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Towards a Sharable Knowledge Base on Recyclable Plastics

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Director

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Contents

TOWARDS A SHARABLE KNOWLEDGE BASE ON RECYCLABLE PLASTICS*

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Abstract

For economic decision processes, recycling of products and production waste is getting more important. In the future the integration of recycling-relevant data into the information structures of companies should be supported by knowledge-based methods. We present the conception of a knowledge base for recycling-oriented product and production planning (RPPP). Then we take a detailed look at the fundamental materials module. We examine which *evolution* techniques are appropriate for the maintenance of such knowledge bases. In particular, we study the *validation* of existing materials and the *exploration* of new ones with regard to their recyclability. An appendix includes a script of a real sample dialogue with our knowledge base on recyclable thermoplastics (RTPLAST).

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Background

The conception of the declarative knowledge base (KB) on recycling-relevant materials presented in this paper was elaborated for a proposed project on knowledge Validation and Exploration by Global Analysis [3] at the DFKI (German Research Center for Artificial Intelligence) in Kaiserslautern, Germany.

The aim of this project is to study and implement algorithms which explore (e.g. pattern abstraction, establishment of associations) and validate (e.g. consistency/completeness checking) knowledge in given declarative (logically formulated) KBs by global analysis (e.g. abstract interpretation, dataflow analysis). Prototypes of these evolution algorithms will then be tested on real-world KBs.

As part of the DFKI project IMCOD and for preparing further projects an application KB is being built. On the one hand this KB should be a suitable testbed for various algorithms to be developed; on the other hand it should be useful for prospective industrial users [12].

Possible Application Areas of a Recycling Knowledge Base

When evaluating possible areas for a knowledge base on recycling, the know-how on recycling-oriented product and production planning [1, 20] appears to be especially suitable: production and recycling planning and control systems [8] can profit from explicitly representing recycling-relevant knowledge that up to now is scattered in the heads of scientists, engineers and decision makers. Not only the strong application pressure (electronic-waste regulation, automobile recycling) or the economic-ecological benefit, but also the prospects of assessing complex materials circulation and computing ecological balances led us to this topic.

In accordance with knowledge sharing/reuse proposals [2, 15, 9, 13] multiple types of application for the RPPP KB are conceivable:

- Supporting the decision-making process of product engineers in regards to raw materials selection, product designs and production processes [18].
- An inter/intra-enterprise comparision of recycling possibilities between one or more companies/departments.
- The environmental commissioners of a company are able to validate the systematics of their activities (e.g. w.r.t. law fulfillment) and explore new possibilities with support from the KB-evolution system.
- KB-exploration programs can find/maintain (qualitative/quantitative) ecological balances for products and production processes.
- A ranking of product designs and existing products can be generated, e.g. w.r.t. the degree of recyclability or energy consumption during the recycling process.

Further areas of application are possible, even ones that cannot be anticipated, because of the declarative representation of the KB [18].

The Materials KB in the Context of the RPPP KB

The magnitude of required information caused by the various application areas enforces a modularization of the RPPP KB into subKBs to decrease complexity at least locally (Fig. 1). This modularization should, if possible, reflect the structure of already existing data.

The module "Requirements" represents demands of customers regarding, for example, the functionality, as well as laws, decrees and regulations that can, for example, be concerned with environmental aspects. The module "Methods" contains production methods which are at the company's disposal and which are determined by the product engineer. At the same time the environmental commissioner can explore and validate a recycling strategy with the help of the sub-module "Recycling". The module "Products" defines the product compositions by way of the structural components and construction units utilized. Recycling strategies are associated either to "Structural Components" or "Construction Units" according to their degree of disintegration after product use. The materials required for the product construction and regained through its recycling are represented in the module "Materials". The modules are designed in such a way that the final phase of the product life-cycle can be taken into account during the product planning phase.

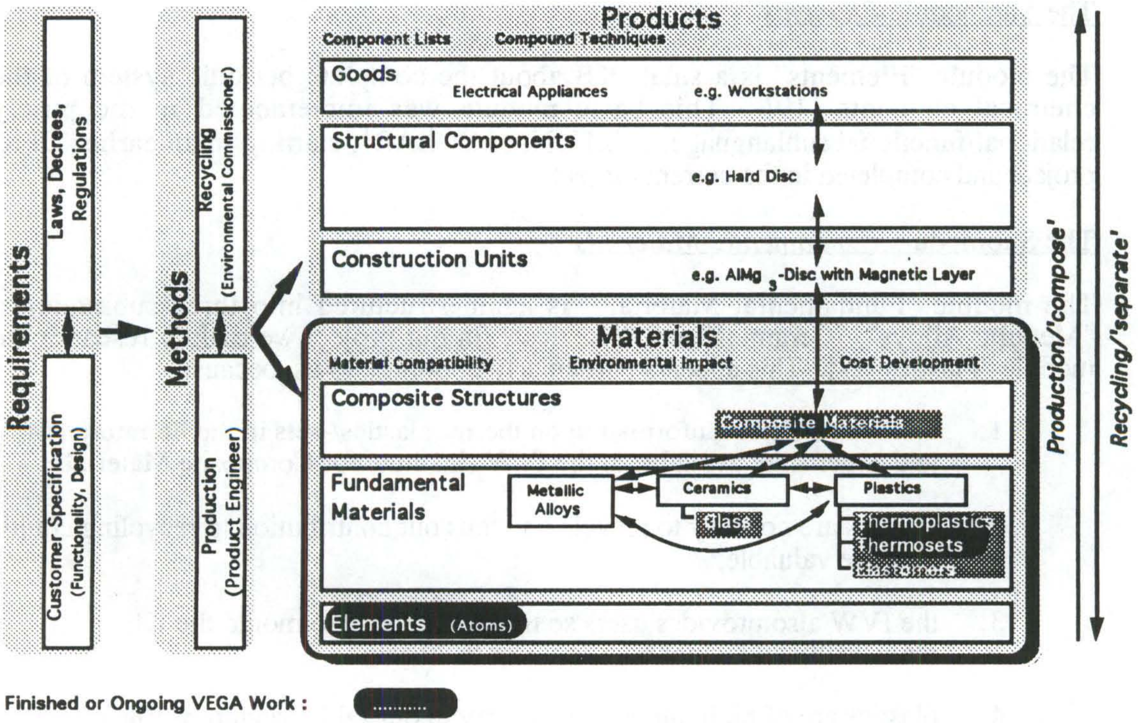

Figure 1 - The Materials KB in the Context of the RPPP KB

When constructing the RPPP KB it is sensible to begin with a well-formulated and reuseable module. We decided to implement parts of the module "Materials", because extensive data/knowledge exists here and both human users and several modules will need to access it. Also, the purpose of recycling is to recover materials from old and already used products for new ones; thus materials constitute the "substance" of recycling and it is natural to begin a modular RPPP KB with the organization of a "Materials" subKB. An important part of the submodule "Fundamental Materials" is implemented by a KB on recyclable thermoplastics (RTPLAST), which draws on the plastics database CAMPUS. The data are extended by recycling-relevant knowledge about, e.g., material compatibility, environmental impact, and cost development. The knowledge-intensive parts make use of AI representation techniques: instead of a tightly formatted extensional database system, a freely formatted intensional KB system with inference rules is used; this will permit, e.g., to generate suggestions on materials selection, cross-reference, comparison, and substitution.

Building on the sub-module "Fundamental Materials", the sub-module "Composite Structures" can be realized. Knowledge on the recycling-friendly composition of products with regard to their separation into homogeneous fractions at the end of the life-cycle will be represented. This knowledge, taken from matrices for recycling compatibility, diagrams (e.g. about material flows in the production process), regulations (e.g. [20]), etc., is represented in a unified declarative form. A more precise specification of the module "Materials" is given in the following section.

The Module *Materials*

Due to the abundance of materials suitable for recycling, a subdivision of the module "Materials" into several submodules is necessary. Fig.1 shows that the module "Materials" consists of the submodules "Composite Structures", "Fundamental Materials" and "Elements". This division is the usual one made by materials engineers, where not only recycling characteristics are being considered, so that the KB can also be used for ordinary production purposes (reuseablity).

The Submodule *Elements*

The module "Elements" is a small KB about the complete periodic system of the chemical elements [19]. This basic module was implemented in the purely relational/functional sublanguage, RELFUN, of COLAB[1], starting in an earlier DFKI project and completed in the current project.

The Submodule *Fundamental Materials*

The module "Fundamental Materials" is again structured into three submodules, "Metallic Alloys", "Ceramics" and "Plastics". In our project we mainly research the module "Plastics" [7]. This appears particularly important to us, because:

1. there is sufficient information on thermoplastics/-sets in the literature [14] and experts are available at the IVW (Institute for Composite Materials),
2. plastics are not easy to recycle and thus our contribution to recycling could be quite valuable,
3. the IVW also provides users so that we are able to mould the KB realistically and under constant user feedback,
4. plastics are of high interest to industry in our DFKI region of Rheinland-Pfalz (Rhineland-Palatinate).

When constructing the KB, we are initially satisfied to represent a subgroup of thermoplastics which can already be recycled in such a quality that with the recycled plastics new comparable products[2] can be constructed[3] The inheritance schema of, and a sample dialogue with the implemented RTPLAST KB are shown in the appendices.

Various types of knowledge pertaining to those thermoplastics are represented in RTPLAST, currently comprising 260 Horn clauses. The KB started off with database-like information such as thermal, mechanical and electrical characteristics, which are considered as numerical attributes in RELFUN. For updates and augmentations such

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[1] COLAB is a hybrid knowledge representation tool which was developed at the DFKI, supporting forward/backward chaining, constraint propagation and taxonomic inheritance [2]. For the current KB we only use the PROLOG-like part of RELFUN and its object-centered extension.

[2] The term "comparable" means the usage of the recycled material in such a way that, say, a former box is reconstructed into a box, and is not used as filling material in the building industry (downcycling). But the reclaimed material is allowed to contain some percentage of new material to maintain the desired quality.

[3] Bernhard Nebel und Hans-Jürgen Bürckert. Reasoning about temporal relations: A maximal tractable subclass of Allen's interval algebra. Research Report RR-93-11, DFKI, 1993

KB parts should be automatically translated from existing databases like CAMPUS[1] [6]. The plastics are structured into an **is-a/instance-of** hierarchy in a way useful for plastics engineers (cf. appendix A)[2]. Similar attempts are pursued for metals [10, 11] and ceramics [21].

The properties relevant for recycling are mostly represented as attributes with qualitative values, e.g. the qualified recyclability of a material (planned: environmental impact such as biodeg-radability), or structured values, e.g., matrices for stress-strain interpolation (planned: the recycling compatibility of plastics co-occurring in products).

Principally, we wish to represent all knowledge in a homogeneous version of our hybrid COLAB language. The design of this new knowledge representation language is being optimized so that KBs can be easily explored and validated. The language first extends DATALOG by constructor symbols, finite-domain constraints, and intensional sorts; it then adds features dictated by KB application or evolution concerns [4].

The Submodule *Composite Structures*

At present the module "Composite Structures" is in its planning phase. In a joint project between the IVW and the DFKI some aspects of the demanding problem of (recycling) composite materials will be examined with the help of AI methods: how to substitute polyamid by polypropylene as part of (glass-fiber-containing) composite materials [16]. For this module other submodules of the "Materials" module are to be used (cf. Fig 1).

Evolving the Materials KB

For describing how evolution techniques can be used on the "Materials" KB in different application scenarios, we first give a brief description of the overall architecture and then characterize our notions of validation and exploration.

The Overall Architecture and the Evolution Process

A knowledge evolution system operates on the KB of an expert system which is applied in an external environment. Thus, for an overall description of knowledge evolution we distinguish two main units (Fig. 2): the knowledge-based system (KBS) and the knowledge-evolution system (KES), used by the knowledge engineer.

The task-knowledge base T of a KBS can become the target knowledge base that is globally analyzed by the evolution system. We assume that it is written in the declarative KB language or can be translated to this language using an input translator.

The evolution-knowledge base E contains general techniques for evolution (e.g., inductive inference techniques, search strategies like hill-climbing) and domain-specific heuristics specifying when to apply which technique and formalizing the interestingness of patterns. The optional domain-knowledge base embodies a model of the environment the KBS is applied in. The general domain knowledge can be used both for the KBS and the KES, for 'understanding' the specific task knowledge. The more knowledge there is in the task KB itself, the less important is the access to the domain knowledge in D for the evolution process.

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[1] CAMPUS is a database about plastics in which most German producers present the data of their products in a unique form.

[2] The reusability of a KB, e.g. the plastics hierarchy, implies that it permits other points of view for requests from, say, a decision maker, in contrast to a materials engineer, without changes in the KB.

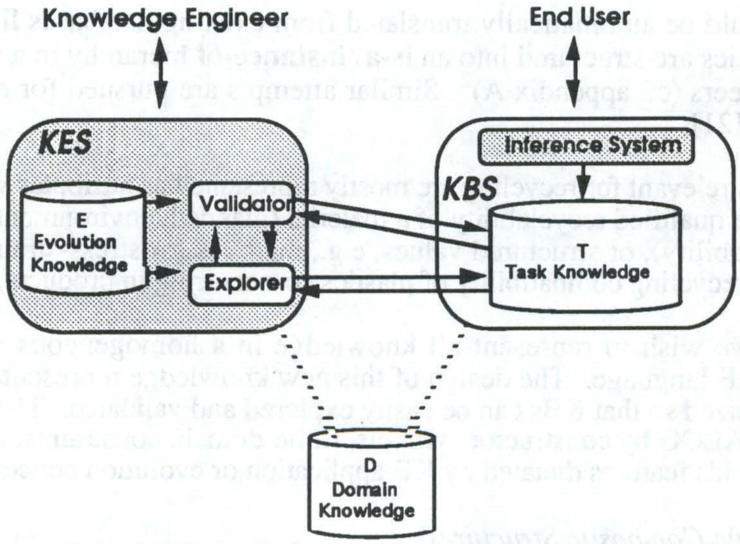

Figure 2 - The Evolution/Inference Architecture (shaded) in Context

Reasoning in the knowledge evolution system is performed by the exploration and validation components.

- The knowledge explorer scans the target KB in search for interesting patterns. Exploration (right part of Fig.3) can be seen as an iterative process starting with the generation of a pattern hypothesis, proceeding with a search for the pattern in the target KB, and resulting in a possible interactive assimilation of the discovered pattern into the KB.
- The knowledge validator examines the target KB to detect structural or functional defects. Validation (left part of Fig.3) can also be seen as an iterative process starting with the generation of a defect suspicion, proceeding with a check for a defect w.r.t. the suspicion in the KB, and resulting in a possible defect description or repair suggestion.

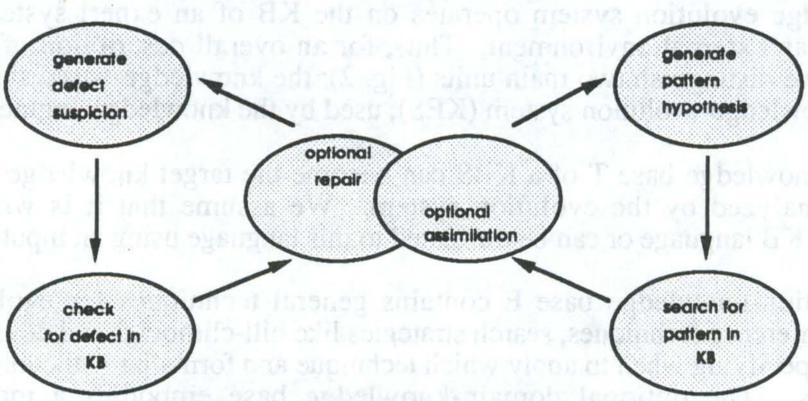

Figure 3 - The Evolution Processes

Knowledge evolution can be focussed on individual modules or guided by hypotheses (or suspicions) concerning the kind, the semantic context, and the location of the pattern (or defect). This evolution-space pruning is influenced by the user's interests, previous evolution steps, and the available evolution techniques.

The iteration cycles shown in Fig.3 can be arbitrarily interleaved, permitting evolution to consist of dual validation and exploration processes. Together they form a heuristic, approximative process that alternates focusing and processing phases and improves the KB any time a sufficient amount of knowledge for an update (i.e., assimilation or repair) has been accumulated within the KES or by the user. For example, assume that the validator has identified a rule whose premises cannot be satisfied in a given target KB. The explorer could then, e.g., try to generalize that particular rule or to complete the missing knowledge reachable from its premises. Conversely, after the explorer has discovered a pattern (e.g., a new or generalized rule that considers additional symptoms) the validator may be asked to verify the KB, focused on the assimilated pattern.

Possibilities of Evolution on the Materials KB

In our first planned application of the "Materials" KB a construction engineer is to be supported when selecting materials for a draft of a compound construction (with recycling-relevant aspects being considered). In this undertaking our expertise-providing partner is the IVW.

We are studying the possibility of using evolution techniques for this material selection process. On one hand we look at the exploration of, e.g., properties associated with materials, and possible substitutions of materials by functionally equivalent, but better recyclable, materials; on the other hand we consider the validation of, e.g., composite materials and plastics regarding environmental protection laws such as guidelines, norms, tolerances and boundary values.

The material selection process divides into material pre-selection, where the type of material is fixed, and into the special material selection for construction, where the most suitable among the pre-selected materials (ca. 10-15), is pinpointed.

Material Pre-Selection: Identification of stored materials M_k according to given characteristics P_i (e.g. elasticity, density, ball thrust hardness, cf. appendix B).

$$P_1,...,P_n \text{ -> } M_1,...,M_m \tag{1}$$

Special Material Selection: Fine-tuning and optimizing of the material pre-selection with regard to optimality criteria φ (e.g. recyclability, cost, cf. appendix B).

$$\text{optim}_\varphi(M_1,...,M_m) = M_k;\ 1 \leq k \leq m \tag{2}$$

Inverting (1), direct and derived characteristics can be associated with a material M_k already stored.

$$M_k \text{ -> } P_1,...,P_n;\ 1 \leq k \leq m \tag{3}$$

A material selection specified for a new product can be optimized with regard to non-changing functional properties of the materials. In that case an already known but not optimized material (M_1) which is missing desirable characterisitics ($P_{m+1},...,P_n$), e.g. recyclability, is being checked to see whether there is a material (M_2) that is identical in its function preserving properties ($P_1,...,P_k$) and furthermore meets the additional characteristics; the non-relevant properties ($P_{k+1},...,P_m$) and ($P'_{k+1},...,P'_m$) may be different. Once such a material is identified, it will be looked upon as a substitute. In order to locate substitutes, we first abstract, within the classification hierarchy of the materials, from the non-relevant characteristics of the given material to be optimised. If a substitute with better characteristics exists, it will be instantiated.

$$M_1(P_1,...,P_k,P_{k+1},...,P_m) \text{ -> } M_2(P_1,...,P_k,P'_{k+1},...,P'_m,P_{m+1},...,P_n) \tag{4}$$

Within an evolution cycle already stored material can be similarly optimized by adding new desirable characteristics. After discovering a less optimal material, the KB will be tested for another suitable substitute. The additional characteristics of the substitute will be transferred to the material to be optimized. The last step will be carried out only after an interactive confirmation by the user. To add new characteristics to some material (M_1), we first abstract again from the non-relevant and desired additional characteristics. We then try to find another material (M_2) which fulfills the function-preserving characteristics of M_1, additionally having the desired characteristics. Finally, M_1 will be hypothetically instantiated with the new characteristics, which of course must be validated.

$$M_1(P_1,\ldots,P_k,P_{k+1},\ldots,P_m),\ M_2(P_1,\ldots,P_k,P'_{k+1},\ldots,P'_m,P_{m+1},\ldots,P_n)$$

$$\to M_1(P_1,\ldots,P_k,P_{k+1},\ldots,P_m,P_{m+1},\ldots,P_n) \qquad (5)$$

Besides an existing classification hierarchy for plastics [14], which we presuppose, further classifications or views, e.g. the classification of plastics producers, can be generated over the stored materials. Classes of materials can be identified exploratively using concept learning and clustering methods due to similarities and differences of the materials properties [17]. The needed classification criteria may for instance be defined by the user, derived from exisiting case bases, or be determined by recycling-specific knowledge.

According to the interactive evolution cycle described in the previous section, the findings which were explored can be fed back into the KB after having been validated. Basically, every change to the KB, for instance the addition of a new material, must be validated. The stored materials can be checked relative to stored patterns, schemes, types, sorts or concepts, through unification or instance testing. Thus, for instance, classification errors can be detected. Furthermore, materials can be tested for consistency w.r.t. given boundary values, guidelines, norms and tolerances. Through update processes within the materials KB integrity constraints on relations between materials of a product or a compound can become violated. Thus, as part of the validation process the checking of such integrity constraints after updates must be guaranteed.

The study of evolution possibilities on materials KBs has hardly begun with the above observations - after all this is the main theme of the planned project. For that reason only our initial attempts, which are directed to the existing thermoplastics KB, could be presented.

Outlook

In general, the future RPPP KB can profit methodologically and w.r.t. content from engineering KBs created in the ARC-TEC project. For instance, we were able to reuse a KB on the periodic system of the elements [19]. On the other hand product-oriented materials databases like CAMPUS 2 [6] have been evaluated in view of extending them by recycling-relevant knowledge.

By our present concentration on thermoplastics in RTPLAST several pragmatic advantages arise: easy accessability (by way of literature, experts, and databases) and of course the broad utilization ("knowledge-sharing-potential") of such materials knowledge (e.g. for production **and** recycling).

In addition to the IVW we are in contact with other materials experts and potential users, e.g. with several DFKI shareholder companies (e.g. IBM, Siemens, Daimler). We make the current versions of our elements and thermoplastics KBs available to interested parties (as ASCII source in LISP-like or PROLOG-like syntax).

Let us come back to the modularization of Figure 1. The completion of the submodule "Thermoplastics" (RTPLAST) is planned together with the IVW. Building on the module "Fundamental Materials", we are currently attacking parts of the module "Composite Structures" (Fig.1). On this basis, a prototype version of a system for recycling-oriented materials selection can be constructed, enriching the prototypical selection shown in appendix B: given a description of desired properties, it should select one or more suitable materials. This system should be tested and expanded under realistic DFKI/IVW-internal and, later, external industrial conditions. Building on this, as a long-term goal we can strive for a reuseable representation of, and various operations on specialized recycling/production knowledge within the modules "Requirements" and "Methods" of the RPPP KB (Fig. 1).

We believe that the work invested in the KB would be justified by a single real-world material substitution or recycling possibility discovered by its interactive validation, exploration, or use. Already the alternative system analysis through our AI formalization could shed new light on known facts.

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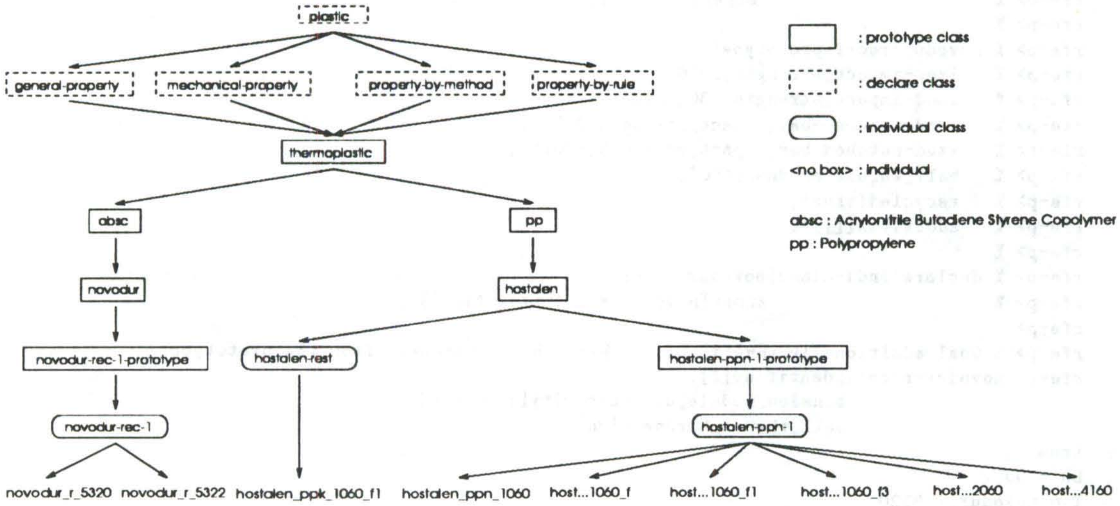
Appendix A: Implemented Inheritance Schema of RTPLAST



Appendix B: Abridged Sample Dialogue with RTPLAST

```
rfi-p> exec rtplast
rfi-p> style prolog
rfi-p> %------------------------------------------------------------------------
rfi-p> %|      A Declarative Knowledge Base on Recyclable Thermoplastics        |
rfi-p> %|       Using Attribute Terms, Sorts, and Inheritance in RELFUN         |
rfi-p> %------------------------------------------------------------------------
rfi-p>
rfi-p> %                                                    April 1994
rfi-p> % (c) Ulrich Buhrmann, Michael Sintek
rfi-p> %
rfe-p>
rfe-p>
rfe-p> %          Original object-centered version of RTPLAST
rfe-p> %------------------------------------------------------------------------
rfe-p>
rfe-p> % Two sample instances of one sample class of recyclable novodurs
rfe-p> % (attribute-value pairs prefixed by the class name)
rfe-p> % novodur-rec-1(
rfe-p> %   identifier[novodur_r_5320],
rfe-p> %   yield_stress[38],
rfe-p> %   yield_elangation[2.1],
rfe-p> %   tension_module_of_elasticity[2000],
rfe-p> %   dimensional_stability_hdt/a[90],
rfe-p> %   dimensional_stability_hdt/b[95]).
rfe-p> % novodur-rec-1(
rfe-p> %   identifier[novodur_r_5322],
rfe-p> %   yield_stress[40],
rfe-p> %   yield_elangation[2.3],
rfe-p> %   tension_module_of_elasticity[2200],
rfe-p> %   dimensional_stability_hdt/a[96],
rfe-p> %   dimensional_stability_hdt/b[100]).
rfe-p>
rfe-p> % Goal retrieving the elasticity modules of both instances
rfe-p> novodur-rec-1(identifier[I], tension_module_of_elasticity[E-module])
true
I = novodur_r_5320
E-module = 2000
rfe-p> more
true
I = novodur_r_5322
E-module = 2200
rfe-p> more
unknown
rfe-p>
```

```
rfe-p> % One sample prototype declared below novodur and above novodur-rec-1
rfe-p> % declare(proto-class[novodur-rec-1-prototype,
rfe-p> %                     super[novodur]]).
rfe-p> %
rfe-p> % novodur-rec-1-prototype(
rfe-p> %   izod-impact_strength_23[60],
rfe-p> %   izod-impact_strength_-30[40],
rfe-p> %   izod-notched-bar_impact_strength_23[12],
rfe-p> %   izod-notched-bar_impact_strength_-30[6],
rfe-p> %   ball_thrust_hardness[90],
rfe-p> %   recycled[true],
rfe-p> %   additives[[]]).
rfe-p> %
rfe-p> % declare(indi-class[novodur-rec-1,
rfe-p> %                    super[novodur-rec-1-prototype]]).
rfe-p>
rfe-p> % Goal additionally inheriting the ball thrust hardness from the prototype
rfe-p> novodur-rec-1(identifier[I],
                     tension_module_of_elasticity[E-module],
                     ball_thrust_hardness[Bh])
true
Bh = 90
I = novodur_r_5320
E-module = 2000
rfe-p> more
true
Bh = 90
I = novodur_r_5322
E-module = 2200
rfe-p>
rfe-p> % Querying the same attributes for all instances below thermoplastic
rfe-p> % (the variable Indi-class will be bound to their class names)
rfe-p> instance>(thermoplastic(),
                 Indi-class(identifier[I],
                            tension_module_of_elasticity[E-module],
                            ball_thrust_hardness[Bh]))
true
Indi-class = hostalen-rest
Bh = 67
I = hostalen_ppk_1060_f1
E-module = 1300
rfe-p> more
...
rfe-p> more
true
Indi-class = novodur-rec-1
Bh = 90
I = novodur_r_5322
E-module = 2200
rfe-p>
rfe-p> % Conjunction implementing simple material pre-selection
rfe-p> % (P1="ball thrust hardness greater 85",
rfe-p> %  M1=novodur_r_5320, M2=novodur_r_5322)
rfe-p> instance>(thermoplastic(), Indi-class(identifier[I],
                                             ball_thrust_hardness[Bh])),
       nonvar(Bh), >(Bh, 85)
true
Indi-class = novodur-rec-1
I = novodur_r_5320
Bh = 90
rfe-p> more
true
Indi-class = novodur-rec-1
I = novodur_r_5322
Bh = 90
rfe-p> more
unknown
rfe-p>
rfe-p> % cost for novodur_r_5320 and novodur_r_5322 added Horn-logically
rfe-p> l cost
cost(novodur_r_5320, 4.3).
cost(novodur_r_5322, 4.5).
rfe-p>
```

```
rfe-p> % Goal implementing special material selection
rfe-p> % (optimality criterion assumed to be cost minimization)
rfe-p> min-cost([novodur_r_5320, novodur_r_5322], M)
true
M = novodur_r_5320
rfi-p>
rfi-p>
rfi-p> %          Translated sorted Horn-logic version of RTPLAST
rfi-p> %----------------------------------------------------------------------
rfi-p>
rfi-p> % listing of one sample class of recyclable novodurs
rfi-p> % (class name becomes unary predicate)
rfi-p> l novodur-rec-1
novodur-rec-1(novodur_r_5320).
novodur-rec-1(novodur_r_5322).
rfi-p>
rfi-p> % ‘object centered’ LISTINGS of the sample instances
rfi-p> % novodur_r_5320 and novodur_r_5322
rfi-p> % (attributes become binary predicates,
rfi-p> %  instances copied into first argument)
rfi-p> l Attribute(novodur_r_5320, Value)
yield_stress(novodur_r_5320, 38).
yield_elangation(novodur_r_5320, 2.1).
tension_module_of_elasticity(novodur_r_5320, 2000).
dimensional_stability_hdt/a(novodur_r_5320, 90).
dimensional_stability_hdt/b(novodur_r_5320, 95).
cost(novodur_r_5320, 4.3).
rfi-p> l Attribute(novodur_r_5322, Value)
yield_stress(novodur_r_5322, 40).
yield_elangation(novodur_r_5322, 2.3).
tension_module_of_elasticity(novodur_r_5322, 2200).
dimensional_stability_hdt/a(novodur_r_5322, 96).
dimensional_stability_hdt/b(novodur_r_5322, 100).
cost(novodur_r_5322, 4.5).
rfi-p>
rfi-p> % ‘attribute centered’ LISTING of tension_module_of_elasticity
rfi-p> % (‘:’ associates the sort hostalen-ppn-1-prototype with the variable X)
rfi-p> l tension_module_of_elasticity
tension_module_of_elasticity(hostalen_ppk_1060_f1, 1300).
tension_module_of_elasticity(X : hostalen-ppn-1-prototype, 1300).
tension_module_of_elasticity(novodur_r_5320, 2000).
tension_module_of_elasticity(novodur_r_5322, 2200).
rfi-p>
rfi-p> % meta-information about the attributes cost and dimensional_stability_hdt/a
rfi-p> l Attribute(cost, Value)
measurement(cost, /[dm, kg]).
rfi-p> l Attribute(dimensional_stability_hdt/a, Value)
method_for_test(dimensional_stability_hdt/a, [iso_75, din_53461]).
measurement(dimensional_stability_hdt/a, c).
rfi-p>
rfi-p> % listing of tension_module_of_elasticity after transformation of
rfi-p> % ‘:’ sorts to unary predicates
rfi-p> l tension_module_of_elasticity
tension_module_of_elasticity(hostalen_ppk_1060_f1, 1300).
tension_module_of_elasticity(X, 1300) :- hostalen-ppn-1-prototype(X).
tension_module_of_elasticity(novodur_r_5320, 2000).
tension_module_of_elasticity(novodur_r_5322, 2200).
rfi-p>
rfi-p> % Earlier object-centered query
rfi-p> % novodur-rec-1(identifier[I], tension_module_of_elasticity[E-module])
rfi-p> % becomes equivalent Ident-conjoined Horn query
rfi-p> novodur-rec-1(Ident), tension_module_of_elasticity(Ident, E-module)
true
Ident = novodur_r_5320
E-module = 2000
rfi-p> more
true
Ident = novodur_r_5322
E-module = 2200
rfi-p> more
unknown
rfi-p>
```

```
rfi-p> % The sample protoype Horn-rule-defined above novodur-rec-1
rfi-p> l novodur-rec-1-prototype
novodur-rec-1-prototype(X) :- novodur-rec-1(X).
rfi-p>
rfi-p> % 'attribute-centered' listing shows ball_thrust_hardness of the
rfi-p> % novodur prototype and the other plastics
rfi-p> l ball_thrust_hardness
ball_thrust_hardness(hostalen_ppk_1060_f1, 67).
ball_thrust_hardness(X, 68) :- hostalen-ppn-1-prototype(X).
ball_thrust_hardness(X, 90) :- novodur-rec-1-prototype(X).
rfi-p>
rfi-p> % Earlier object-centered, inheriting goal
rfi-p> % novodur-rec-1(identifier[I],
rfi-p> %               tension_module_of_elasticity[E-module],
rfi-p> %               ball_thrust_hardness[Bh])
rfi-p> % becomes equivalent I-conjoined Horn query, inheriting via the above rules
rfi-p> novodur-rec-1(I),
       tension_module_of_elasticity(I, E-module),
       ball_thrust_hardness(I, Bh)
true
I = novodur_r_5320
E-module = 2000
Bh = 90
rfi-p> more
true
I = novodur_r_5322
E-module = 2200
Bh = 90
rfi-p> more
unknown
rfi-p>
rfi-p> % Query of all instances below thermoplastic with fixed ball_thrust_hardness
rfi-p> %  instance>(thermoplastic(),
rfi-p> %            indi-class(identifier[i],
rfi-p> %                       tension_module_of_elasticity[e-module],
rfi-p> %                       ball_thrust_hardness[90]))
rfi-p> % becomes horn conjunction starting with thermoplastic predicate
rfi-p> % (no indi-class variable)
rfi-p> thermoplastic(i),
       tension_module_of_elasticity(i, e-module),
       ball_thrust_hardness(i, 90)
true
i = novodur_r_5320
e-module = 2000
rfi-p> more
true
i = novodur_r_5322
e-module = 2200
rfi-p> more
unknown
```

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