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Prof. Dr. Horst O. Bunke
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Table of Contents

Configuration Expert Systems: a Case Study and Tutorial

Bernd Neumann

Summary

This contribution discusses the architecture of expert systems for configuration tasks in technical domains with the objective to develop application-specific tools for expert system development. In the first part of the paper four configuration systems (XCON, SICONFEX, MMC-Kon and ALL-RISE) are analyzed with regard to their architectural features and experiences gained during the development. From these examples and similar evidence in several other systems one can conclude that a knowledge-based architecture much different from the conventional rule-based architecture is adequate for configuration systems. The main components of the configuration system architecture are described in the second part. The particular design presented in this paper is based on research in project TEX-K.

1. Introduction

As expert systems are being developed for an increasing range of applications, it becomes necessary to distinguish classes, find commonalities and recognize domain-dependent features. This is, of course, common practice in all fields where progress depends on practical experience and experimentation. As more and more examples can be studied, the conceptual structure of the field becomes apparent. It seems, however, that this development is particularly slow in the field of expert systems. While the number of systems being developed is skyrocketing and the number of systems being put to use is also increasing, though much more modestly, application-dependent architectural distinctions remain quite coarse.

This is not to say that application categories are not being distinguished in this field. Hayes-Roth et al. [15] suggest the 10 categories interpretation, prediction, diagnosis, design, planning, monitoring, debugging, repair, instruction, and control which henceforth have been cited abundantly. But there are few specific architectural characteristics which can be associated with each of these categories. The best one can do is to distinguish two main categories among the 10, diagnosis type and configuration type applications. In diagnosis applications backward chaining prevails, while most configuration applications employ forward chaining. Also, one often needs uncertain reasoning for diagnosis but rarely for configuration. Apart of these major distinctions the notion of an expert system frame work supposedly common for all applications is generally put forth. If distinctions in architecture are discussed, they are usually related to varying degrees of problem complexity rather than types of applications. In [15] we find a decision tree relating particular problem solving methods (and hence architectural distinctions) to rather abstract domain characteristics. For example, constraint propagation should be employed if subproblems interact, belief revision employed if search efficiency needs improving, etc.

A similar picture is drawn in a recent 450 page tutorial on expert systems [19]. Variations in system architecture are described in terms of the relative importance of the five main components of a system: inference engine, knowledge-base, user-system interface, explanation facility, and knowledge acquisition facility. Real-time process control systems, for example, would have little need for a system-user interface; if problem solving knowledge was still unfolding, one would need a good knowledge acquisition facility, etc. This amounts to saying that there is essentially one basic expert system architecture for all applications.

A 'flat' view of expert system architectures is also taken by most tool builders: Expert system development aids and shells are generally designed to cover 'all' applications. As the requirements vary noticeable, hybrid tools are provided which offer a selection of alternative components and methods to choose from. But there are few tools specially designed for particular application categories, diagnosis tools being the prominent exception (see e.g. the excellent analysis in [28]). As it turned out, even diagnosis tasks may not be treated alike. For certain domains 'second generation expert systems' [29,37,38] are being proposed and developed. Their architecture may be quite different from conventional systems, employing, for example, deep models of the respective domain to support causal reasoning. Hence the boundary lines of diagnosis application categories are quite likely to be redrawn according to the need for such architectural features.

This contribution discusses the architectural requirements of another traditional application category, configuration expert systems. We use the term 'configuration' here in a broad sense:

> A configuration system is an expert system which helps to assemble components into an aggregate according to some goal specification and using expert knowledge.

Components may be physical objects or other entities (e.g. actions or methods). They may be chosen from an infinite repertoire (e.g. including objects with a continuous range of attribute values). The process of assembling components into a configuration may involve decisions concerning type and properties of individual components as well as relations between several components. The goal specification may contain any information regarding the final aggregate including constraints, optimality criteria, functional requirements, etc. There may be any number of acceptable solutions, including none at all.

We also assume that the configuration system does not employ a closed-form solution procedure but a step-by-step strategy. Each step typically involves a decision or assumption concerning the solution aggregate. Hence one may think of a configuration system as an AI problem solver and the configuration steps as decisions in a search graph.

Much of what is known about control techniques in AI problem solving also applies to the configuration task. Finding an acceptable configuration may require judicious choices at intermediate decision nodes, possibly based on heuristic information. In general, control strategies ranging from simple depth-first search to dependency-directed backtracking may be called for.

It should be clear by now that our definition of configuration encompasses construction, design, planning and other rather diverse activities. Here are some examples which are in accord with our definition:

- selecting components for a power supply given performance requirements
- designing the floor plan of a house
- planning a sequence of laboratory experiments

- configuring a computer system according to customer wishes
- selecting and placing office furniture
- specifying work plans for a manufacturing process
- configuring a computer vision system for quality control

The paper is organized as follows. In Section 2, following this introduction, we review the literature and discuss selected systems in more detail. We focus on a major subcategory of configuration systems, loosely called 'technical' configuration systems. Their distinguishing feature is highly structured domain knowledge, or more precisely, a solution space which is decisively governed by well-documented technical information. Most configuration tasks tackled by expert systems so far and all of the examples given above fall into this category.

In Section 3 we describe the details of a knowledge-based architecture adequate for configuration systems. The architecture differs from the conventional expert system architecture in several respects, particularly in its deemphasis of rule-based knowledge representation. The search for a solution is prestructured to a large extent by a hierarchical representation of admissible configurations.

We also report about the configuration system tool PLAKON which is being developed in a joint project in the FRG. Much of the insights presented in this paper have resulted from research for PLAKON. At this point I want to express my gratitude and appreciation for contributions of R. Cunis, A. Günter and I. Syska at the Universität Hamburg and of all other project members.

2. What Can We Learn from Experience: Four Examples

In this section we tap the considerable body of experience concerning the design of configuration systems. Our goal is a critical analysis of implemented systems with regard to their architectural features. What can we learn from these applications?

To this end we view each system as a problem solving system whose behavior depends on three types of knowledge:

1. general domain knowledge
2. problem-specific domain knowledge
3. problem-solving knowledge

The first body of knowledge encompasses facts, properties and relations of the application domain including the underlying conceptual structures. Different from the second type, domain knowledge is assumed to be valid for all problems of an application domain, hence it is sometimes called 'static'. For configuring power supplies, for example, domain knowledge would include component descriptions, relevant physical laws, cooling requirements, industrial standards, etc. We do not want to distinguish from general, domain-independent knowledge, e.g. laws for spatial and temporal reasoning. Such knowledge is assumed to be part of the domain knowledge base.

The second type of knowledge is specific for a particular problem. It includes the problem specification and all other information pertaining to a specific solution. As more and more problem-specific knowledge is accumulated in course of the problem solving process, this knowledge base is often called 'dynamic'. Note that both (1) and (2) can be viewed as knowledge constraining the solution space. Both account for admissible solutions but **not** for procedures to find them. This is left for the third knowledge type.

Problem-solving knowledge is defined here as knowledge pertaining to the order in which configuration decisions should be made. It provides control for the problem solving process in terms of strategies, methods, subtask organizations, sequencing information, etc. We shall see that problem-solving knowledge - although conceptually separable - is mixed up with domain knowledge in most applications. This is largely due to the use of situation-action rules which encourage unstructured knowledge representation. We want to elaborate this point a little further.

Control in a rule-based system tends to be diffuse by the very nature of rule-based systems: Rules are essentially a way of defining a process without defining control. Hence rule-based systems are best suited for applications where a global flow of control need not be specified. If one has to enforce a certain order of problem-solving steps in a rule-based system, one must provide control knowledge in terms of appropriate firing conditions on the left-hand sides of the rules. This is often accomplished by introducing 'contexts' which are turned on and off to enable rules in the proper sequence. A second form of control, of course, is given by the conflict resolution strategy which provides arbitration when more than one rule is ready to fire.

The three knowledge types have been introduced to permit a structured inquiry into the use of knowledge in the application examples which will be discussed. We shall examine how the respective bodies of knowledge are represented and put to use for the respective problem solving tasks.

2.1 R1/XCON

As a first example of a configuration system we take a look at R1/XCON, the expert system for configuring DEC computers

[1,20,32,43]. Given a customer's purchase order, XCON determines substitutions and additions to make the order consistent and produces a number of diagrams showing the spatial and logical relationships among the components. The decisions to be made concern component types and properties, placement of components into boxes and cabinets, electrical connections among components, etc. XCON is a very large rule-based system. It currently contains more than 6200 rules which draw on a database of approximately 20,000 parts. Furthermore, each year about half of the rules are expected to change. Hence XCON also presents a formidable software maintenance task.

Static domain knowledge in XCON can be roughly subdivided into component descriptions and knowledge about valid (partial) configurations. Component descriptions are read in from a component database. After reading them in they are represented as simple OPS5 frame structures. We use the knowledge representation features such as defaults, inheritance, facets, or procedural attachment. Knowledge about valid (partial) configurations, e.g. compatibility of components or placement requirements, is expressed in terms of OPS5 rules, so-called productions. A production consists of an arbitrary number of condition elements on the left-hand side, in XCON on the average about 6, and an arbitrary number of actions, e.g. modifications of the current working data, on the right-hand side.

```
ASSIGN-POWER-SUPPLY-1

IF:     THE MOST CURRENT ACTIVE CONTEXT IS ASSIGNING A POWER SUPPLY
        AND AN SBI MODULE OF ANY TYPE HAS BEEN PUT IN A CABINET
        AND THE POSITION IT OCCUPIES IN THE CABINET IS KNOWN
        AND THERE IS SPACE IN THE CABINET FOR A POWER SUPPLY
        AND THERE IS NO AVAILABLE POWER SUPPLY
        AND THE VOLTAGE AND FREQUENCY OF THE COMPONENTS IS KNOWN
THEN:   FIND A POWER SUPPLY OF THAT VOLTAGE AND FREQUENCY
        AND ADD IT TO THE ORDER
```

Figure 1: Sample rule of XCON (paraphrased)

The example in Figure 1 illustrates how static domain knowledge about valid configurations is coded in terms of actions to be taken in a certain problem solving context. This technique, although common practice in configuration systems, leads to considerable unclarity as will be argued further down.

The problem description of XCON - which is part of the second body of knowledge to be examined - is a list of components. XCON detects missing or wrong components and corrects the list while performing the configuration task. Note that a problem specification in terms of a component list is much less problematic than an indirect specification, e.g. in terms of functional requirements or constraints. The latter would necessitate component selection as part of the configuration task. For DEC computers this is done by the separate expert system XSEL - discussed in [19] - which accepts customer wishes as input and delivers a component list as output.

We now turn to problem-solving knowledge as represented and used in XCON. It is explicitly expressed by rules and implicitly by the conflict resolution strategies of OPS5. The control thus achieved is remarkable. The configuration task is organized into contexts which in effect specify a hierarchical system of tasks, subtasks, sub-subtasks, etc. Figure 2 shows a sequence of contexts taken from a trace in [20]. The number preceding each context is the cycle on which that context was entered.

Each leaf of the subtask hierarchy typically consists of about 10 configuration steps corresponding to as many cycles of the inference component. At the end of a subtask an appropriate rule fires to establish a new subtask. Thus the order of configuration steps is well-defined and - as it turned out - hardly ever leads to backtracking.

```
215   MAJOR-SUBTASK-TRANSITION
216          DELETE-UNNEEDED-ELEMENTS-FROM-WORKING-MEMORY
235          FILL-CPU-OR-CPU-EXTENSION-CABINET
240                 ADD-UBAS
246                 ASSIGN-POWER-SUPPLY
251                 ADD-MBAS
252                        DISTRIBUTE-MB-DEVICES
260                               ASSIGN-SLAVES-TO-MASTERS
269                 ASSIGN-POWER-SUPPLY
272                 FILL-MEMORY-SLOTS
278                        SHIFT-BOARDS
298                        ADD-MEMORY-MODULE-SIMULATORS
305                 ASSIGN-POWER-SUPPLY
312                 FILL-CPU-SLOTS
318                 ASSIGN-POWER-SUPPLY
322                 ADD-NECESSARY-SIMULATORS
326                 DELETE-TEMPLATES
340          DELETE-UNNEEDED-ELEMENTS-FROM-WORKING-MEMORY
353          FILL-CPU-OR-CPU-EXTENSION-CABINET
356                 ADD-MBAS
359                 ASSIGN-POWER-SUPPLY
362                 ADD-UBAS
364                 FILL-MEMORY-SLOTS
369                        SHIFT-BOARDS
389                        ADD-MEMORY-MODULE-SIMULATORS
396                 ASSIGN-POWER-SUPPLY
399                 TERMINATE-SBI
402                 ADD-NECESSARY-SIMULATORS
406                 DELETE-TEMPLATES
415   MAJOR-SUBTASK-TRANSITION
```

Figure 2: Sequence of contexts in XCON trace

As pointed out earlier, rule-based programming is best matched to problems with a predominantly local control structure. XCON is an atypical example as it uses rules to establish a global flow of control. We want to learn from this example, hence let us consider advantages and disadvantages of the XCON architecture. Some interesting points are made in a recent analysis [32] concerning the intelligibility of XCON's written code. When modifying the rule set XCON's rule developers find it increasingly difficult to insure rule firing in the proper order. As one of the reasons they name the inhomogeneity of the code: Diverse tricks have been used over the years to force rules into a particular firing order. Also having a rule for more than one situation turned out to decrease intelligibility. When changing a rule one could not be sure about its original purpose.

As a partial remedy a new high-level language RIME has been developed for recoding XCON. RIME provides several means of expressing structure in a rule-set. First, rules of common purpose can be assigned to a 'problem space' corresponding to a subtask. Hence the XCON subtask structure can be better supported. Second, problem solving methods can be defined and assigned to a problem space. For example, many subtasks can be solved by performing four conceptual steps (the following is a highly simplified description):

1. PROPOSE: Suggest operators for current goal.
2. ELIMINATE: Evaluate appropriateness of operators prune.
3. APPLY: Activate and execute operators.
4. EVALUATE: Review goal, redo or exit problem space.

By assigning this method to a problem space, RIME provides rules which reinforce the corresponding sequence of steps. Third, rule templates are provided which establish permissible categories of rules and prohibit inhomogeneous coding.

In summary, we find that a system like XCON requires means for defining control, both in terms of a context structure and methods for subtasks. A rule language such as OPS5, however, is not well suited for defining control. The disadvantages may not be decisive in small systems, but they become significant in systems as large as XCON. Certainly, good software engineering also applies to the design of expert system: A mismatch between problem structure and programming language decreases software intelligibility and should be avoided.

2.2 SICONFEX

After having discussed XCON it is interesting to take a look at the configuration system SICONFEX which provides a very different solution for a similar task. SICONFEX has been developed by Lehmann et al. at Siemens, Munich, in 1985 [14,17]. It is an expert system for configuring the operating system of SICOMP process control computers distributed by Siemens. The input data consist of the hardware configuration and application-specific customer requirements, e.g. with respect to the intended use of system and user software. Requirements may be graded according to various degrees of desirability. All input data are obtained in a user-friendly dialogue supported by graphical displays. The system expects only a naive understanding of hardware and software components. After the input phase the system performs the partitioning of the main storage. This is the core of the configuration task. The system generates output in terms of configuration statements for a generator program.

There are four distinct main storage regions to be configured, three for the operating system and one for user programs. Human experts were able to supply some 200 rules concerning the configuration of the first three regions. However, many heuristics and guide-lines had to be added by the developers of SICONFEX. The system encompasses 6 MByte of code (including 4 MByte of INTERLISP-D/LOOPS code) which is equivalent to a rule-based system of several thousand rules. SICONFEX is not a rule-based system, however, as it employs diverse methods of the LOOPS environment.

Let us examine the representation and use of the three different types of knowledge again which we have introduced earlier. Structuring static domain knowledge played a significant part in the development of SICONFEX. As the authors report in [14], they found this task much underrated in popular expert system literature. The SICONFEX domain consists of at least three distinct areas with quite diverse characteristics:

1. the world of physical objects which are the configuration components
2. the abstract world of existing software modules
3. the artificial world of hypothetical memory partitionings

A variety of techniques have been used to represent such a heterogeneous domain: frame-like object structures, conceptual taxonomies, inheritance mechanisms, rules, message passing, active values and LISP functions. The authors stress that rules play only a subordinate role. They are used with logical interpretation:

IF <premisses> THEN <conclusion>

Production rules as in OPS5, on the other hand, have procedural semantics:

IF <pattern> THEN DO <actions>

Such rules are deemed unfit for representing static domain knowledge in SICONFEX - much in accord with our earlier remarks concerning XCON.

Problem-specific knowledge enters the system via the elaborate user-interface mentioned above. The need for considerable programming efforts in this department has also been reported by other authors [2,9], and it is worthwhile to understand when and why this is so. Problem data are often obtained from a user belonging to a category much different from the knowledge engineers who structured the domain knowledge. In the case of naive users (as with SICONFEX) instant knowledge engineering has to be performed to translate user input into internal structures. The more elaborate the system's knowledge representation and the more naive the user's, the wider is the gap which has to be bridged by the user interface. Note that problem-specific domain knowledge is structurally not much different from static domain knowledge. Hence components for acquiring domain knowledge during system development may be put to use for user interfacing and vice versa.

There appears to be no extensive representation of problem solving knowledge in SICONFEX (in the sense defined earlier). As the authors state in [17], experts could not provide consistent strategies for partitioning the main storage. The solution adopted in SICONFEX has algorithmic character. It involves discrete optimisation but also incorporates heuristics and hypothetical decisions liable for backtracking. Control is not expressed in terms of rules.

In summary, SICONFEX is a configuration system with an architecture radically different from XCON. Its prominent features are (1) a highly structured knowledge-base, (2) an elaborate user interface for acquiring problem data, and (3) hybrid problem-solving techniques including optimisation algorithms.

2.3 MMC-Kon

Our next example is the system MMC-Kon which configures distributed automation systems based on the SICOMP MMC 216 multi-microcomputer system. MMC-Kon has been developed by Baginsky et al. at Siemens, Erlangen, as a first prototype for testing general principles of configuration system design [2]. The particular domain of interest is rolling mill automation. A typical task is defined in terms of several automation functions to be performed by the system, e.g. thickness control, position control, automatic slow-down. The user specifies a task interactively making use of reference systems and MMC-Kon's knowledge base which contains all standard automation functions.

As a first configuration step MMC-Kon generates a function plan containing the function processors for the automation functions. Various criteria have to be taken into account, e.g. process structure, functional integrity, volume of inter-process communication, bus capacity. Next, each processor is configured by selecting suitable components (memory and peripheral units). Then all modules are placed into sub-racks with consideration given to the number of slots, the available power supply, preferred module locations and combination options. The next configuration step is to assign parameter settings to the modules according to the required operational characteristics. Finally, the sub-racks are assigned to cubicles considering placement constraints. The output is a complete documentation of the automation system.

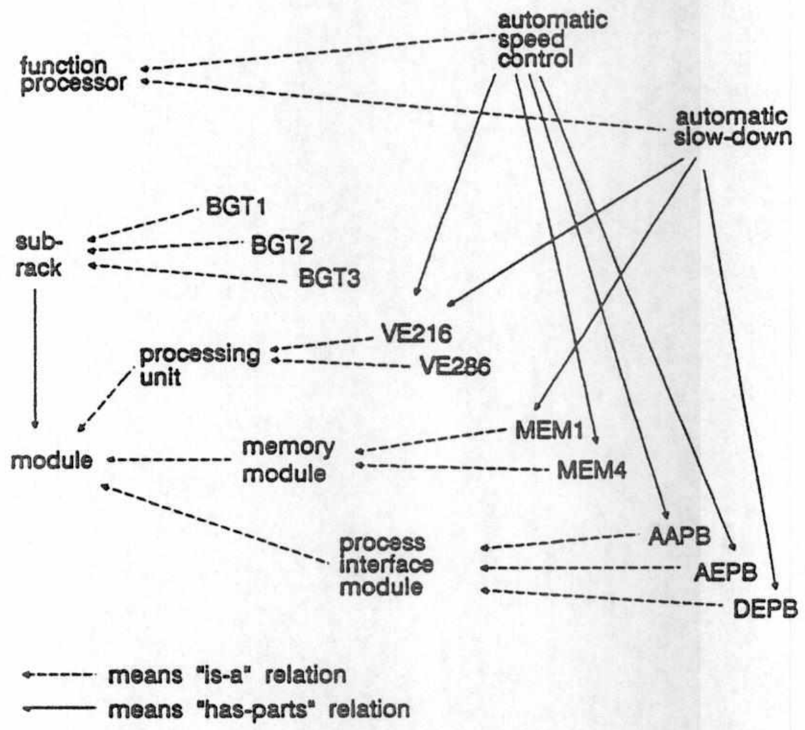

Figure 3: Hierarchical structure of domain knowledge in MMC-Kon

The inherent characteristics of this application do not seem much different from the preceding examples, yet there are some novel features. As we examine the relevant domain knowledge we find - as would be expected - conceptual descriptions of all objects which can make up a configuration. In addition, however, the object frames are related to each other by is-a and has-parts relations. The resulting hierarchical structure is shown in Figure 3 (taken from [2]).

Note that the individual modules (e.g. processing unit VE216 or memory unit MEM1) are represented from two perspectives: as physical objects and as carriers of a function. The ability to view objects from different perspectives, exposing certain attributes and hiding others, is a valuable asset for knowledge structuring and appears to play an important role in configuration system design.

Similar to SICONFEX the task definition is acquired interactively. The system supports this phase using its domain knowledge and the display capabilities of a modern workstation. There is also the option of referring to library configurations. In this case the current task is defined by modifying the selected reference task.

Control does not seem to play a critical role in MMC-Kon. There is a natural order in following through the configuration steps, but the system has been designed to permit free user interaction and changes of the order of configuration steps at virtually any time. MMC-Kon ensures that the resulting configurations are consistent, whichever decisions the user has made interactively. This desirable characteristic is in distinct contrast to XCON where the order of configuration steps is fixed and precludes user interaction. One may attribute this to differences of the respective application domains, but I am prepared to argue that MMC-Kon's pleasant properties are mainly the result of better knowledge representation.

We now turn to a different field of application: design in engineering. Design has been characterized in [22] as a problem solving activity aimed at constructing artifacts and meeting certain conditions. The artifact must

1. satisfy a given functional specification,
2. conform to limitations of resources, and
3. satisfy implicit and explicit criteria on its form.

From this definition design has enough in common with the configuration examples encountered so far to be included in our discussion. The main difference seems to be the emphasis of form design rather than composition of components.

2.4 ALL-RISE

There is a rich set of literature on design aided by knowledge-based systems. For an excellent analysis see [42], for references see [8]. It is not immediately clear which systems fall into the category of configuration expert systems and which do not. Most of the expert knowledge in engineering is formalized and well documented to begin with, hence automatising design is not really a matter of replacing or simulating human experts. Consequently, much of the relevant literature is oriented towards design automation and not towards expert system development. But judged by performance, knowledge representation techniques, and design methods, several of these innocent-looking engineering tools deserve the attention of expert system developers for configuration and - following [26] - possibly also diagnosis tasks.

We focus now on the design system ALL-RISE [33,34] which supports the preliminary structural design of buildings. The input to ALL-RISE is an architectural or spatial plan of a building represented by a three-dimensional grid (see Figure

4). The topology of the grid is defined by the number of stories, bays and aisles. Also load and clearance constraints are given.

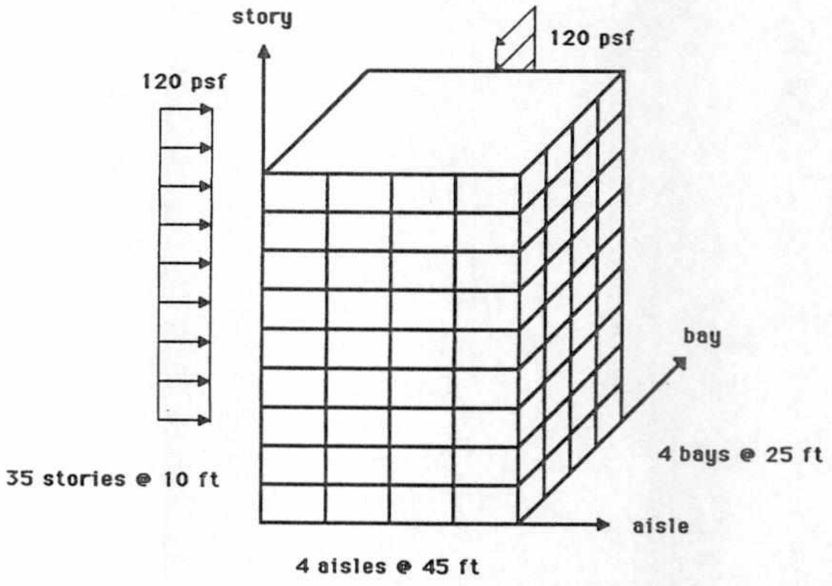

Figure 4: Sample input of ALL-RISE

The output is a set of feasible alternative 'structural systems' ranked according to their appropriateness for the given building. Figure 5 shows a typical output. It is a preliminary design as only basic structural design categories are distinguished, e.g. various types of steel or concrete structures.

The design process is a depth first search through a hierarchy of predefined structural systems, subsystems and components. Constraints prune alternatives, ensure compatibility of design decisions and rank competing solutions. The system is implemented in SRL, the schema language of the expert system development tool Knowledge Craft.

```
Alternative 1:

3D-material: steel
3D System:   orthogonal
2D Subsystems:
      Lateral-load:
            Outer (bay & aisle):   rigid-frame (beam-column)
            Inner (bay & aisle):   rigid-frame (beam-column)
      Gravity-load:
            Floor-type:   Reinforced slab
            Floor-support in aisle direction:   2
            bay:   column-plate
            aisle:   simple-frame

NOTE:   Lateral-load primarily resisted by rigid-frames
```

Figure 5: Partial output of ALL-RISE

ALL-RISE is interesting for our discussion of expert system architectures because of two significant features. One is the organization of static domain knowledge, the other is the extensive use of constraints. We shall discuss these features in order.

The static knowledge hierarchy of ALL-RISE is similar to other knowledge bases with respect to its use of schemas (frames) and the predominance of is-a and has-parts relationships for describing and relating the entities of the domain. It is special, however, because of the interpretation assigned to the top node of the hierarchy. The top represents an acceptable structural system (a successful design) at its most abstract level. Hence all solutions must be instances of this node or its specializations. Subordinate nodes represent either alternative specializations (e.g. steel or concrete) or partial designs (e.g. lateral-load design and gravity-load design). Leaves of the hierarchy represent design choices which need not be further refined. A complete design is a subtree with the top node as the root, exactly one successor for is-a branchings and all successors for has-part branchings. Note that this corresponds to a solution in a conceptual AND-OR tree. Is-a branchings represent logical OR relationships, has-part branchings represent logical AND relationships. Representing domain knowledge in this fashion has the interesting property that decisions required for a feasible design are explicitly represented. Furthermore, conceptually related decisions are grouped together. Hence making decisions in depth-first order beginning at the top node is natural and conceptually justified. One can also argue that this order tends to minimize backtracking. The advantages of a control flow following the AND-OR structure of a problem domain are well-known in AI problem solving [25]. Similar schemes have also been used in several other design and configuration systems [7,41].

The is-a and has-part hierarchy of ALL-RISE does not contain complete domain knowledge as a large part is encoded by constraints attached to the knowledge hierarchy. The authors distinguish (1) synthesis constraints which affect the generation of feasible solutions, (2) interaction constraints which arise from the interaction of structural subsystems, (3) causal constraints which represent equations of equilibrium and other physical laws, (4) parametric constraints which constrain component attributes, and (5) evaluation constraints which are used to rank alternative structural designs. The following is a synthesis constraint represented by a SRL schema:

```
{{braced-frame-constraint
        CHILD-NODES:  "mat-steel"   "stories-less-than-40"
        CONNECTION-TYPE: and
        STATUS:
}}
```

The constraint can be paraphrased as the rule:

```
IF      the current alternative is a braced frame, AND
        the material used is steel, AND
        the number of stories is less than 40
THEN    eliminate the current alternative.
```

As a matter of fact, a rule representation has been used in HI-RISE, a precursor of ALL-RISE.

Constraints are instantiated, propagated and satisfied when encountered in the knowledge hierarchy. Interesting control issues arise as design decisions of one partial design may be affected by constraints triggered by another partial design. Constraints are related to each other through common attributes and form a network. Different from other work on constraint-based reasoning [11,12,13,36] the developers of ALL-RISE did not implement an independent constraint propagation machinery capable of satisfying multiple constraints simultaneously. They preferred a step-by-step procedure oriented at the domain knowledge hierarchy.

2.5 Planning

Another application area related to our topic is planning, at first glance quite different from configuration and design. The basic similarities become apparent, however, if one views a plan as a configuration of operations or actions. Plan formation means selecting operations from a repertoire to meet certain boundary conditions and constraints, e.g. a desired final state.

There is a vast body of literature concerning planning systems as planning has been an AI research area long before the advent of expert systems [10,30,31,39]. Today, several different models are considered interesting, for a survey see [18,35]. The most popular originated from the work of Sacerdoti [30,31]. Each step in a plan is modeled as an operator along with preconditions and a description of the state change caused by that operator. Sacerdoti also emphasized the need for hierarchical planning in two respects. First, he organized the repertoire of operators into a hierarchy to allow planning at different levels of abstraction (e.g. 'travel' vs. 'travel-by-train'). Second, he differentiated the preconditions along a coarse-to-fine scale.

In modern application-oriented planning systems several other features are also important [18], for example flexible user interaction, display facilities, alternative plans, special planning strategies, optimization methods, etc. The basic structure of a planning system, however, including the preference of a hierarchical approach, conforms well with the basic structure of a configuration system. A more detailed proposal for implementing a planning system with configuration system components has been worked out in [4].

3. The Kernel of a Technical Configuration System

The discussion of selected configuration systems in the preceding section has revealed differences and commonalities, convincing solutions and less convincing ones. This should provide some background for the following sections where we propose components and architectural features for future configuration systems. The proposal is largely based on research carried out in project TEX-K which will be described later. But many ideas have also been put forth in the literature in connection with application-oriented work as evident from the examples in the preceding section.

We are guided by the following main insights concerning configuration system architecture:

1. For a large class of configuration tasks, especially in technical domains, the configuration process is governed by highly structured knowledge about components and aggregates. Expert rules play a subordinate role.

2. Domain knowledge is naturally organized into two bodies: an object-oriented knowledge hierarchy based on is-a and has-parts relationships, and a constraint network relating object properties to each other.

3. The order of configuration steps may vary considerably depending on the particular problem, the availability of library solutions, the amount of user interaction and the strategy chosen.

4. An elaborate user interface is a major subtask of configuration system development. Its main purpose is interacting with the knowledge base.

The kernel which will be described in the following constitutes an architectural framework in accord with the above views.

3.1 Conceptual Knowledge

Conceptual knowledge is a structured description of permissible configurations. As stated above we distinguish between a hierarchical object-oriented representation and constraints. In the following we focus on the hierarchical representation and begin with the conceptual hierarchy.

3.1.1 Conceptual hierarchy

The conceptual hierarchy is a lattice of conceptual object descriptions based on the is-a relationship. Its purpose is to characterize the objects with which one has to deal in the application domain. A flat collection of frames is clearly not sufficient as different levels of abstraction play an important role in step-by-step configuration. The is-a relationship supports well-known techniques of property inheritance [3].

The top-most part of the conceptual hierarchy is domain-independent and predefined. Figure 6 (adapted from [6]) shows a typical root section of the conceptual hierarchy.

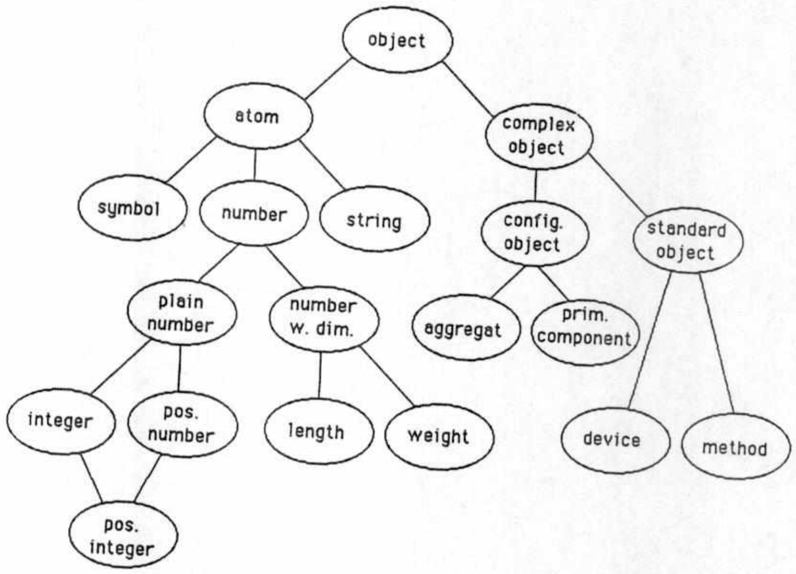

Figure 6: Root section of conceptual hierarchy

An 'atom' is a predefined object class of the representation language, its is-a refinements are essentially data types and templates. A 'complex object' is the most abstract class of objects of the application domain. Each object class is represented by a frame with attributes and values. Some attributes are predefined, e.g. has-parts, has-instance and their inverse. The range of attribute values is defined by object descriptors which in turn are represented by conceptual nodes in the hierarchy. The following expression (in a hopefully self-explanatory syntax) defines the new object class 'body' for the domain of vehicles.

```
((a body) is   (a aggregate)
               (part-of      (a car))
               (has-parts    (some (a door) 2 5)
               (has-color    (a color)))
```

Note that the set-type values of has-parts are associated with a number restriction. For ordered sets one might also want to have a sequence primitive.

All these techniques are well-known in AI knowledge representation but unfortunately not always supported in expert system tools. We shall not elaborate these techniques but rather briefly discuss an additional, less well-developed representation feature which is useful for configuration systems: aspects of an object.

The need for aspects has been pointed out in the discussion of MMC-Kon where a configuration was viewed as a system of automation functions in the first phase and as a hardware system in the second. The configuration as a whole encompasses both, attributes and components of the functional aspect and attributes and components of the hardware aspect. To represent aspects in the conceptual knowledge hierarchy we allow attributes to be bundled and bundles to be given aspect names. For example, we define the software and hardware aspects of a computer system as seen below. With 'computer-system/SW' one can address the software aspect of the concept 'computer-system' just like a complete node. Also, is-a and has-parts successors can be defined within any of the aspects. See [6] for a more detailed presentation of the aspect feature.

```
(a computer-system) is
                (a aggregate)
                (:SW (a software-system)
                        (has-parts (set (a operating-system)
                                        (a user-program))))
                (:HW (a device)
                        (has-parts (set (a processor)
                                        (a memory)))))
```

The has-parts attribute, of course, is a key attribute for representing aggregates. As the main idea is to represent permissible configurations, the has-parts attribute is used to build a compositional hierarchy with 'permissible-configuration' as the top node. All possible alternatives for partial configurations and components can be reached from the top node via is-a and has-parts refinements. The graph below 'permissible-configuration' can be interpreted as an

AND-OR graph as pointed out earlier. The solution of the configuration problem is a solution tree in this AND-OR graph. The complete hierarchical knowledge base encompasses additional nodes, however, as should be clear from Figure 6.

3.1.2 Constraints

Constraints are a common way to express conditions on, or mutual dependencies between, objects and properties. For discrete property values, a constraint can be viewed as a relation in the mathematical sense. It defines a restricted subset of combinations of property values among the set of all possible combinations, e.g. the subset of exhaust systems compatible with car engine types and export destinations. Constraints can be viewed as a general way of expressing N-ary relationships, complementing the binary attribute relationships in frames.

For several reasons constraints require special treatment. First, they do not conform with the object-oriented style of knowledge representation discussed so far. A typical constraint involves more than one object and cannot be assigned to any single object by a good reason. Second, constraints tend to affect the order of configuration steps in a way much different from the path lined out by the hierarchical knowledge base. This is known from human problem-solving where narrowly constrained choices are typically considered first. There is also a growing body of research concerning constraint-based problem-solving and effective procedures for evaluating constraint knowledge [4,13,21,36,40]. Third, humans frequently use constraints in their own thinking and language when they want to characterize a solution space. Hence it certainly facilitates knowledge engineering if constraints can also be formally expressed in a computer system. In summary, there is much evidence that a tool box for configuration system development should provide means for representing and exploiting constraints. In the following we outline an approach originally proposed by Güsgen [13] and further developed in project TEX-K [24].

Constraints are defined using constraint classes. A constraint class is comparable to a procedure declaration with formal parameters and a body specifying the restrictions or functional dependencies between the parameters. Constraints are tied to domain knowledge via so-called conceptual constraints. A conceptual constraint consists of two parts, one specifying the bindings of constraint variables to objects of the knowledge base, the other specifying the bindings of the parameters of a constraint class to attributes of the selected objects. The following expression describes a conceptual constraint which may be used to force the 'has-weight' attribute of a car to take on the sum of the component weights.

```
(constrain  ( (?C   (a car))
              (?B   (a body   (part-of  ?C)))
              (?F   (a frame (part-of   ?C))))
            (add  (?B has-weight) (?F has-weight) (?C has-weight)))
```

It is assumed that a constraint class 'add' with three parameters has been defined. Note that the formal syntax is just a way of entering constraints into the knowledge base. The internal representation is a frame-like data structure with links into the appropriate attribute slots of object frames.

This short sketch of constraint classes and conceptual constraints, of course, is not all there is to be said about constraints. The theme will be taken up again in the following sections.

3.2 Problem-Specific Domain Knowledge

In a configuration problem we deal with concrete instances of components, aggregates and constraints. For example, we may have to construct a configuration from a component list as in XCON or from certain grid measures and load constraints as in ALL-RISE. Given a conceptual knowledge base as discussed above, such items are represented as instances linked bidirectionally to the proper concept nodes via 'has-instance' and 'instance-of' links. Instances inherit all attributes and predefined values. To maintain strict inheritance, instance properties may not 'overwrite' inherited properties. All this corresponds to common practice in AI knowledge representation and will not be elaborated further.

We focus now on the dynamic aspects of problem-specific knowledge. In course of the configuration process many, possibly tentative, decisions are made and partial, possibly alternative, configurations are constructed. These partial configurations will be called elaborations henceforth. In order to realize various control strategies, including sophisticated techniques like dependency directed backtracking, we must be able to represent the history of elaborations. It has the structure of a lattice with each node representing an elaboration and links connecting successive elaborations. Each link also contains information about the configuration step represented by that link. The problem with such a structure is its size in terms of required storage. In order to avoid multiple representations each instance should be represented only once. The elaboration history can thus be reduced to a history of changing attribute values. In some programming environments (e.g. Knowledge Craft) a context mechanism is provided which can be used for this purpose. Generally, however, expert system tools do not supply effective representation techniques for the elaboration history.

Another representation requirement is related to the dynamic use of constraints. Constraint propagation is a dynamic process which generates restrictions on attribute values. The workings of constraint propagation will be discussed further down, at this point it is important to note that attribute value restrictions, changing over time, have to be represented as part of the problem-specific knowledge. Furthermore, one may want to distinguish between value restrictions arising from different constraint sets, for instance 'soft' constraints and 'hard' constraints. All this requires an organization of attributes into multiple facets, each facet corresponding to a distinct value modality.

3.3 Problem-Solving Knowledge and Control

We have designed the domain knowledge base in such a way that information about permissible configurations is made explicit. Hence inferences concerning the properties of a configuration can be based upon this knowledge and need not resort to rules. What remains to be defined is the order of such inferences and the mechanism which carries them out. As we have departed from a rule-based approach we can devise a control scheme which is largely independent of domain knowledge and allows the explicit representation of control knowledge.

3.3.1 Elementary configuration steps

At any given time an elaboration consists of a set of object instances linked to conceptual nodes at various levels of the knowledge hierarchy. The following elementary configuration steps can be carried out depending on the state of the elaboration:

1. decomposition of an object along has-parts
2. specialization of an object along is-a-inverse
3. aggregation of components along part-of
   (= has-parts-inverse)
4. merging of objects which can be replaced by a single one
5. value assignment or restriction
6. instantiation of a new object

The first two kinds of operations are required for a top-down refinement strategy. The third is for bottom-up composition. The fourth covers situations where one object may be part of several aggregates. The fifth kind of operation, often called parameterization, decides upon object properties and will usually be employed very often. The sixths operation, finally, introduces a new object instance irrespective of the existing structure.

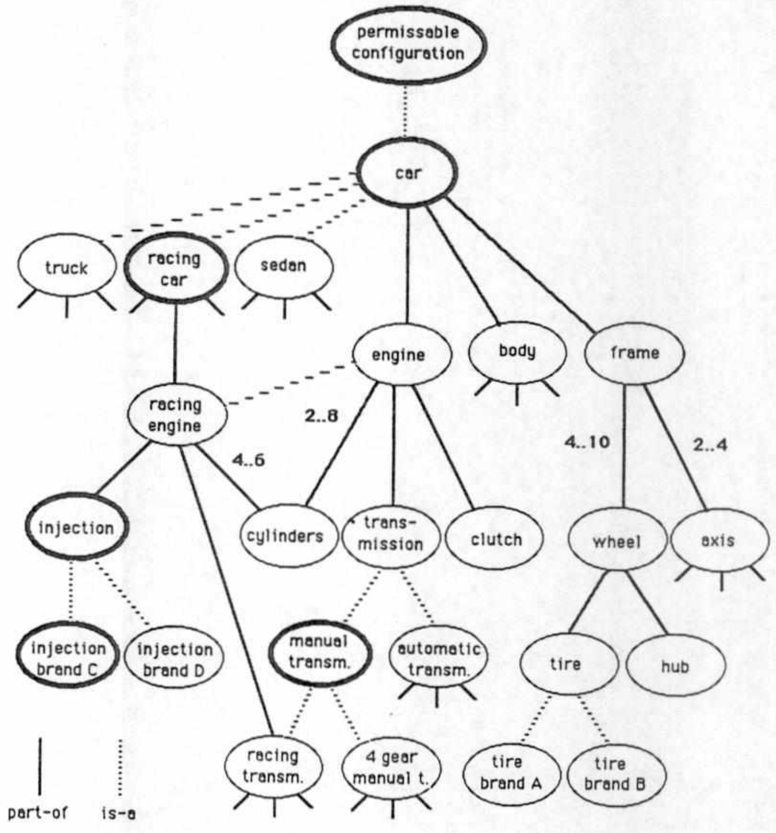

Figure 7: Configuring a racing car

Figure 7 shows an elaboration for a car configuration task to illustrate the possible operation steps. For simplicity, only a few conceptual nodes are shown. The links express is-a and part-of relationships. The numbers associated with some of the part-of links indicate restrictions on the number of parts. Nodes which are assumed to be instantiated are drawn in heavy lines. Up to this stage it has been decided to configure a racing car with manual transmission and a particular brand of fuel injection. The following elementary configuration steps can be carried out next:

- decompose 'racing car'
- specialize 'manual transmission'
- assign values to any of the instantiated objects
- instantiate a new object

This example also demonstrates the advantages of top-down strategies regarding conflict avoidance. If 'manual transmission' is specialized to '4 gear manual transmission' instead of 'racing transmission', this would be in conflict with the choice of a 'racing car'. A strict top-down strategy does not produce incompatible decisions of this kind.

3.3.2 Representing control knowledge

The preceding section has shown that in general, one of several configuration steps can be carried out at any time. We now discuss ways to make use of this degree of freedom. The main idea is to define explicit control strategies which provide selection criteria and other useful control information. In more detail, a strategy contains the following:

1. Operation focus: This criterion focuses on a subset of the six elementary configuration operations.

2. Partial configuration focus: This criterion screens out all operations except those which apply to a particular part of the configuration.

3. Selection criteria: Predefined or user-defined procedures which rank configuration steps on the agenda.

4. Conflict rules: These rules are consulted in case of a conflict. They typically provide backtracking information.

5. Value selection procedures: This criterion allows to specify any of a number of possible procedures for assigning attribute values, e.g. user interaction, optimisation techniques, constraint net usage, heuristics, etc.

6. Constraint net activation: This information specifies conditions on activating the constraint propagation mechanism.

A strategy is associated with a phase and will be activated upon entering that phase. A phase (or subtask) structure can be defined for a configuration task as part of the control knowledge. Such a structure has been found useful in many applications (see e.g. the context hierarchy of XCON). One way to define phases is by means of rules which are conditioned on the elaboration lattice and the currently active phases. The action part is restricted to phase activation and phase deactivation. Thus control knowledge and domain knowledge are clearly separated. As the rule system controls the control of the configuration process, it is often called meta-control.

3.3.3 The configuration cycle

A configuration cycle comprises selection and execution of a configuration step. It is roughly equivalent to the recognize-act cycle of a rule-based system but quite distinct in detail. A cycle consists of the following steps:

1. Meta-control determines phase and strategy.
2. Strategy determines focus, selection criteria, etc.
3. Possible configuration steps are determined and placed onto an agenda.
4. A configuration step is selected according to the selection criteria.

5. The step is executed using a particular value selection procedure.
6. The constraint net is activated optionally.
7. The new elaboration is checked for conflicts and termination.

Note that in step 1 meta-control is not expected to fire at each cycle. Also constraint propagation will typically not be activated for each cycle. The constraint propagation mechanism is a separate tool which will be briefly described in the following section.

3.3.4 Constraint propagation

We have already discussed constraint classes and conceptual constraints which constitute the first two levels of the constraint system. The third level is comprised of constraint instances which are created automatically as soon as the objects are instantiated to which a conceptual constraint is bound. Constraint instances form a network as several constraints may pertain to a single variable.

The input of the network is provided by current attribute values which are bound to constraint variables. Typically, some constraint variables are not yet bound and are free to take on values or sets of values as the result of constraint propagation. These values are fed into the 'admissible values' (AV) facet which coexists with the 'current value' (CV) facet of an attribute. It takes a distinct configuration step of the main configuration cycle to feed a value of the AV facet into the CV facet. As a result of constraint propagation, a conflict may be discovered, indicating that current attribute values are incompatible and must be revised. Conflict indications are taken care of in the main configuration cycle using the conflict resolution rules of the active control strategy.

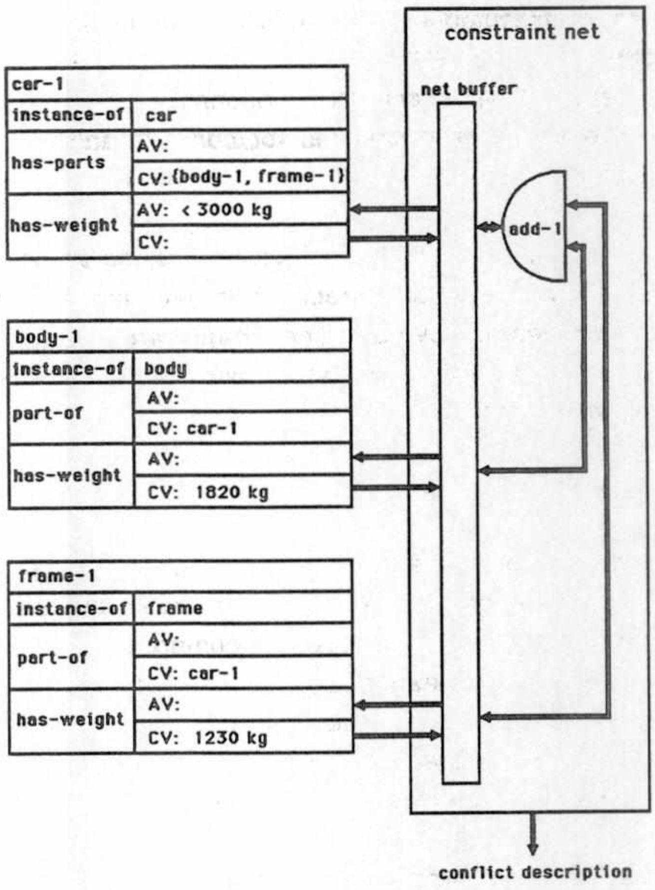

Figure 8: Evaluating a constraint

Figure 8 illustrates the flow of information for a constraint net consisting of an 'add' constraint as introduced in an earlier example.

3.4 The Expert System Tool PLAKON

The architectural components presented in the preceding sections as well as several additional features are implemented in the context of the joint project TEX-K [5,6,12,24] which is supported by the German Ministry of

Research and Technology (BMFT). The objective of this project is to develop a tool system - called PLAKON - for planning and configuration tasks in technical domains. The project has begun in 1986 and is scheduled until 1989. It comprises 57 person-years of work shared between five project partners: Battelle Institute (Frankfurt), Philips GmbH (Hamburg), Siemens AG (Erlangen), URW (Hamburg) and the University of Hamburg. PLAKON is designed to support diverse applications. Six applications are implemented in the context of TEX-K:

- configuration of multi-microcomputer systems for industrial automation (MMC-Kon, see 2.3)

- configuration of computer vision systems for quality control in manufacturing [23,41]

- configuration of automatic systems for industrial x-ray analysis [27]

- configuration of systems for laboratory experiments

- generating work plans for mechanical manufacturing

- configuration of electrical engineering aggregates using standard components

The architecture of PLAKON is shown in Figure 9. The main properties of the kernel have been discussed in the preceding sections leaving out a considerable amount of detail for the sake of conciseness. The peripheral components of PLAKON which can be seen in the diagram reflect some of the needs which have become apparent from the discussion of the examples, e.g. a component for library solutions. Details of these components are still being worked out.

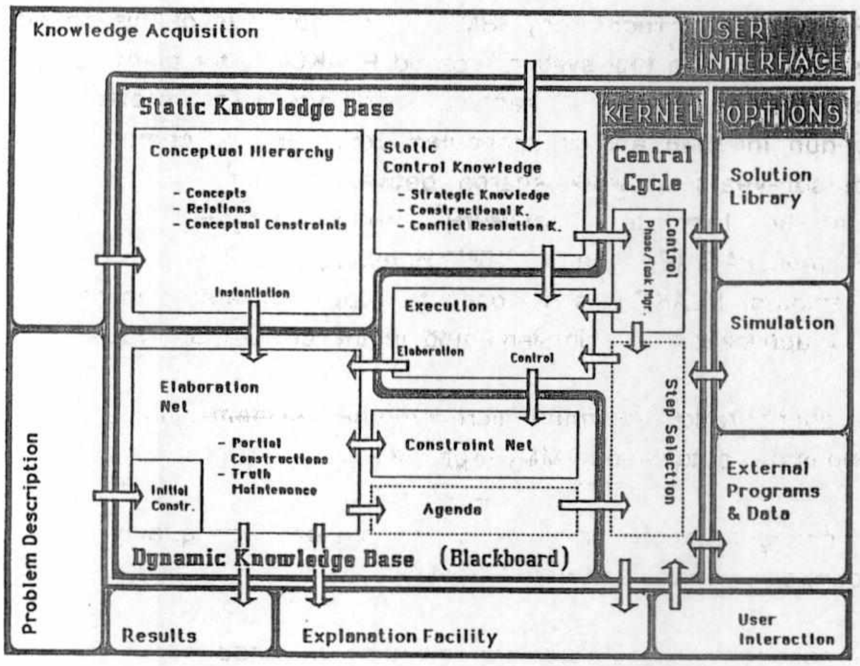

Figure 9: The architecture of PLAKON

4. Conclusions

An efficient development and maintenance of an expert system requires application oriented tools. In this contribution we have discussed requirements for configuration systems. We have analyzed several examples and found that in technical domains both configuration systems (in the narrow sense) and design systems have many features in common. Hence it is reasonable to consider them part of the common application category of configuration systems.

1. The configuration process obeys highly structured knowledge about admissible configurations.

2. This knowledge is naturally represented in terms of an is-a and has-parts knowledge hierarchy with associated constraints.

3. Configuration requires flexible control and an explicit representation of control knowledge.

We have proposed a configuration system architecture in accord with these requirements. Its distinguishing features are (1) provisions for highly-structured knowledge representation, (2) configuration steps specified by the knowledge hierarchy, (3) an independent constraint propagation system interacting with the knowledge hierarchy, (4) provisions for a compact representation of the configuration history, and (5) an explicit representation of control strategies. Several other features could not be discussed in detail but are also important, e.g. the sophisticated use of library solutions [16] or special techniques for dealing with spatial constraints [4].

A tool for building configuration systems with this architecture is being developed in project TEX-K and applied to several different tasks.

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