorporate the prototype in the ordinary design work at the case study design office.

Today CAD software increasingly uses the product modeling technique. A product-model-based representation contains not only geometrical entities, it also contains real world entities that are modeled using the object-oriented technique. These are also the entities that the designer creates and changes in the course of the design process. For this reason a product-model-based representation creates new opportunities to acquire the required information. It has been reported that the product modeling approach provides benefits, such as higher efficiency and better quality, both in the design work and in the collaboration with other disciplines (Kam et al. 2003), and, when it comes to design re-use, it creates greater opportunities to acquire the required information, automate the adaptation of details (www.tekla.com) and incorporate feedback information (Mukhtar el al. 2004, Karlsson and Mathiasson 2004). For this reason, it can be stated that the product modeling approach should also be used for design knowledge re-use. To enable this to be used in practice, it is, however, important to understand the traditional design knowledge re-use process and the information that is used in this process.

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