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Towards a Standard-Independent Design Process

Vers une normalisation du processus de la conception

Der normunabhängige Konstruktionsprozess

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SUMMARY

The design process for most engineered products involves the use of knowledge found in product-specific design standards. As a result, creating formal models of these standards and processes has been an active goal of computer-aided engineering. This paper first reviews an early approach to formalising the use of design standards during the design of structural component cross sections and then describes two more recent approaches applied to more difficult detailed design problems for reinforced concrete columns and beams. The last section of this paper discusses the advantages and disadvantages of these three approaches.

RÉSUMÉ

L'élaboration du processus de la conception de la majorité des produits requiert l'utilisation d'une connaissance contenue dans les normes de calcul spécifiques au produit. Un des principaux objectifs de la conception assistée par ordinateur est la création de modèles formels de ces normes et de procédures permettant leur mise en application. Cet article passe en revue une première approche visant la formalisation de l'organisation des normes de calcul dans le cas du dimensionnement d'une section d'un élément porteur. L'article expose ensuite deux approches récentes appliquées à un domaine plus complexe, celui du dimensionnement des poteaux et des poutres en béton. L'article présente enfin les avantages et les désavantages de chacune des trois approches.

ZUSAMMENFASSUNG

Der Konstruktionsprozess der meisten Ingenieurprodukte wird durch Wissen beeinflusst, das aus den produktspezifischen Normen abgeleitet werden kann. Die Entwicklung sowohl formaler Modelle für die Abbildung des Normwissens als auch expliziter Prozesse für deren Nutzung ist damit ein wesentliches Ziel der Forschungsaktivitäten auf dem Gebiet des 'Computer Aided Engineering'. In diesem Beitrag wird zunächst ein früher Formalisierungsansatz für die Nutzung des Normwissens bei der Konstruktion von Bauteilquerschnitten beschrieben. Weiterhin werden zwei Systeme jüngeren Datums für die detaillierte Bewehrungsführung in Stahlbetonstützen bzw. Balken vorgestellt. Im letzten Abschnitt werden die Vor- und Nachteile der drei unterschiedlichen Ansätze diskutiert.

1. Introduction

The design process for most engineered products, such as load–bearing structures, involves the use of knowledge found in product–specific design standards, such as structural safety codes. These design standards, also referred to as codes or specifications, may define limitations on product attributes, prescribe design processes, or define limitations on product performances with respect to safety, reliability, usability, constructability, etc. As a result, creating formal models of these standards and processes for applying them has been an active goal of computer–aided engineering.

Initial research led to systems in which the information provided in the provisions of a standard were hard–coded into design synthesis procedures; the provisions of a standard were represented as lines of code interleaved with the design synthesis and process control knowledge. Early research in standards modeling proposed the use of declarative languages for describing the relationships between design data and requirements described in standard provisions. More recent research activity has focussed on automating the process of evaluating a synthesized design for conformance to such declaratively modeled standards. Early attempts led to systems that separated standards from design procedures, but that only checked designs for standard conformance after these designs have been created. Creating computer–aided design systems that make use of such standard models more proactively during the process of synthesizing a design (i.e., a standard–independent design process) has also been a research objective.

This paper first reviews an early design system that uses design standard models to determine the parameters of structural component cross–sections and then describes two more recent approaches applied to more difficult detailed design synthesis problems for reinforced concrete columns and beams. The last sections of this paper discuss the advantages and disadvantages of these three approaches and present some conclusions.

2. An Early Approach—SPEX

One of the earlier such attempts to formalize the use of design standards in the design process was the SPEX system developed by Garrett and Fenves [2]. SPEX uses a standard–independent approach for sizing and proportioning structural member cross–sections. The system reasons with the model of a design standard, represented as a set of decision tables and functions that each define how to derive a data item value, to generate a set of constraints on a set of basic data items that represent the attributes of a design to be determined. These constraints are then given to a numeric optimization system to solve for an optimal set of basic data item values (see Fig. 1).

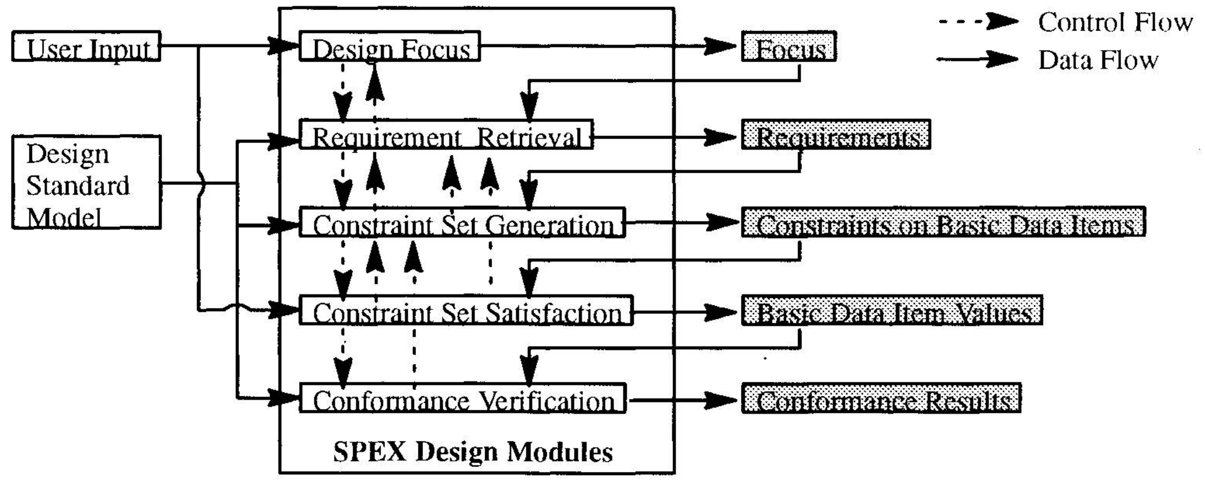

Figure 1 — SPEX Approach to Structural Component Design

SPEX is described as being a standard–independent design process in that both the process of generating the set of constraints from the standard and the process for finding the optimal solution of these constraints is generic and thus not specific to the design standard being used. The results of the process are certainly dependent on the standard being used, but not the process. The design process in SPEX basically consists of the following steps: (1) the type of structural component being designed, the set of behavior limitations of that component on which to focus the design process, the design context (e.g., loads and support conditions), and the design objectives (in terms of a basic set of design attributes called *basic* data items) are specified by the user; (2) SPEX then finds the requirements in the standard that correspond to the design focus; (3) SPEX then generates a set of constraints from the identified requirements by backward–chaining through the decision tables and functions until only basic data items are referenced (all decision table conditions and functions in the backward chain form the constraint set); SPEX then sends this set of constraints off to a constraint solver and finds a set of values for the set of basic data items referenced in the constraints. Thus, it is assumed that both the objective function and all derived data item definitions in the model of the standard are expressed in terms of the basic data items (design attributes) of the object being designed.

3. More Recent Approaches—KEXPS and KOORDS

More recently, this issue of standard usage in detailed design has been investigated by Meinecke and Scherer in the development of KEXPS, a system for assisting in the design of reinforced concrete members, and by Mehrafza and Scherer in the development of KOORDS, a system for assisting in the design of reinforced concrete frames.

The problem of designing the reinforcement bar layouts for beams, columns, and their connections has many more parameters, mostly geometrical, than do the cross–section design problems that Garrett and Fenves addressed in SPEX. In addition, the EUROCODE 2 [1] for Reinforced Concrete Structural Members contains only a few provisions that relate to the detailed placement of the bars, while there are many more provisions relating to the required area of steel, depth of steel, and other more abstract design parameters. There are, however, several manuals that accompany the EUROCODES with additional design knowledge. As a result, Meinecke, Mehrafza, and Scherer had to develop approaches to their respective design problems that incorporated knowledge not found in a standard with the requirements that are found in EUROCODE 2. The next two sections describe each of these approaches in more detail.

3.1. KEXPS—A System for Design of Reinforcement Layout for Concrete Members

KEXPS consists of two separate components: a design process model and a product model (see Fig. 2). The fundamental design idea of KEXPS is to solve a design problem by generating and evaluating different design alternatives. Each of these alternatives is represented in the object–oriented product model as a hypothesis method. These methods generate the different design alternatives. KEXPS has been verified and fully implemented for the design of the longitudinal and transverse reinforcement of concrete columns.

For reinforced concrete columns, there are a limited number of widely accepted cross–sectional layouts for the reinforcement bars. As such, the design process usually proceeds from selection of basic layout alternatives to a detailed design of that layout for the specific loading context. While these layouts are not specified within the standard, they do greatly influence the details and the practicality of the resulting design. Also, the number and location of various parameters that need to be checked for conformance to a design standard will vary with each of these alternative layouts. Thus, in KEXPS, the representation and checking of EUROCODE 2 was organized around these layout alternatives.

The design process for a reinforced concrete column is performed in KEXPS in four major modules, as shown in Fig. 2: hypothesis, analysis, evaluation, and system selection [7]. First, the hypothesis module proposes several different bar layout design alternatives from a set of standardized layouts for concrete columns. These standard layouts are described in the manuals that accompany EUROCODE 2, such as [5]. Each fundamental alternative layout is represented as a hypothesis method. Before the alternatives are worked out in detail, a fundamental mechanical review takes place and mechanical behavior constraints are checked. These methods are comple-

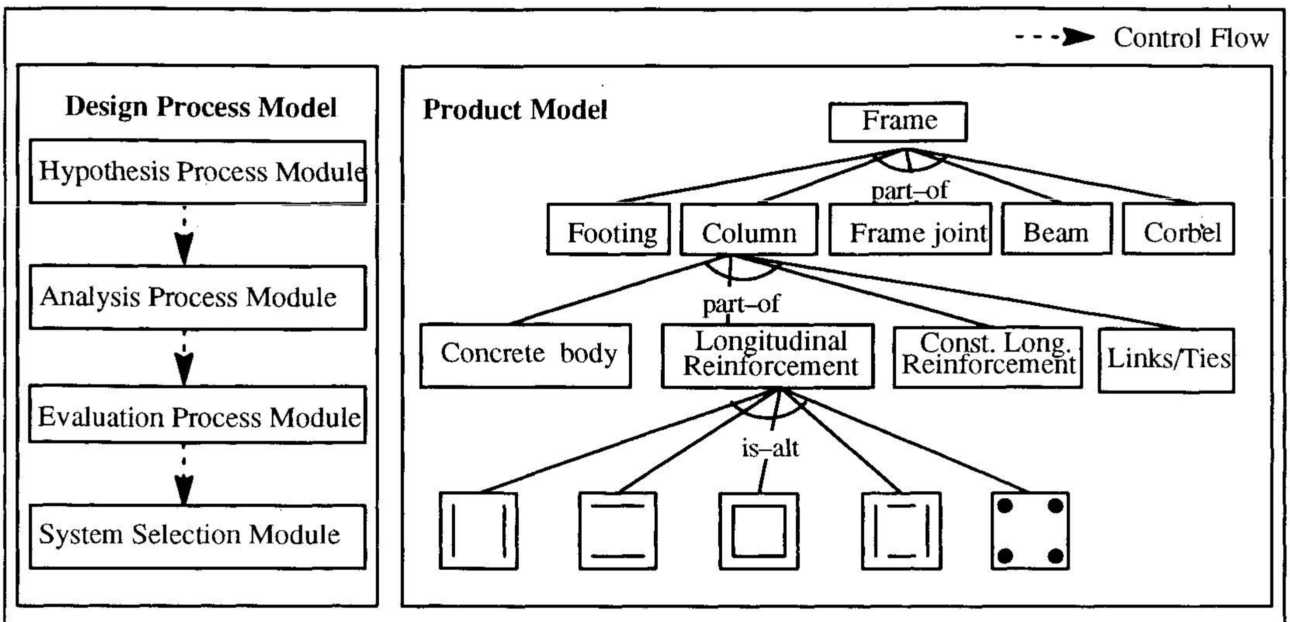

Figure 2 — KEXPS Approach to Structural Component Design

mented by refinement methods that develop the fundamental layout towards a specific design aspect (e.g. minimum of steel area). Together, the hypothesis methods assign values to various attributes such as bar spacing, bar sizes, edge distances.

The analysis module checks the generated design alternatives against standard requirements which are not considered in the hypothesis module. These requirements are represented as rules that evaluate the attributes of the alternative column reinforcement layouts. The evaluation module uses additional non–standard–related criteria, such as ease of construction, cost or bonding, to evaluate the various design alternatives that were found to conform to the standard requirements. The results from the evaluation module for the remaining alternative bar layouts are compared using a fixed formula to select the best alternative. Finally, the selection module gives the user the opportunity to view and select a layout from the remaining alternatives by using the commercial CAD–System UNICAD (Hochtief AG [4]).

3.2. KOORDS—A System for Synthesis of Reinforcement Layouts for Reinforced Concrete Frames

KEXPS is able to take great advantage of the limited number of acceptable layouts for reinforced concrete columns in organizing and using the requirements from EUROCODE 2. However, the design of the reinforcement layout for beams is more complicated than for columns because the layout of the bars for a beam framing into two columns may have very complicated layouts that do not easily breakdown into a small number of standardized layouts. Instead of following a SPEX or KEXPS approach, where the template of parameters is first selected and then the parameters are computed, KOORDS builds up, i.e., synthesizes, the reinforcement bar layout using a generative system. KOORDS must thus deal with a large number of possible design contexts and must determine which standard requirements apply to which contexts. Both the design process and design product models are implemented in a full object–oriented environment. The design process in KOORDS involves: generation of reasonable solution alternatives, verification of alternatives, evaluation of alternatives and selection of the optimal alternative. The optimization of reinforcement layout is based on concepts developed by Mehrafza and Scherer [6].

The synthesis process in KOORDS integrates complicated geometric reasoning with domain and heuristic knowledge for generating layouts. The heuristic knowledge for locating pieces of reinforcement bar refers to standard–derived limiting values (e.g., bar spacing) that are assumed to be defined in any standard for reinforced

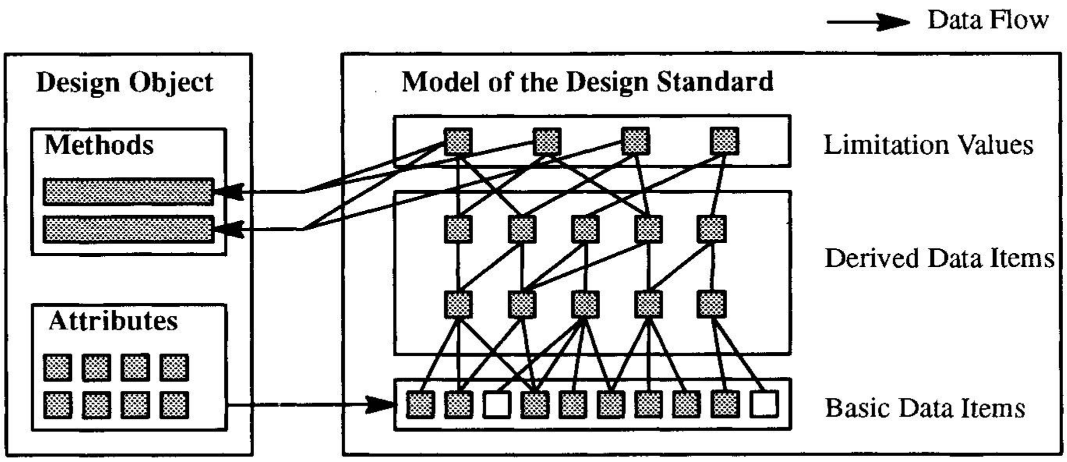

Figure 3 — KOORDS Approach to Structural Component Design

concrete beams (see Fig. 3). If a standard does not provide a definition for such a limiting value, a default value is used (and hence becomes a heuristic and not a requirement). Thus, in this way the design knowledge is integrated with the formal models of design standards through this interface of anticipated limiting values. The standard is thus represented as an object–oriented model similar to that described in [3], with the top level data items not a set of requirements, but rather a set of limiting values defined in terms of a network of other data items.

Object classes for the various components of the layout have slots for these limiting values that are sent a message when the limiting values are needed during the synthesis process. When a limiting value is requested, the method associated with that slot is evaluated, which causes other data items in the standard model to be evaluated. Eventually basic data items are reached, which are mapped back to the object requesting the limiting value. These data items are referred to as mappings. A new standard can thus be added to this system by creating a set of definitions for limiting values, definitions of supporting data items, and the basic data item mappings.

4. Discussion

In this section, the advantages and disadvantages of SPEX, KEXPS and KOORDS are discussed, with special attention paid to the separation of the standard knowledge from other design knowledge.

SPEX was originally described as a standard–independent member design process, because SPEX symbolically reasons with a formally modeled design standard and generates a set of constraints which are then solved generically by a standard–independent optimization process [2]. However, SPEX can be more precisely defined as a system for standard–independent proportioning (a kind of design process) of structural component cross–sections. It performs no synthesis task in the sense that synthesis is the combining some objects to build a meaningful and more complex object which provides some specific functions. SPEX does not reason with arbitrary collections of related objects, but rather assumes a fixed set of interrelated objects to exist as the basis of both the product model and the standard model. Because SPEX is based on the assumption that the product model used by the design process is the same as that used in the standard model, the design process employed by SPEX is not truly standard–independent.

The approach taken in SPEX works well for design problems in which: (1) an appropriate cross–section type can be *a priori* determined for a given design problem, (2) each of these types can be described in terms of basic data items found in the standard, and (3) the standards provide ample constraints on these basic data items describing the cross–section. As a result of these limitations, the SPEX approach for standard independent member design cannot be directly applied for more complicated design contexts, such as the design of reinforcement layout for a concrete column or beam. SPEX could be used to determine some of the more high–level decisions, such as the depth of a concrete beam or the amount of tensile and compressive steel. However, to use SPEX for layout of the reinforcement, the layout would have to be parameterized so that all parameters are unique variables and the requirements would have to be expressed in terms of these variables, making the solution very problem–specific. This limitation exists because SPEX makes the assumption that the data model (i.e., the set of basic data items) used in the standard is exactly the same as the data model used to describe the resulting design.

Even if a complex reinforcement layout could be parameterized, the objectives and constraints would also have to be expressed in terms of the large set of parameters to make the problem amenable to a SPEX–based approach. Some specific limits, such as flange buckling for steel structural members and bar spacing for reinforced concrete structural members, are expressed in terms of detailed parameters. However, standards do not normally express most requirements in terms of such detailed design parameters. Rather, standards normally express limitations in terms of high–level performance measures (e.g., crushing stress) or sizing parameters (e.g., area and depth of reinforcing steel). As such, even if a more detailed design problem such as reinforcement layout could be parameterized, the objectives and constraints derived from the design standard would mostly be in terms of more abstract design attributes. Additional knowledge describing the relationships between those abstract design attributes and the detailed design attributes would be necessary to solve this problem using a SPEX–based approach. Defining this knowledge in terms of equality constraints would likely be very difficult if not impossible for a complicated bar layout for a reinforced concrete beam. Thus, detailed design problems, such as reinforcement bar layout, cannot be realistically solved by a SPEX–based approach.

Like SPEX, the design approach employed in KEXPS is a standard–independent design approach. The design process invokes the hypothesis methods associated with the alternative templates, and then analyzes, evaluates and selects among these generated alternatives (i.e., using a generate and test approach). Both the hypothesis methods of the product model and the analysis rules are dependent on the constraints and criteria defined within a standard. KEXPS is able to handle more difficult detailed design problems than SPEX, but only after all design alternatives are *a priori* enumerated as templates and the appropriate design standard knowledge is represented for each alternative template.

KEXPS is able to get around the need for a large, complicated set of parameters for describing all alternatives (a problem with SPEX) by using an object–oriented approach to represent each design alternative as a template object. In KEXPS, standard provisions that are appropriate for an alternative are represented as either hypothesis methods or analysis rules associated with that alternative's template object. KEXPS thus organizes the representation of the standard around a product model. For the column design problem, the product model is a small group of the column reinforcement layout templates, as illustrated in Fig. 2. The product model contains all domain and standard–specific knowledge, which is required for the design process, while the process model comprises only generic design process knowledge and is thus standard–independent. Thus, when a new standard is to be used, only the product model must be modified, not the design process. However, KEXPS divides the standard information *a priori* into that used during design and that checked after the design has been created. In other words, there is no redundancy of representation of the standard between hypothesis methods and analysis rules. This fixed, *a priori* division of standard information makes it difficult to use the model of the standard in processes other than the KEXPS design process. For example, if attempting to check designs generated by systems other than KEXPS, some requirements may go unchecked or unconsidered during design. Also, by building the representation of the standard directly into the product model, KEXPS is built upon the same exact assumption as was SPEX — the data models for the product and the standard model are one in the same.

In KOORDS, the standard is declaratively modeled and then used both during the design optimization process and in the post–design standard conformance checking process. In this respect, KOORDS is similar to SPEX in keeping the standard knowledge separated from other design knowledge, thus allowing for independent creation of the standard model(s). The standard model in KOORDS is very similar to that used in SPEX except for one major difference. In KOORDS, the standard is modeled as a set of limiting values, where these limiting values are referred to in the design methods of the objects being designed (e.g., minimum–bar–spacing for reinforced concrete member design). In SPEX, the standard is modeled as a set of requirements representing various behavior limitations. SPEX reasons with the standard model by identifying the relevant requirements for the behavior limitations specified by the designer on which to focus. KOORDS starts by evaluating the design methods in an object and requesting the limiting values its needs from the standard model. The standard model computes the values using data for the existing design situation provided by the requesting design object and returns these values. Thus, for KOORDS, the parts of the standard model to use in designing an object are fixed for that object to be those limiting values referred to in its design methods. In contrast, SPEX provides more flexibility for a designer to specify the requirements on which to focus when designing an object; the user may issue a design focus statement that will greatly influence what part of the standard is considered during design of that component.

KOORDS is different from SPEX in the way that it then processes the information it gets from the standard model. In KOORDS, the optimization process is packaged in methods which apply to the special objectives and constraints of each class of design object while the SPEX optimization process is based on a generic optimization approach. Each object in KOORDS is responsible for all processes which should be performed on itself, including determining optimal proportions. Therefore a reinforcement group in a beam uses a specialized method, different from that used for a reinforcement group in a column, to optimize its proportions. Because the scope of the KOORDS system, in contrast to SPEX, is creating objects, relating them to each other and proportioning them in order to satisfy the design requirements, it is able to handle a complicated assembly of bar pieces, which SPEX cannot.

KOORDS thus maintains the intentions of the SPEX system (i.e., to make use of a separately modeled design standard within a standard–independent design process) and overcomes the limitations of the SPEX approach (i.e., lack of a structured product design data model). The standard independent nature of the design procedure in KOORDS comes not from the usage of a generalized optimization procedure, but rather from the definition of a standard–independent interface consisting of a set of limiting values assumed to be defined in all design standards for the design of reinforced concrete beams.

5. Conclusions

Thus, with KEXPS and KOORDS, we have illustrated how this concept of a standard–independent design process, a concept earlier illustrated in SPEX but for limited types of problems, can be made more robust and able to handle much more complicated, detailed design processes, specifically the layout of reinforcement for reinforcement concrete columns and beams. While SPEX maintained standard–independence by using a domain–independent optimization procedure, it was limited to solving problems defined by a set of scalar parameters and constraints defined in the standard over those parameters (e.g., steel and reinforced concrete cross–sections, but not entire components). KEXPS and KOORDS illustrated that it is possible to still maintain standard–independence when solving more difficult detailed design problems by using a domain–specific, but still standard–independent, design process. KEXPS models the standard within its product model requiring that the product model be changed if the standard being used is changed. In KOORDS, the specific standard being used in the design process is accessed through a standardized set of limiting values assumed to be defined by all standards applicable to the given design domain. Thus, by using this interface, KOORDS keeps the standard model separated from its design objects making it possible to change from one design standard to another without having to modify the design methods. In both KEXPS and KOORDS, the optimal design methods are defined for and stored with the individual design objects, making it much easier than in SPEX to incorporate specific design methods and knowledge .

6. Acknowledgements

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MiniCode Generator: A Practical Research Application for Standards Processing

Générateur de minicodes: recherche pratique pour le traitement des normes

Ein "Bauvorschriften-Generator" für die praxisbezogene Normenverarbeitung

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SUMMARY
MiniCode Generation permits users to extract project-specific building codes based on a user-assisted selection of building attributes. A rule-based pre-processor queries the user for details on the construction type, building size, and occupancies, as well as features such as sprinklers, fire alarms, and combustibility rating. The MiniCode Engine then extracts the relevant provisions from the building code in less than 2 seconds on a standard personal computer. The user is then free to browse the resulting MiniCode or modify the attributes and generate a new MiniCode.

RÉSUMÉ
Le générateur de minicodes permet au concepteur de consulter une norme de construction d'après un ensemble de caractéristiques du bâtiment. Un pré-processeur demande à l'utilisateur des précisions concernant le type de construction, les dimensions et l'usage du bâtiment, ainsi que certaines particularités, telles que la présence d'extinction automatique à eau, le système avertisseur d'incendie ou la classe de combustibilité. Le système extrait alors de la norme de construction, en moins de 2 secondes, les dispositions applicables, et cela à l'aide d'un ordinateur personnel conventionnel. L'utilisateur peut dès lors parcourir le minicode ainsi obtenu ou changer les caractéristiques de départ pour en obtenir un autre.

ZUSAMMENFASSUNG
Dem Planer wird die Möglichkeit geboten, projektbezogene Bauvorschriften durch benutzergesteuerte Eingabe von Gebäude-Kenndaten abzurufen. Ein regelgestützter Vorverarbeitungsrechner erfragt vom Benutzer Einzelheiten über Bauart, Abmessungen, Höhe und Nutzungsart des Gebäudes sowie über spezielle Bauelemente wie Sprinkleranlage, Brandmelder und Brennbarkeitsklasse. Das Computersystem wählt dann über einen Standard-PC in weniger als 2 Sekunden die einschlägigen Bestimmungen aus den Bauvorschriften aus. Der Benutzer kann in dem auf diese Weise zusammengestellten Bauvorschriftenauszug beliebig recherchieren oder die Ausgangskenndaten ändern und dadurch einen neuen Vorschriftenauszug erstellen.