

Structured Development of Problem Solving Methods

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Abstract. *Problem solving methods* (PSMs) are domain-independent reasoning components, which specify patterns of behaviour which can be reused across applications. While the availability of extensive PSM libraries and the emerging consensus on PSM specification languages indicate the maturity of the field, a number of important research issues are still open. In particular, very little progress has been achieved on foundational and methodological issues. Existing libraries of PSMs lack a clear theoretical basis and only provide weak support for the method development process, usually in the form of informal guidelines. In this paper we will address these issues by illustrating a framework which characterizes PSMs in terms of *problem commitments*, *problem-solving paradigms* and *domain assumptions*. This framework provides i) a theoretical foundation for situating PSM research and individual PSMs, as well as ii) an organization which allows us to characterize method development and selection as a process of navigating through a three-dimensional space (defined by the three components of our framework). Individual moves through this space are specified by means of *adapters*. In the paper we will illustrate these ideas in detail, with examples taken from parametric design problem solving.

Primary Keywords. Knowledge Acquisition; Problem-Solving Methods.

1. INTRODUCTION

Problem solving methods (PSMs) describe domain-independent reasoning components, which specify patterns of behaviour which can be reused across applications. For instance, *Propose&Revise* (Marcus et al., 1988; Zdrahal and Motta, 1995) provides a generic reasoning pattern, characterized by iterative sequences of model 'extension' and

'revision', which can be reused quite easily to solve scheduling (Stout et al., 1988) and design (Marcus et al., 1988) problems. PSMs provide an important technology for supporting structured development approaches in knowledge engineering: they can be used i) to provide strong, model-based frameworks in which to carry out knowledge acquisition (Marcus, 1988; van Heijst et al., 1992) and ii) to support the rapid development of robust and maintainable applications through component reuse (Runkel et al., 1996; Motta, 1997; Motta and Zdrahal, 1997). More in general, the study of PSMs can be seen as a way to move beyond the notion of knowledge engineering as an 'art' (Feigenbaum, 1977), to formulate a task-oriented systematization of the field, which will make it possible to produce rigorous handbooks similar to those available for other engineering fields. From a philosophical perspective, such a systematization could be used as the source for experimenting with "functional theories of intelligence" (Chandrasekaran, 1987).

Thus, the study of PSMs is important for both practical and theoretical reasons. So far, most of the research effort has focused on identifying and specifying PSMs. As a result, several PSM libraries are now available (Marcus, 1988; Breuker et al., 1987; Benjamins, 1993; O'Hara, 1995; Breuker and van de Velde, 1994; Motta, 1997) and a number of PSM specification languages have been proposed, ranging from informal notations (Benjamins, 1993; Schreiber et al., 1994) to formal modelling languages (Fensel and van Harmelen, 1994). The latter area of research is now well established, to such an extent that two projects, one in Europe, IBROW³ (Benjamins et al., 1998), and one in the US, High Performance Knowledge Bases (HPKB, 1997), have been set up with the aim (among other ones) of producing standard formalisms for PSM specification.

While the availability of extensive PSM libraries and the emerging consensus on PSM specification languages indicate the maturity and the 'healthy state' of the field, a number of important research issues are still open. In particular, very little progress has been achieved on foundational and methodological issues. Existing libraries of PSMs lack a clear theoretical basis (typically, they are just associations of problem solving components to tasks) and only provide weak support for the method development process, usually in the form of informal guidelines (Benjamins, 1993; O'Hara, 1995). As a result, practitioners have encountered problems when trying to reuse these libraries. An interesting case study is reported by Orsvarn (1996), who discusses the problems he experienced when attempting to reuse Benjamins' library. For example, he found that in some cases not all assumptions associated with a method were made explicit in the method specification. He also found "tacit dependencies" between different parts of the library (more precisely, different branches of the *task-method structure* - see section 2.1). As a consequence of these problems, he had to modify the structure of the library quite extensively, despite the fact that his target application was relatively straightforward.

In our view these difficulties stem from three aspects of published libraries of problem solving methods: they lack a clear theoretical basis, the components are only informally specified and the method refinement operators are not explicitly represented. As a result, i) it is difficult to characterize the coverage of a particular library (i.e. what is the space of problem solving behaviours covered by a library); ii) it is difficult to compare and contrast PSMs associated with different tasks; iii) it is difficult to understand how a PSM was developed (and what alternative specifications are feasible); iv) it is difficult to support automatic method selection and configuration, as envisaged in the IBROW³ project; and v) it is difficult to verify the properties of a library formally. For instance, it is impossible to check whether or not a library satisfies the requirements of *method correctness* and *method generality* postulated by Orsvarn.

In this paper we will address these issues by illustrating a framework which characterizes

PSMs in terms of *problem commitments*, *problem-solving paradigms* and *domain assumptions*. This framework provides i) a theoretical foundation for situating PSM research and individual PSMs, as well as ii) an organization which allows us to characterize method development and selection as a process of navigating through a three-dimensional space (defined by the three components of our framework). Individual moves through this space are formally specified by means of *adapters* (Fensel and Groenboom, 1997; Fensel, 1997). In the rest of the paper we will illustrate these ideas in detail, with examples taken from *parametric design problem solving* (Wielinga et al., 1995; Motta and Zdrahal, 1996).

2. FOUNDATIONS OF PROBLEM SOLVING METHODS

2.1 PROBLEMS WITH THE TASK-CENTRED PERSPECTIVE ON PROBLEM SOLVING METHODS

PSMs are normally described informally as "ways to solve a task" (Benjamins, 1993). This informal 'method-solves-task' association is used as a structuring principle for organizing libraries of PSMs. The resulting organization, which is shown in figure 1, has been used in several approaches (Steels, 1990; Chandrasekaran et al., 1992; Benjamins, 1993; Puerta et al., 1992) and is normally referred to as a *task-method structure*.

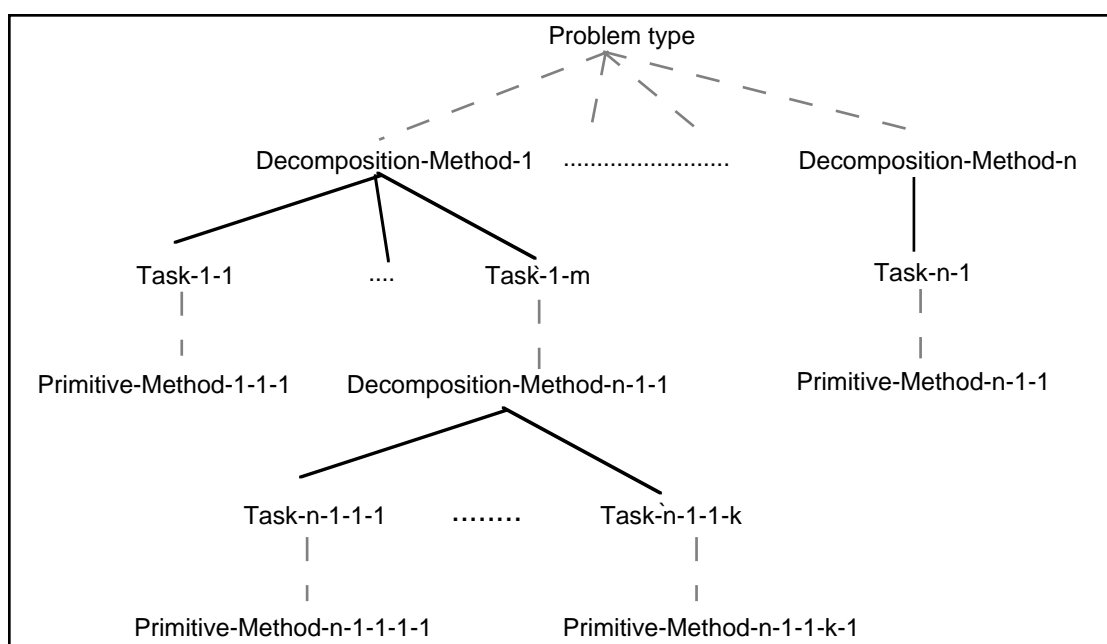


Figure 1. Generic structure of task-method hierarchies.

The root of a task-method structure is given by a high-level task, such as diagnosis or design. These high-level tasks specify *problem types*. Tasks are either solved directly (by means of *primitive methods*), or are decomposed into subtasks (by means of *decomposition methods*). Thus, the resulting libraries are organized in a strong, task-oriented way. This approach permeates most recent research not just on PSMs but on knowledge systems in general and its origins can be found in the reaction to the so-called *weak methods* (Newell and Simon, 1972), which characterized early artificial intelligence research. In a nutshell, researchers in knowledge systems believe that intelligent (i.e. efficient) problem solving is not so much a function of clever algorithms, as a function of the availability of task-specific and domain-specific problem solving knowledge. In the context of PSMs, this approach has been reali-

zed by developing *strong methods* (McDermott, 1988), which embed strong commitments to the available domain knowledge.

While it is hard to imagine anybody in the knowledge engineering community objecting to the knowledge-intensive stance characterizing research in this area, a number of researchers have highlighted problems and limitations associated with task-oriented PSM specifications. For instance Beys et al. (1996) have pointed out that task-specific formulations unnecessarily restrict the reuse of PSMs across tasks and have proposed that PSMs be specified in a task-independent style. In (Fensel et al., 1997) we showed that this could be achieved with no loss of functionality and no loss of abstraction (i.e. without resorting to a lower level of description). In particular, we provided a task-independent specification of a Propose&Revise problem solver, which replaces task-related commitments (e.g. valid design model) with task-independent notions, such as correctness and consistency.

Another problem with the use of task-specific conceptualizations is that, in some cases, these can make it difficult to understand what a PSM actually does. For instance, Motta and Zdrahal (1996) discuss the competence of a number of Propose&Revise problem solvers and show that differences in their competence can be accounted for by formulating them as search algorithms and comparing their state-selection strategies¹.

In summary, while task-orientation has traditionally been the defining feature of PSM research, there is growing awareness in the field that this feature is not just unnecessary but can even be counter-productive.

2.2 PROBLEM SOLVING METHODS AS TASK-SPECIFIC FORMULATIONS OF SEARCH ALGORITHMS

The work by Motta and Zdrahal (Motta and Zdrahal, 1996; 1997; Motta, 1997; Zdrahal and Motta, 1995; 1996) attempts to provide a task-independent foundation to PSMs. Their approach, which is based on the *Task/Method/Domain/Application* (TMDA) framework - see figure 2, considers a PSM as a specialization of a task-specific, but PSM-independent, *problem solving model*, which is in turn constructed by instantiating a generic *problem solving paradigm* (e.g. search) in terms of a *task ontology*. Motta and Zdrahal instantiated their approach in the area of parametric design and showed that several PSMs existing in the literature - e.g. *Propose&Backtrack* (Runkel et al., 1996), *Propose&Exchange* (Poeck and Puppe, 1992) and Propose and Revise - could be characterized as specializations of a common problem solving model, obtained by instantiating an ontology for parametric design tasks in terms of a search model of problem solving. In particular, all PSMs in the parametric design library described in (Motta, 1997) subscribe to a common, generic control regime. As discussed in (Motta, 1997; Motta and Zdrahal, 1997), this approach i) makes it possible to plug and play functionally equivalent components with no change to the control structure and ii) facilitates the comparative evaluation of alternative PSMs.

This work is important because it shows that i) it is possible to provide task-independent foundations to PSMs, even within a task-oriented approach, and that ii) the reliance on a common problem solving model facilitates the construction and the analysis of a library of problem solving methods. However the TMDA framework is limited insofar as it only allows the analysis of PSMs tackling the same class of tasks - i.e. while the framework generalizes from a particular class of tasks, it is still task-centred. Another limitation of the

1. Interestingly, this problem seems to be specular to the one reported by Clancey (1985), which complained about the "blinding effect" of the implementation terminology used in rule-based systems, which made understanding the problem solving competence of these systems much more difficult.

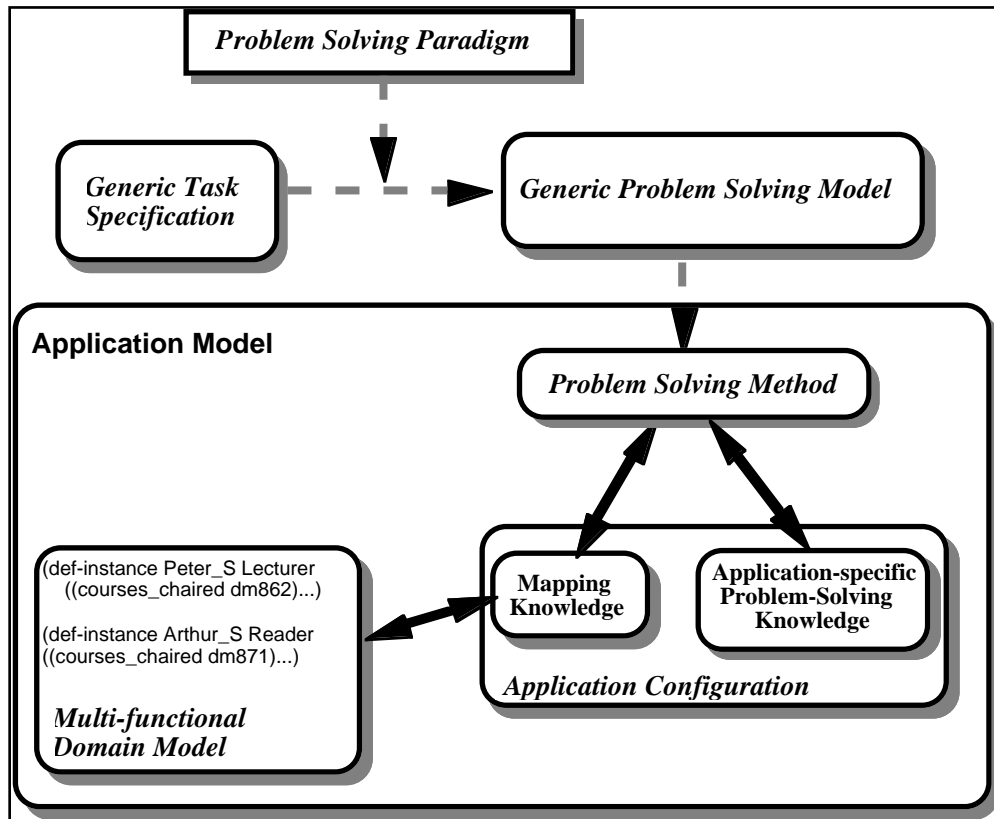


Figure 2. The TMDA modelling framework.

approach is that it only characterizes method development informally, as a relatively unstructured specialization process. The framework we propose in this paper, which is called *PPA (Problems, Paradigms, Assumptions)*, addresses these problems by generalizing from the TMDA approach and by proposing the notion of *adapter* as a construct for formalizing PSM refinement steps.

The *adapter* maps the different terminologies of task definition, problem-solving method, and domain model. Moreover, it gives further requirements and assumptions that are needed to relate the competence of a problem-solving method with the functionality given by the task definition. The task, the problem-solving method, and the domain model can be described independently and selected from libraries because adapters relate the three other parts of a specification to each other and establish their relationship in a way that meets the specific application problem. The consistent combination and adaptation of the three different components to the specific aspects of the given application—since they should be reusable they need to abstract from specific aspects of application problems—are provided by the adapter.

The explicit characterization of moves through the PSM space is important both to formalize the method development process and also to ensure that not only problem solving components but also the process of creating them becomes part of a library. The importance of recording the knowledge engineering experience in a library has been recognized for a number of years (Stutt and Motta, 1995; van de Velde, 1994). However, approaches to capturing design expertise in knowledge engineering have mostly centred on recording informal guidelines. In contrast with these approaches, adapters provide a formal way of capturing the method development process, thus providing the basis for automatic method configuration. The PPA framework is discussed in the next section.

3. A THREE-DIMENSIONAL CHARACTERIZATION OF THE SPACE OF PROBLEM SOLVING METHODS

A problem-solving method in the PPA framework consists of three ingredients (see figure 3).

- **Problem-solving paradigm.** This is a high-level description which specifies a type of problem solving rather than an actual algorithm. A problem-solving paradigm fixes some basic data structures, provides an initial task-subtask decomposition and (optionally) a generic control regime. As in the TMDA framework, this generic control regime is meant to be common to all PSMs which subscribe to the same problem solving paradigm. Examples of problem solving paradigms are: generate & test, local search, problem reduction, etc. (Smith & Lowry, 1990). An important hypothesis in AI is that all intelligent problem solving can be characterized as a search process (Newell and Simon, 1976). If this hypothesis is adhered to, then PSMs can be characterized as specializations of the search paradigm.
- **Problem commitments.** These specify ontological commitments to the type of problem that is solved by the problem-solving method. These commitments are expressed by subscribing to a particular *task ontology*. A task ontology specifies a task in terms of initial and goal states in the universe of discourse and introduces the terminology necessary to express task-specific commitments. The ontological commitments introduced by a task (in particular, by a problem type) can be used to refine the competence of a PSM, the structure of its *computational state* and the nature of the *state transitions* it can execute. For instance, a generic search method can thus be transformed into a more specific method for model-based diagnosis or parametric design. A task-specific refinement of a method is still reusable because it is formulated independently of any domain. That is, the method may be applicable to technical or medical diagnostic problems. However, it is limited to a specific class of tasks. The advantage of refining PSMs in a task-specific way is that the resulting model provides much stronger support for knowledge acquisition and application development than a task-independent one.
- **Domain Assumptions.** These are assumptions on the domain knowledge that is required to instantiate a PSM in a particular application. These assumptions specify the types and the properties of the knowledge structures which need to be provided by a domain model, in addition to those required to instantiate a task ontology. For instance, when solving a design problem by means of Propose&Revise, a domain needs to provide the knowledge required to express *procedures* and *fixes*, in addition to the knowledge needed to formulate the specific design problem - e.g. parts and constraints. Domain assumptions are necessary to enable efficient problem solving for complex and intractable problems. The reliance on such domain-specific knowledge is the defining feature of knowledge-intensive approaches to problem solving.

While these three components cannot be said to specify truly orthogonal dimensions (the choice of a problem solving paradigm may impose constraints on the domain knowledge), they effectively provide alternative degrees of freedom for method specification and refinement (although some points in the three-dimensional space may not be reachable). For instance, PSMs can be specified in a task-independent way - i.e. with no problem commitments; they can be specified with no domain assumptions - i.e. by instantiating a problem solving paradigm with respect to a task ontology, without further commitments; and they can be specified without introducing any control regime or task-subtask decomposition. Such a specification won't necessarily be operational, but it would be good enough to support

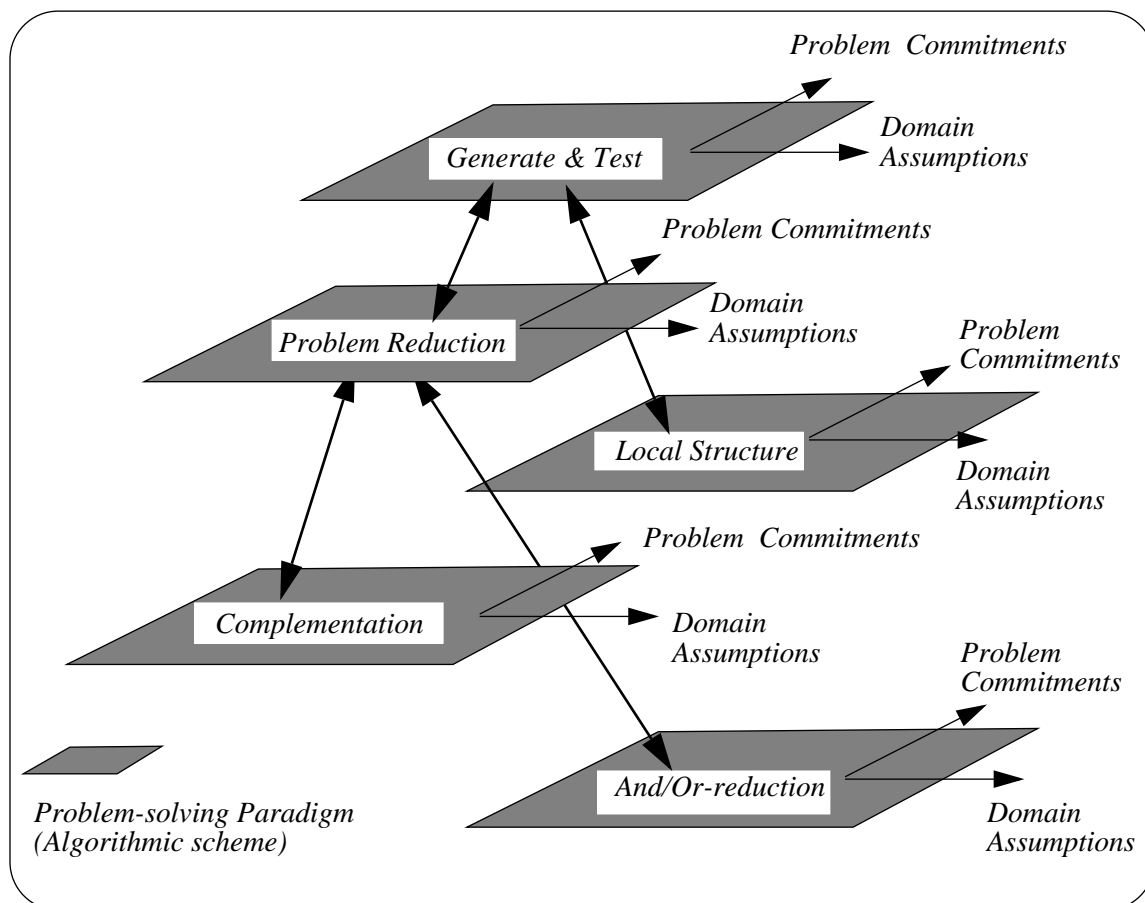


Figure 3. The navigation space for developing problem-solving methods.

a PSM *broker*, such as the one envisaged in the IBROW³ project (Benjamins et al., 1998). The feasibility of this kind of PSM specifications was shown in an earlier paper of ours (Fensel et al., 1997), where we illustrated a declarative specification of a Propose&Revise problem solver, which abstracts from all procedural and control aspects associated with a PSM. Incidentally, this specification was also task-independent, thus showing that it is possible to characterize PSMs purely in terms of domain assumptions, with no commitments to a task and only generic commitments to a problem solving paradigm.

Clearly identifying and separating the problem-solving paradigm, problem commitments, and domain assumptions enables a principled way to developing a problem-solving method and structuring libraries of problem-solving methods. Current approaches to problem-solving methods usually merge these different aspects, thus limiting the possibilities for reuse, obscuring the nature of the methods, and making it difficult to reconstruct the process which led to a particular PSM specification. In the PPA framework, the development and adaptation of problem-solving methods is characterized as a navigation process in this three-dimensional space. The nature of the navigation process itself differs with respect to the dimensions of the development process. Moves through the dimension of problem solving paradigms are not necessarily structure-preserving. In fact, changing the problem-solving paradigm is a revolutionary act that creates new structures in the problem-solving process. In contrast with paradigm-shifting activities, moves which refine the problem type or the domain assumptions are structure-preserving.

Moves through the three-dimensional space can be represented by means of *adapters*. In some cases these are needed to map the different terminologies associated with task, method

```

adapter propose & revise for parametric design tasks
import propose&revise; parametric design
export propose&revise for parametric design tasks
rename
  state → DesignModel,
axioms
  goal(output)
   $d < d' \leftrightarrow \text{cost}(d) < \text{cost}(d')$ 
   $\text{Partial completeness}(d) := \{p \mid p \in \text{assigned}(d)\}$ 
endadapter

```

Figure 4. Specializing Propose&Revise for parametric design tasks.

and domain specifications. For instance, figure 4 shows an adapter which specializes a task-independent specification of a Propose&Revise problem solver for a parametric design task. In more complex cases, adapters can introduce further commitments needed to relate the competence of a problem-solving method with the goal associated with a task specification. For example, let's consider the case in which we specialize a task-independent Propose&Revise for an optimal parametric design task - see figure 5². In general, optimality can only be guaranteed by introducing strong assumptions on the available propose and fix knowledge. Thus, the resulting adapter not only maps method-specific to task-specific terminology, but

```

adapter propose & revise for optimal parametric design tasks
import propose&revise for parametric design
export propose & revise for optimal parametric design tasks
axioms
  /* The output is a complete, correct and optimal design model. */
   $\text{complete}(\text{output}) \wedge \text{correct}(\text{output}) \wedge$ 
   $\neg \exists d. (d \in \text{ParametricDesignModel} \wedge \text{complete}(d) \wedge \text{correct}(d) \wedge \text{output} < d)$ 
  /* The propose knowledge never fails and monotonically extends the design
  model. */
   $\neg \text{complete}(d) \rightarrow \text{Partial completeness}(d) < \text{Partial completeness}(\text{propose}(d))$ 
  /* The application of a propose leads to an optimal design model. */
   $\neg \text{complete}(d) \rightarrow$ 
   $\neg \exists d' (d' \in \text{ParametricDesignModel} \wedge \text{correct}(d') \wedge \text{propose}(d) < d' \wedge$ 
   $\text{Partial completeness}(d') = \text{Partial completeness}(\text{propose}(d))$ 
  /* The revise knowledge never fails. */
   $\neg \text{correct}(d) \rightarrow \text{correct}(\text{revise}(d))$ 
  /* The application of revise does not change the completeness of a design model. */
   $\text{Partial completeness}(\text{revise}(d)) = \text{Partial completeness}(d)$ 
  /* The application of revise leads to an optimal design model. */
   $\neg \text{correct}(d) \rightarrow$ 
   $\neg \exists d' (d' \in \text{ParametricDesignModel} \wedge \text{correct}(d') \wedge$ 
   $\text{Partial completeness}(\text{revise}(d)) = \text{Partial completeness}(d') \wedge$ 
   $\text{revise}(d) < d')$ 
endadapter

```

Figure 5. Specializing Propose&Revise for optimal parametric design tasks.

2. This example is described in detail in (Fensel et al., 1997).

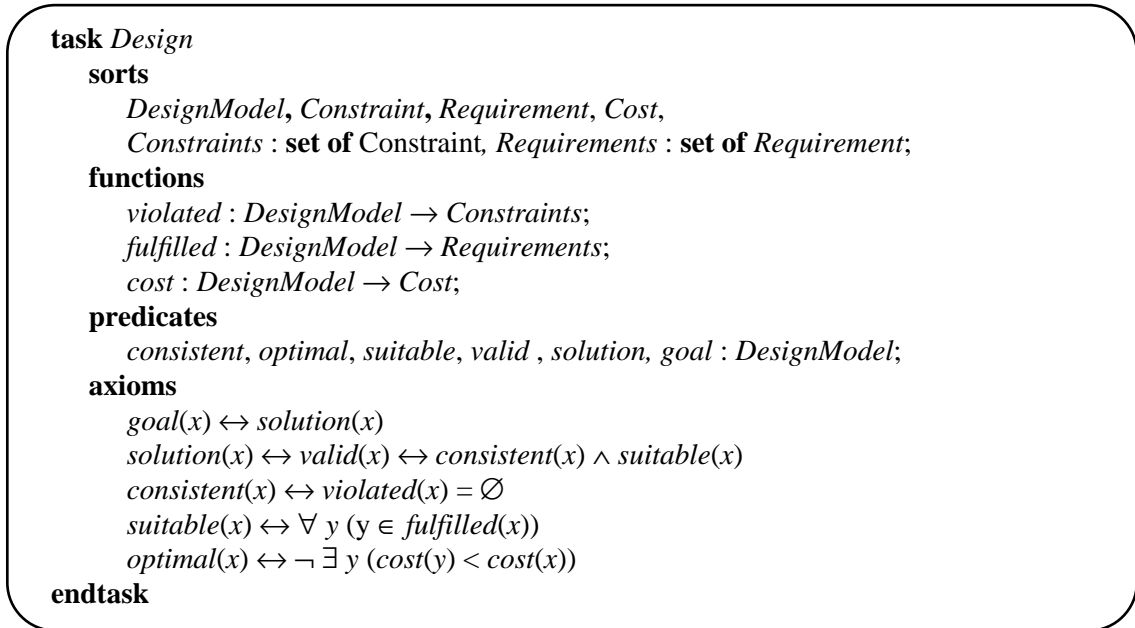


Figure 6. Specification of problem type design.

also introduces additional commitments required by the optimality criterion. For instance, it introduces the requirement that propose and revise steps must be optimal.

Adapters can also be used to refine task or method specifications. These cases are illustrated in figures 6-8. Figure 6 shows the definition of a generic design task - see section 4.1 for more details on this problem type - and figure 7 shows an adapter specializing the definition of the generic design task for parametric design. Finally, figure 8 shows an adapter which refines a generic hill climbing method to produce a set minimizer.

The adapters described here are similar to the *adapter patterns* discussed by (Gamma et al., 1995), where adapters are given as patterns which make it possible to reuse object classes. While this functionality is provided also by our notion of adapter, our characterization also makes it possible to specify explicitly the commitments and assumptions which are necessary to 'bridge the gap' between a problem definition (task) and the competence of a problem-solving method.

Natural candidates for the formal definition of adapters are algebraic specifications. These have been developed in software engineering to define the functionality of a software artefact (Bidoit et al., 1991; Wirsing, 1990). Briefly, algebraic specifications comprise a *signature* (consisting of types, constants, functions, and predicates) and a set of axioms that define the properties of these syntactical elements.

In the next section we will illustrate these ideas by showing how the PPA approach can be used to carry out a rationale reconstruction of part of the library for parametric design described in (Motta, 1997)³. The resulting structure teases out the various types of task-specific and domain-specific commitments associated with different problem solving components and makes explicit the model development process by means of the relevant adapters.

³.Henceforth, the 'Motta library'.

```

adapter Problem Type Parametric Design
import
  Problem Type Design;
export
  Problem Type Parametric Design;
terminology mapping
  DesignModel → ParametricDesignModel;
sorts
  Parameter = { $p_1, \dots, p_n$ },
  Parameters : set of Parameter,
  ValueRange1, ..., ValueRange $n$ ;
functions
  ParametricDesignModel : Parameter →  $ValueRange_1 \cup \dots \cup ValueRange_n$ 
    where  $DesignModel(p_i) \in ValueRange_i$  for all  $i=1, \dots, n$ ;
  assigned : ParametricDesignModel → Parameters;
predicates
  complete : ParametricDesignModel;
axioms
   $solution_{Export}(x) \leftrightarrow solution_{Import}(x) \wedge complete(x)$ ;
   $complete(x) \leftrightarrow \forall y (y \in assigned(x))$ ;
endadapter

```

Figure 7. Parametric design as a specialization of problem type design.

4. A CASE STUDY: PROBLEM SOLVING COMPONENTS FOR PARAMETRIC DESIGN

As indicated earlier, the library of problem solving components for parametric design developed by Motta (1997) characterizes each problem solving method as a specialization of a generic problem solving model obtained by instantiating a generic search model of problem solving by means of a parametric design task ontology. Here we show how the various steps in the process can be made explicit by means of the relevant adapters. Because of limitations in the available space, we will only show the steps necessary to formalize the high-level com-

```

adapter set minimizer
import hill climbing
export set minimizer
axioms
  /* The input set must be correct. */
   $correct(input)$ 
  /*  $select_1$  must select the input set. */
   $select_1(x) = \{x\}$ 
  /* Successors are subsets that contain one less element. */
   $successor(x, y) \leftrightarrow \exists z. (z \in x \wedge y = x \setminus \{z\})$ 
  /* We prefer smaller sets if they are still correct. */
   $x < y \leftrightarrow correct(y) \wedge y \subset x$ 
endadapter

```

Figure 8. Set minimization by adapting hill-climbing.

ponents of the library. However, these should be sufficient to illustrate the suitability of the approach - more details can be found in (Fensel and Motta, 1998).

4.1 DEFINING THE PROBLEM TYPE

Design can be characterized in generic terms as the process of constructing artefacts. Usually, the target artefact should fulfil a number of requirements, should not violate the relevant constraints and should follow the principle of economy - i.e. it should have minimal cost (Motta and Zdrahal, 1996). Figure 6 shows a possible characterization of the class of design problems. This definition can be specialized for parametric design problems by introducing parameters and value ranges, as shown in figure 7. Parametric design problems reduce the complexity of the design task by assuming the existence of a *parametrized solution template* for the target artefact. Hence, as shown in figure 7, a design model can now be defined as a partial function from parameters to value ranges and a solution can be defined as a *valid and complete* design model. This is a model in which all parameters are bound, all requirements are satisfied and no constraint is violated.

4.2 INITIAL PSM SPECIFICATION

We start with the algorithmic scheme *local search* that defines the common pattern of all problem-solving methods described in (Motta, 1997). A generalized, task-independent version of this control regime is shown in figure 9. Basically, *LocalSearch* initializes the search process and *RecursiveSearch* searches until a solution has been found. At each cycle a node is selected and its successors derived. *UpdateNodes* takes as input the current search space and the newly generated nodes and produce a new search space. Different search strategies can be modelled by defining alternative methods for this task. For instance, *best-first search* can be modelled by performing a simple union of *Nodes* and *SuccessorNodes*, while *hill-climbing* can be modelled by ensuring that *UpdateNodes* returns only *SuccessorNodes*.

The local search model can be specialized for design tasks by means of the adapter shown in figure 10. Essentially, this adapter introduces the term *design model* into the method and maps the notion of task solution to that of method solution. The resulting PSM is still unspecified, as it does not say how to select design models, how to derive successor designs, and how to update the set of designs. Because of space restrictions we are not able to discuss these tasks here, which are described in detail in (Motta, 1997).

Refining the resulting model of design problem solving for parametric design is simply a matter of importing the problem type *Parametric Design* and the PSM *Local Search for Design*, to produce the PSM *Local Search for Parametric Design*.

4.3 CAPTURING A FAMILY OF PSM SPECIFICATIONS

A summary of parametric design problem solving in terms of its states and state transitions is provided in Figure 11. This style of specification results from the approach adopted here, which consists of choosing an algorithmic scheme and applying several adapters that refine its state descriptions and state transitions. Such a specification is more abstract than what is usually called a PSM in the literature. For instance, let's consider Propose&Revise. Propose&Revise for parametric design instantiates the framework by distinguishing two *contexts*⁴

4. In the Motta library the notion of design context is used to characterize typical design scenarios, such as fixing an inconsistency, reducing the cost of a design, extending the current model, etc.

PSM Local Search

/ There are some simplifications to report: We ignore the case when *SelectNode* does not deliver an output and when *DeriveSuccessorNodes* does not deliver an output. In consequence we only terminate when we have found a solution and we do not terminate for intermediate empty inputs. */*

control flow

LocalSearch()

/ Initializes and starts the search. */*

Nodes := Initialize();

Output := RecursiveSearch(Nodes)

RecursiveSearch(Nodes)

/ Searches. */*

Node := SelectNode(Nodes);

SuccessorNodes := DeriveSuccessorNodes(Node);

Nodes := UpdateNodes(Nodes, SuccessorNodes);

IF OptimalSolution(x) for a $x \in Nodes$

THEN RETURN these x 's

ELSE RecursiveSearch(Nodes)

ENDIF

sorts

Object, Objects : set of Object;

functions

Node : Object;

Nodes, Output, SuccessorNodes : Objects;

predicates

OptimalSolution : Object;

elementary inferences

DeriveSuccessorNodes,

Initialize,

SelectNode,

UpdateNodes

Figure 9. The *local search* problem solving method.

when deriving successor design models:

- Propose context. Consistent design models are extended until they are complete or inconsistent.
- Revise context. Inconsistent design models are repaired until they are consistent.

That is, this PSM can be derived from our framework by simply refining some of its parameters. An extensive discussion of how various PSMs for parametric design can be derived as specializations of a generic search model is provided in (Motta, 1997).

Figure 11 also includes a slot for specifying the competence of a PSM. This describes its functionality (and utility), abstracting from how it is achieved (Akkermans et al., 1993; Fensel and Groenboom, 1997; ten Teije, 1997). Such competence descriptions enable black-box reuse. The general problem of establishing competence descriptions of problem-solving methods stems from the fact that they can only be established in terms of assumptions about the required knowledge. The termination, completeness and correctness of generic search

```

adapter Problem-Solving Local Search for Design;
import
  Problem Type Design, Problem Solving Local Search;
export
  Problem-Solving Local Search for Design;
rename
  Object → DesignModel;
axioms
  goal(Output)
endadapter

```

Figure 10. Specializing local search for design.

methods like A* (or specialized ones, such as Propose&Revise) can only be guaranteed by placing strong requirements on the knowledge that is used to guide the search process. As a consequence, the association of a competence specification to a PSM is not a bijective relation. On the contrary, it depends on the assumptions associated with the PSM (Benjamins et al., 1996).

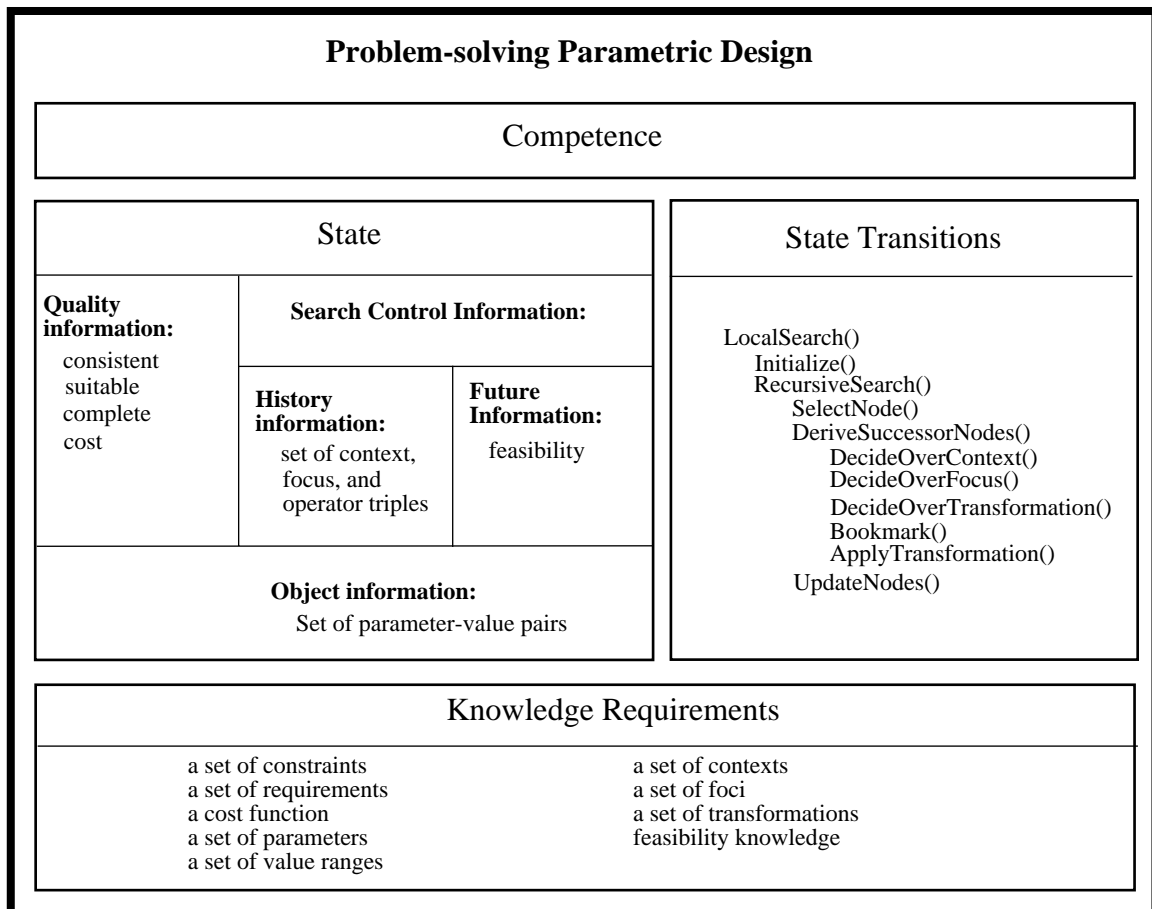


Figure 11. An abstract specification of parametric design problem solving.

5. CONCLUSIONS

In this paper we have presented a systematic approach enabling the structured development, adaptation, and reuse of PSMs. A large number of PSMs can be described by means of i) a structured set of generic task and problem-solving patterns and ii) adapters formalizing the relevant refinement steps. These are explicitly modelled, thus allowing their reuse for new problem types and different problem-solving schemas.

Adapters introduce a new modelling element into existing modelling approaches, which makes the method development process explicit and external to the model, i.e. separated from problem solving components. In most other approaches, adaptation is treated as a side issue and adaptation via several levels is not considered at all. As discussed in section 1, this is especially a problem for libraries of PSMs. In our view, by providing a clear foundation for both PSM specification and specialization we can construct sound and reusable libraries. While this is only an unproved claim as far as reuse is concerned, the experience reported by Motta and Zdrahal (Motta, 1997; Motta and Zdrahal, 1997) shows that the reliance on clear theoretical foundations allows a better understanding of PSMs and facilitates their evaluation and comparison.

Still, our current adapter concept may be too general and we are currently working on a typology of adapters. So far we have identified two basic dimensions for organizing adapters: in terms of their purpose (*teleological dimension*) and in terms of the syntactical entity refined by an adapter (*epistemological dimension*). The first dimension indicates whether an adapter is used to refine a problem type, a domain dependency via assumptions, or a problem-solving paradigm. The second dimension distinguishes whether an adapter refines, for instance, a state definition, a state transition, or a declarative competence specification. Working this out in more detail will help transforming the development process of PSMs into a more structured engineering activity.

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