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Knowledge Modeling for Eco-design

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Abstract: The present major concern on sustainable development is at the beginning of a growing interest on product recyclability. More and more strict norms and regulations will be prescribed to companies in order to increase the level of recyclability of industrial products. Usually described in natural language, these norms can be difficult to interpret for the product designer. There will also be an increasing need in tools to verify the compliance of a product with given norms and standards. A prototype of such a system is described in this article: the information to be added to the product model is first specified. It is then shown how the knowledge contained in standards and norms in textual form can be translated into constraints which can be propagated through the product structure in order to identify the inconsistencies between the present design and a given norm. An example of the literature is used to illustrate the suggested methodology and the results of its application through a software prototype.

Key Words: product model, design for recycling, knowledge modeling, eco-label, ORM, constraint propagation, Claire language.

1. Introduction

Sustainable development, including product recyclability, nowadays becomes a mandatory social problem, especially for companies. Indeed, norms and standards, which were previously only advisory, are more and more mandatory, binding them for instance to define the way their products could be recycled, and the corresponding channels for collecting and disposal. Usual solutions like incineration have a poor economical interest. An alternative is to consider the recyclability of a product during its design phase, in order to improve its efficiency, or even to make out of it a new competitive advantage.

In order to make the designers aware of the knowledge allowing product recyclability, it is in the authors' opinion, mandatory to make this knowledge available within the tools that they already use during their design task, i.e., the CAD–CAM systems. Therefore, the basic idea which will be developed in this article is to develop a decision support system assessing the product recyclability, based on the knowledge disseminated in standards, in consistence with the usual model of an industrial product, i.e., its bill of materials¹. This should allow as a final objective to directly connect such a system to a CAD–CAM system of the market.

For this purpose, the first step is to add to the usual design parameters of a product (already present in the bill of materials, like nature of materials or weights of parts) those typical from the recyclability area. A number of standards already well-known on the market have been considered, together with research works on the area: these sources have first allowed us to suggest an extended model of the product, gathering the main data required for assessing the quality of recyclability of the product.

A second step is to be able to assess to what extent the product described by this extended model is consistent with a given norm, standard, or eco-label. Usually expressed in natural language, these standards can be difficult to interpret by a human actor, and *a fortiori* by software. A first mandatory step is to translate them into design constraints which could be clearly applied on the design entities, allowing a check on their consistence with the product definition. The ORM methodology [13] has been used in order to develop this model, aiming at translating the knowledge present in the standards and norms into constraints. This approach is for instance close to the one suggested in [1] in another area: the design of safe machines.

In order to propagate these constraints in the design model of the product, the criteria contained in the standards have first been modeled through rules, and as a second step translated into constraints thanks to the Claire language.

This article is structured as follows: in Section 2, a state of the art shows the major issues of the design for recyclability domain. Comparable works of the

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Figures 1–4 and 6 appear in color online: <http://cer.sage.pub.com>

¹This study has been performed within the INTERREG PREMI project aiming at the dissemination of technologies linked to sustainable development in small and medium enterprises (<http://www.premi.cf.ac.uk/>).

literature, aiming at defining decision support systems for helping to improve the recyclability of industrial products, are addressed in more detail. In Section 3 is described the suggested extended model of a product using the ORM formalism. It is shown in Section 4 how the pieces of knowledge included in the norms and standards can be modeled by rules including facts based on the data present in this model. The Claire language is suggested in Section 4 as a means for propagating these constraints into the product structure. In Section 5 is shown an example of the literature (the Motorola display/keypad microphone described in [2]) how this framework can be used for listing the constraints which are not satisfied by the characteristics of the product.

2. The Context of Design for Recyclability

2.1 The Legal Context

In the context of sustainable development, the design, use, and end-of-life management of the industrial products are more and more governed by a legal framework, sometimes as simple advice but more and more as obligations. This is for instance the case in the European Union area, where directives enacted by the Parliament² aim at guaranteeing the low environmental impact of given product families: see e.g., Directive 2000/53/EC on end-of-life vehicles, Directive 2002/95/CE aiming at restricting hazardous substances in electrical and electronic equipments, or Directive 2002/96/CE which aims to minimize the impact of these equipments on the environment during their life time and when they become waste. In all countries where this directive is active, the responsibility of the manufacturers is engaged on the management and cost of the recycling activity of their products.

With a more voluntary approach, and in consistence with the legal context, norms and standards have been suggested in order to certify the conformity of given product families with environmental criteria. The family of ISO 14000 norms (see [19]) allows to define the main principles related to the environmental impact of products. Among others are discussed aspects related to (a) the description of environmental performances, notably based on life cycle analysis methods (ISO 14040 family), (b) the improvement of the environmental performances based on eco-design methods (ISO 14062 family), and (c) the communication on the compliance of a product with environmental criteria, which constitutes the family of the eco-labels (ISO 14020 family). Among these eco-labels can be distinguished

(i) the eco-labels of type I (ISO 14024) defining official labels like Blue Angel or Nordic Swan, (ii) the eco-labels of type II (ISO 14021) consisting in self-declarations like the 'point vert' in France, and (iii) the eco-labels of type III (ISO 14025) dealing with ecoprofiles, i.e., the guarantee that a given category of environmental criteria has been satisfied (like the VOLVOTM ecoprofile on the emission of CO₂). Although official, some of these standards have a local sphere of activity, like Blue Angel in Germany, Nordic Swan in the Nordic countries, Eco-Mark in Japan, etc., or have an industrial target, limited to an industrial sector or to a family of products: e.g., the SIEMENSTM standard SN 36350-1 and of the European Computer Manufacturers Association (ECMA) standard dealing respectively with electrical and electronic equipments and with computers. Even if they all have a normative ambition, the respective frameworks of the directives, norms, and standards can be distinguished by their formulation. Whereas the two first ones only edict generic principles which can be difficult to interpret and apply in product design, the eco-labels (local or domain-related) are much more precise on the technical points that an eligible product should satisfy. As a consequence, these standards will be the main target of this study. Nevertheless, because of their formulation in natural language, providing a systematic translation of these standards allowing automatic data processing is nothing less than an obvious task.

2.2 Support to the Design Activity in a Sustainable Development Context

Eco-design is the main target of numerous studies dealing with taking into account environmental constraints in design. In the literature, this concept, also known as design for environment (DFE) (ISO 14062) suggests approaches and general design principles allowing to minimize, with similar performance, the environmental impact of a product during its entire life cycle. Among the suggested tools the eco-design strategy wheel [4] is one of the best means for analyzing the performance of a product in relation with environmental criteria associated to each step of its life cycle. This visual tool, based on a spider diagram, allows especially to compare a product to an 'ideal' version on the point of view of environmental criteria, in order to identify the weak points requiring high attention. A detailed synthesis of the eco-design tools can be found in [33].

More specifically oriented in the recycling problem, the design for recycling (DFR) [16,18,36] also gathers studies focussing on specific sub-problems, like the optimization of the disassembly of a product: design for

²http://europa.eu.int/eur-lex/fr/lif/reg/fr_register_15103030.html

disassembly (DFD) [5,8,23]. These studies have a great interest in the context of eco-labels, the disassembling problem being one of the important aspects addressed in these labels.

A complementary question, especially relevant for the manufacturer, and as a consequence for the designer, is to increase the value of the product reaching its end of life, since, according to the law, the manufacturer can be charged with the cost and management of the recycling activity (see Directive 2002/96/CE). In [25], four types of works are distinguished for that purpose: (1) design for disassembly (DFD) [9,20,31,34], especially by making easier the separation of the materials, the identification of the elements, their accessibility, and their handling during disassembling (2) the end-of-life strategy, mainly interested in the support to product retirement [17,28]; (3) the design for no-disassembly, a concept that suggests alternative approaches to manual disassembly, e.g., grinding and sorting. This approach promotes for instance methods for an appropriate choice of compatible materials, which can be crushed and recycled without disassembly [16], or separable materials, for instance materials of very low density which can be easily separated after grinding; (4) the design for the valorization system, a new method combining the previous ones in a systemic approach. The problem here is to optimize the design by maximizing the value of the product reaching its end of life according to mass and economical criteria. In this context, a major concern is the availability of data on the economical performance of the recycling channels.

In the area of eco-design, most of the studies appear as mainly oriented on the definition of methods aiming at minimizing the environmental impact of a product. Those which target the optimization of the recycling activity (often oriented on disassembly) mainly suggest design rules for improving recyclability, like those described in [9,11,22,31,34]. In the following, new approaches are not sought for improving recycling, but the integration of design rules in a decision support system is focussed on, since the interest is basically on the tools which may allow such approaches to be made available on the designer's workstation.

2.3 Objectives of the Study

Within the framework of the PREMI project, the objective of this study is to develop a decision support system (DSS) with the following characteristics:

- on-line access on the designer's workstation, with a possible integration to CAD–CAM tools,
- possibility of selection of a given standard or eco-label in a database,

- possibility of assessment of the ongoing product design according to the selected standard.

This DSS should be able to communicate with existing design systems, since a part of the required information is already contained in the CAD–CAM tools used by the designer, or in the product lifecycle management (PLM) system of the company. Therefore, its definition has been made using the methodology summarized in Figure 1.

- The data on the product contained in the bill of materials, always produced during the design process, was considered as a base;
- A set of selected norms and eco-labels was analyzed for listing the data required by the recyclability analysis which are not present in usual bills of materials (Step 1 on Figure 1);
- The consequence of the previous step is the definition of an extended bill of materials (Step 2). The additions may be of different types: new objects (symbolized by a dark square in the bill of materials); data on the links between products (describing for instance how the sub-components are assembled), symbolized by the dark circle, or new data related to components already described in the bill of materials (dark line in the light rectangle);
- The standards or eco-labels have to be modeled through a set of 'criteria', so that these criteria can be applied on the data present in the extended bill of materials.

The expected use of the system is then the following:

- When a standard of eco-label is selected in the database, the corresponding criteria are extracted (Step 3),
- The criteria are then instantiated and propagated in the bill of materials (Step 4). In some cases, questions to the designer can be required when the data

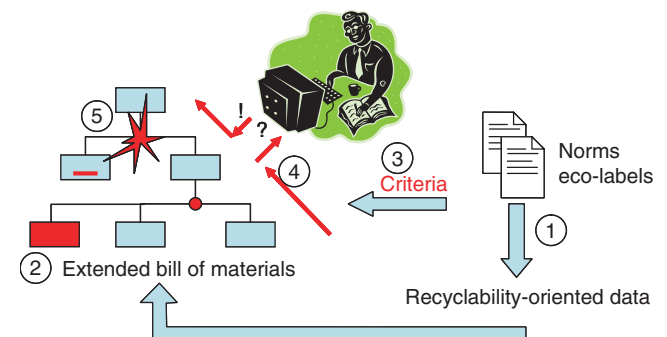


Figure 1. Principle of the suggested system.

available are not sufficient for allowing to state whether a criterion is verified,

- Data which are inconsistent with the criteria are identified, which is summarized by the dark star in Figure 1 (Step 5), then submitted to the designer with an explanation (reference to the criterion which is not satisfied).

On the basis of a rough analysis of relevant eco-labels, the extension of the product model required by the assessment of the recyclability of a product (Step 1 on Figure 1) is presented in the next sections.

3. Extensions of the Product Model

Following the methodology described in Figure 1, the first step of development of the decision support system is to identify the data which have to be added to those already contained in a ‘classical’ bill of materials, in order to be able to assess the compliance of a product with a given standard.

This step is of course difficult, since the objective is to develop a model that would remain valid whatever the considered norm or standard is. For that purpose, the most well known and representative norms and standards on the subject have been considered, and an extended product model has been defined on that basis. A valuable base has been the overview of the design for environment (DFE) standards provided by the Western Electronic Product Stewardship Initiative [38] in the case of computers. In this overview the following standards are considered:

- the German Blue Angel eco-label [29]
- the Nordic Swan eco-label [26]
- the European Computer Manufacturers Association (ECMA) (technical report on product-related environmental attributes) [10]
- a paper on DFE by the America Electronics Association (AEA),
- the TCO’99 Swedish eco-label program [32]
- the SIEMENS ‘SN 36350-1, Environmentally Compatible Products’ corporate standard [30]
- the Japanese PC Green Label system [27]

Although most of these standards are oriented on computers or electronic devices, they can be considered as representative from general concerns on recyclability. An important point to note is that these standards and labels do not only concern the product. For instance, the Nordic Swan eco-label [26] also contains requirements on the chemical use, manufacture, and packaging issues. These requirements are considered

as outside the scope of the study, dedicated to the product design.

While performing this survey, a very encouraging point has been that it has been quickly noticed that all these standards are based on the same type of data, which are listed in the following section.

3.1 Types of Data Involved in the Standards

The requirements contained in the above listed standards mainly address the following issues:

- *identification of the materials*. A first mandatory point for allowing recyclability is that the nature of the materials included in the product can be easily identified. Therefore, each standard includes some requirements aiming at insuring that the materials (and especially plastics, which have very different abilities for recycling according to their nature) are correctly identified, e.g., by molded codes on plastic parts or by labels.

Examples:

ECMA ‘The system is designed for disassembly by using marking on plastic parts >25 g, according to ISO 11469’
 AEA ‘Materials should be identified by label (molded on, embossed, or printed with compatible inks)’
 Blue Angel ‘Have the plastic parts been labelled according to ISO 11469?’
 Siemens ‘Mark plastic components suitable for recycling’

- *homogeneity of the materials*. Since the way to recycle a material depends on its nature, it is important that materials of different natures are not combined if they can hardly be separated. This point includes painting issues.

Examples:

Nordic Swan ‘Single plastic parts (over 25 g) in the housing and chassis must consist of one type of polymer (homopolymer or copolymer) or recyclable plastic blend’.
 Nordic Swan ‘Large plastic parts (over 25 g) may not be painted’.
 TCO ‘All plastic components weighing more than 100 g shall be made from the same type of plastic material’.
 Blue Angel ‘Large-size case parts made of plastics shall consist of a homopolymer or copolymer’
 Blue Angel ‘Avoidance of coatings and composite structure materials’
 AEA ‘Plastics should have no paint or sprayed metallics on the surfaces’

It can be noted that the application of the rules promoted by these standards may itself lead to new problems: e.g., labels stuck on a material for its identification may result in mixing inhomogeneous

materials. New rules are then designed for avoiding problems, such as:

Nordic Swan ‘Labels (including marks and stickers) must be made of the same material as the parts to which they are affixed or they have to be separable and fulfil VDI 2243’

– *nature of materials*. Some materials are not suitable for recycling, others may be dangerous for the persons in charge of the disassembly: these elements have to be included in the product database.

Examples:

TCO ‘Plastic containing chlorinated or brominated polymers, e.g., PVC, are not accepted in plastic components of any size’.

Siemens ‘Employ recyclable material’.

Nordic Swan ‘The housing and chassis must not contain chlorine-based plastics’.

Nordic Swan ‘Cadmium or lead must not be actively added to plastic parts (over 25 g)’.

Nordic Swan ‘The flame retardants based on poly-brominated organic components may not be used in the plastic parts (over 25 g)’.

AEA ‘In general, thermoset plastics should be avoided if possible, as their cross-linked structure makes recycling very difficult, if not impossible’.

– *disassembly process*. Incineration is a very poor method of disposal, according to environmental as well as economical criteria. Therefore, recyclability heavily depends on the facility of the disassembly process. In the standards can be found criteria related to various aspects of disassembly, such as:

- components should be easily separable

Examples:

AEA ‘Joining should allow disassembly and not mix incompatible materials – use snap fits, break or inserts, or screws; do not use adhesives’.

Siemens: ‘Design all connections that require dismantling to be readily identifiable’.

- clear directions should be available for disassembly.

Example:

Blue Angel ‘Did the manufacturer carry out a check disassembly and prepare a disassembly report listing weak points?’

- there should not be any need for special tools in the disassembly process.

Examples:

Nordic Swan ‘It must be possible to carry out the dismantling without special tools’

Blue Angel ‘Can disassembly be done with all-purpose tools exclusively?’

- there should be enough space for inserting tools during the disassembly process.

Examples:

Blue Angel ‘Is the product equipped with the necessary points of application and working spaces for disassembly tools?’

Siemens ‘Design all connections that require dismantling to be easily accessible’


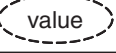
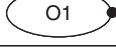
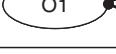


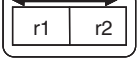
These various examples illustrate that, in order to address these different types of criteria, it is necessary to take into account some product characteristics already available in CAD–CAM systems (nature of a part, weight . . .), but also to enlarge the product model to the way the parts are assembled (types of connections) or to the tools which are required to perform the disassembly task. The product model which has resulted from this preliminary analysis is described in the next section, after a short presentation of the chosen modeling tool.

3.2 Choice of a Modeling Tool: the ORM Language

In order to define a decision support system for improving the product recyclability, the necessity to translate the normative knowledge included in the standards into exploitable criteria has been insisted on. For that purpose, the ‘extended model’ of the product on which these constraints will be applied has to be based on an ontology, i.e., a specification of a representational vocabulary for a shared domain of discourse [12]. Therefore, the interest is on ontology-based languages, which have the required features for describing an ontology. The NIAM/ORM language, more and more used in the area of the support to design. The domain where it is necessary to include the knowledge on the field into the product model [1] has been chosen.

Object-role modeling (ORM) is described as a conceptual modeling and query language for information systems. A follower of the natural language information analysis method (NIAM) which is still its most common denomination in Europe, is based on a description of the universe of discourse in terms of objects playing roles. Its main interest, compared to other languages like UML, lies in its ability to express information by simple relationships (the roles) allowing to verbalize the universe of discourse through business rules or constraints [14]. The interest in its recognized power of expression is increased by its simplicity of formalization, using graphical notations easily understandable (see Table 1). Moreover, its orientation on roles allows to specify a great variety of constraints and

Table 1. Main ORM notations.

	Entity
	Attribute
	Mandatory role
	O1 must play at least one of the two roles
	Pointed on a role: internal unicity
	Binary relationship
	"Objectified" predicate: relationship playing a role

also allows to avoid the necessity to manage attributes (they are managed like objects; see the Lexical Object Types of Table 1), which leads to a better stability in consideration with the model evolution [13]. Finally, a relational model (tables) can be automatically generated from an ORM model, allowing the implementation of the model in a database.

Building an ORM model can be carried out according to the conceptual schema design procedure (CSDP) suggested by Halpin [13], and consisting in (1) expressing the initial knowledge through elementary facts, (2) building a preliminary model including the ORM constraints, and (3) integrating the ORM constraints in the preliminary model.

It is assumed that the translation of norms with the CSDP method of the ORM formalism is not entirely automated in this case. Indeed, which concepts (and their associated relations) define the product recyclability domain as it is described in the considered sources (i.e., the norms) need to be identified: a human interpretation of these sources is then needed.

In order to define this extended product model, the model suggested in [15] has been taken as a base, aiming at allowing to reuse design knowledge, since this model already takes into account concepts which can be of interest for this study.

Three points of view are considered on the product in the following, according to:

- its structure; which provides the classical model of a product, allowing for instance to describe a bill of materials,
- its recyclability, allowing to deal with the criteria concerning the nature of materials contained in a product,
- its disassembly, in order to provide the data required for assessing the corresponding criteria described in the standards.

This way to divide the problem is consistent with most of the recycling guidelines: see for instance [3] which considers three categories: component design, material selection, and fastener selection.

For a better readability, these three points of view are described separately, although they can be gathered using Harani's concepts. The recyclability point of view is detailed in the following.

The recyclability point of view is shown in the model of Figure 4. The main additions to the structural point of view are:

- a product is made of a given material, which is a critical point regarding the recyclability issue. Especially, some classes of materials (see bottom entity `class_material`) prevent an efficient recycling (Cu-alloys, Al-alloys, PVC, ...). In addition, some materials are not mutually compatible. According to tables of compatibility already mentioned (`material_compatibility_table` entity, left bottom corner), the best known is included in the norm VDI 2243.
- as stated before, some substances are often added to a product during its manufacturing, like paint or varnish. Recyclability also requires the precise identification of each part included in the product, either through marking (see top-left role) or labels. Since many criteria of the standards specifically concern these additional materials (see Section 3.1), it is preferred to define a specific entity named 'substance' concerning these additional products. Incompatible substances are also described in a table (bottom left of Figure 4).

4. Translation of Norms and Standards into Constraints

The translation of norms into an exploitable form, as considered in this study, is concerned with the domain of knowledge engineering area. Indeed, the main issue here is to extract critical knowledge which could be hidden or partially hidden from textual sources. Several conceptual modeling languages, devoted to this kind of issue have been proposed. As stated earlier, an interesting advantage of ORM for this study is that it is possible to model constraints, and so to 'incorporate' knowledge on recycling in the model when the relational model is generated. Nevertheless, it was here mandatory to separate the model from the constraints in order to be able to choose the specific eco-label to be applied on the product model for a given application. As a consequence, an external way to check the criteria satisfaction on the data present in the model was required. In a step-by-step approach, it was decided to first translate the standards written in natural language

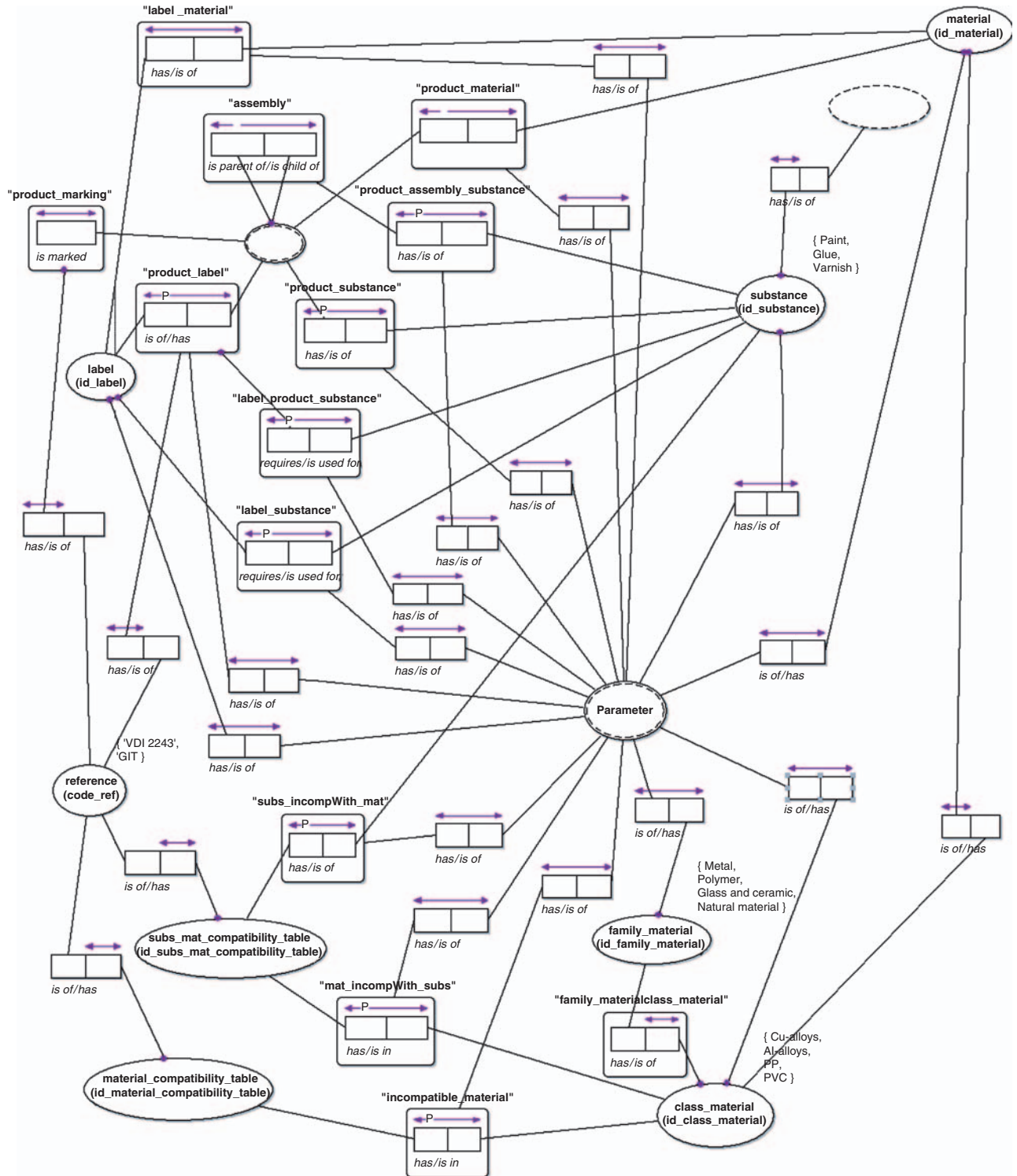


Figure 2. Recyclability point of view of the proposed model.

in structured rules, then to choose an adequate language for their processing.

4.1 Modeling of Constraints Through Rules

The facts used in the criteria for recycling can be modeled according to the following simple template,

based on the object and attributes identified in the models described in the previous section:

<A> <O> <V>: an attribute A of an object O has a given value V
 <type_item> <item 1> <electrical_module> = 'The item is an electrical module'

Table 2. Examples of rules extracted from Blue Angel.

Blue Angel criterion	Facts and production rule
A1. Can components made of incompatible materials be removed separately or via separation aids?	F1: <connected><(item 1, item 2)><yes> F2: <name_material><item 1><Material X> F3: <name_material><item 2><Material Y> F4: <connection><(item 1, item 2)><Link 1> F5: <incompatible><(Material X, Material Y)><yes> F6: <Link 1><separable><without_tool> F7: <Link 1><separable><with_tools> IF (F1 \cap F2 \cap F3 \cap F4 \cap F5) THEN (F6 \cup F7)
A2. Are electrical modules easily traceable and removable?	F8: <type_item><item 1><electrical_module> F9: <item_identification><item 1><yes> F10: <removability><item 1><yes> IF F8 THEN (F9 \cap F10)
A7. Can all screwed connections between modules be separated with no more than three tools?	F20: <connection_type><product><screwed_links> F21: <number_of_tools><screwed_links><inf. to 3> IF F20 THEN F21
B8. For components with a mass ≥ 25 g, are the plastic parts marked according to ISO 11469?	F32: <material_family><item 1><plastic> F33: <mass><item 1>< sup. to 25 g.> F34: <mark><item 1><according_ISO11469> IF (F32 \cap F33) THEN F34

An attribute can also concern several objects:

<incompatibility> <material 1, material 2> <yes> = 'Materials 1 and 2 are incompatible'

The values of some attributes can be numerical:

<number_required_tools_for_disassembly> <module 1> <inf. to 3> = 'Less than 3 different tools must be required for disassembly'

but also qualitative:

<space_for_disassembly> <module 1> <enough> = 'There must be enough space for inserting tools during disassembly'

Sometimes, being able to assess the satisfaction of a criterion would require an exaggerated increase of complexity of the data model. In that case, it is preferred to process the criterion through a question asked to the designer:

<question> <fasten_component_during_disassembly> = 'Is it possible to fasten the component during disassembly?'

<question> <functional_expansion_possible> = 'Is the system ready for functional expansion?'

Forty-four facts have for instance been identified in the Blue Angel eco label. The second step is to translate the criteria into rules of type (IF *A* THEN *B*), *A* and *B* being combinations of facts through Boolean operations. Twenty-four rules have been extracted from the part of Blue Angel concerning recyclability, among which 75% were mandatory and 25% were advisory. Eight other criteria were modeled by questions. The potential automatic processing of the Blue Angel eco-label by this modeling framework was hence

of 75%. Tests of other standards led to comparable results:

- Nordic Swan: 11 criteria among which 64% were mandatory and 36% advices; 73% of criteria modeled by rules.
- Siemens Norm SN 36350-1: 13 criteria, no distinction between mandatory criteria and advices: 65% modeled by rules.

Some examples of rules extracted from Blue Angel are provided in Table 2, showing the original criteria of the eco-label and their translation through facts, then rules.

These 'rules' are not production rules in the sense of expert systems: conclusion parts are not inferred when the premises are verified, but generate a constraint which has to be satisfied. In other terms, 'required facts' are generated by the conclusion part of a rule (like F6 or F7 in rule 1 of Table 2), which should be present in the fact base (for the authors, in the product model) in order to satisfy the criterion. Therefore, the problem here is a constraint satisfaction problem (CSP).

Table 2 also illustrates that some of the constraints can be verified 'on-line' during the design phase: e.g., B8 can be checked as soon as the characteristics of a plastic component have been entered in the model. Others, like A7, require that the product has been entirely designed, since they deal with global characteristics, like the total number of tools required to disassemble screwed connections.

This first modeling of the criteria present in some representative eco-labels allow to better state the

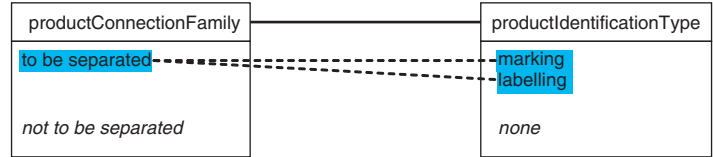


Figure 3. Traceability of separable connections.

requirements for a processing language, since it is necessary:

- to manipulate lists easily (forbidden materials, tables of compatibility, etc.)
- to easily model constraints
- to dynamically handle these constraints, since it can be seen in Table 2 that the constraints to be satisfied (the ‘THEN’ part of the rules) depend on a condition (the ‘IF’ part of the rules).

These requirements have brought the authors to implement these rules as constraints using Claire, a language which is justified in the next section.

4.2 Choice of the Claire Language

Claire³ is a high level open source language providing a set of orientations of great interest for this study, among which are object orientation, description of concrete or abstract sets, or production rules [6].

The prime feature of Claire is that it is very easy to write facts describing the membership of an element to a set. It is also very easy to modify such facts, by modifying the list of the elements of a set.

In addition, even if Claire is not a constraint propagation language on its own, it easily describes constraints, for instance using the CHOCO solver which is a rich library of some useful algorithms.

Among the tools of constraint propagation, arc consistency (see for instance [7]) checks whether the values of variables located on nodes or links of a graph are consistent with a constraint, which allows the processing of most of the constraints identified in this study. In short, it is easy to manipulate with Claire both the production rules like those described in the previous section and constraints using constraint propagation algorithms.

4.3 Modeling Constraints using Claire

After stating the constraints related to the considered problem (is a given product compliant with a norm?) a CSP algorithm is used to solve it.

A CSP is defined in Claire through the following steps: (1) create a problem, (2) create variables, (3) state

constraints. The following instruction creates for instance a problem **p**, named ‘‘First recyclability analysis’’ with at most 20 variables:

```
p := makeProblem('‘First recyclability analysis’’, 20)
```

Two examples are considered here, again extracted from Blue Angel:

Example 1. ‘Connections to be separated must be easily traceable’

The associated CSP is summarized in Figure 3.

Translation in Claire:

For the example depicted in Figure 3, two variables are created:

```
pConnectionFamily := makeIntVar(p,
  '‘pConnectionFamily’’, 1, 2),
pIdentificationType := makeIntVar(p,
  '‘pIdentificationType’’, 1, 3),
```

The numbers 1 and 2 in the first instruction respectively stand for ‘to be separated’ (1) and ‘not to be separated’ (2), whereas 1, 2, and 3 stand for ‘marking’, ‘labeling’, and ‘none’ in the second instruction.

A binary constraint between these two variables is then defined in two steps. A relationship is first created that defines the authorized pairs of values between two domains. Second, a binary constraint is stated, related to the concerned relation and the problem previously defined:

```
pIdentificationRel :=
  makeBinRelation(1, 2, 1, 3, list
    (tuple(1,1), tuple(1,2))),
post(p, binConstraint(pConnectionFamily,
  pIdentificationType, pIdentificationRel, 3)).
```

The last parameter, 3, indicates the arc consistency algorithm used (here, it states for an arc consistency algorithm called AC3) for checking whether the constraint is satisfied or not.

Example 2. ‘Connection to be separated must consist at least 50% of plug/snap connection (if plastic components)

³<http://claire3.free.fr/>

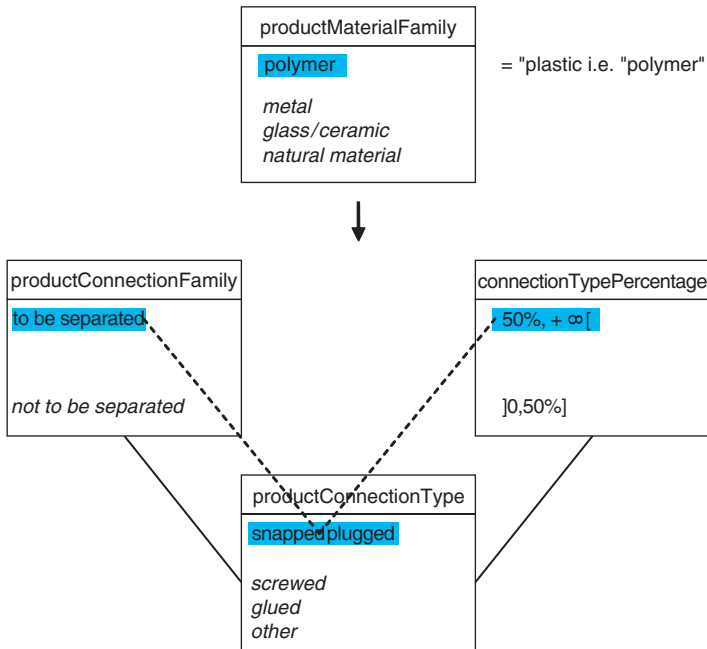


Figure 4. Characteristics of the connections.

This criterion uses the data described in Figure 4. i.e., the case of a constraint ('50% of plug/snap connections') depending on a condition (*if* plastic components).

Translation of the problem in Claire:

```
post(p, implies(pMaterialFamily in {1},
feasTupleConstraint(
  list(pConnectionFactory,pConnectionType,
  connectionTypePercent),
  list(list(1,1,1) ) ) ,
```

The unary constraint `pMaterialFamily in {1}` is the condition that triggers the constraint ('1' standing for 'polymer'):

```
feasTupleConstraint(list(pConnectionFactory,
pConnectionType,connectionType
Percent),list(list(1,1,1) ) )
```

which defines the feasible triples of values authorized between the three concerned variables.

The following section shows the result of the propagation of constraints written in Claire on a limited but representative example.

5. Example of Constraint Propagation in the Extended Product Model

This example aims to validate the technical feasibility of the proposed system. In order to perform the first tests, a case available on the net has been chosen: the Motorola display/keypad microphone, already

discussed by other authors on the point of view of disassembly optimization [2]. The components of this product are shown in Figure 5, together with a simplified view of the corresponding bill of materials. An interesting point is that a complete list of the components (including connectors) is provided in the document, together with their mass, materials, accessibility, and tools required for their disassembly. Therefore, it was required only to complete the database with some additional features for being able to assess the compliance of this product with constraints extracted from the selected standards.

For an illustration purpose, the implementation of the criterion A1 is described: 'can components made of incompatible materials be removed separately or via aids?'

The following variables are concerned with this criterion:

`Link := {lk}` which is the set of all the links of the bill of materials. A link is here defined as a couple of components, where one of them is considered as the father component and the other is considered as the child component. Some examples with the product described in Figure 5 are for instance the link between the 'base' and the 'lever', the link between the 'base' and the 'label', etc.

`Product := {pki, pkj}` which is the set of the two components that define a link `lk`.

```
TypeOfProduct := {'case', 'electrical
module', 'chassis', 'mechanical
```

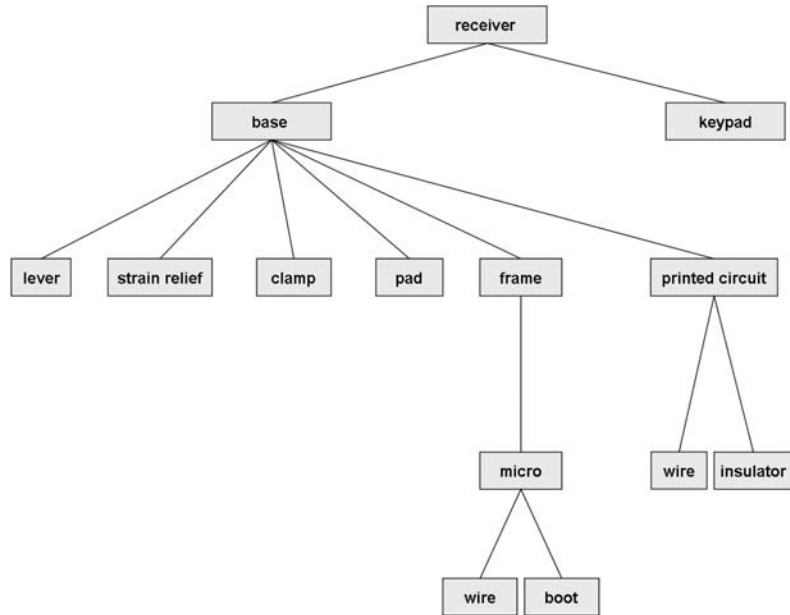


Figure 5. Components of the display/keypad microphone.

part'', ''other'' } which is the set of the different types of components.

$Material := \{ m_i, m_j \}$ and $ClasseOfMaterial := \{ cm_i, cm_j \}$ which represent respectively the materials that compose the components of a link, with their associated classes of material. An example of material is for instance 'polymer', the examples of classes of material which are 'ABS', 'PVC'. It is assumed that incompatibility between materials is defined through their respective classes of material. This explains why one needs to define the variable *ClasseOfMaterial*.

$LinkSeparability := \{ \text{''essy''}, \text{''other''} \}$ which is the set of the different levels of the separability of a link.

The following constraints are then defined: The first constraint states that a given link in the bill of material is composed of two components; the second constraint states that each of these components is defined with a given material; the third constraint states that each material corresponds to a specific class of material; the fourth constraint states that some class of material is incompatible with some other class of material (according to the incompatibility table provided in the literature); and finally the fifth constraint states that a link may have some level of separability.

As stated earlier, for this criterion, the four first constraints define the condition that triggers the verification of the fifth constraint.

An excerpt of the associated implementation is presented in Figure 6.

A loop is made over each link of the bill of material (see line 32) and then, for a given link, the two associated components are retrieved, with their respective materials and classes of material (from lines 37 to 43). The variables 'material' and 'class of material' are defined respectively in lines 45 and 46; the combination of the possible values between these variables is also defined (see line 47). The constraint between the concerned variables, defined by the restriction of the possible values as stated in the line 47, is defined in line 58. The other variables and constraints are defined in the same manner. The AC-3 algorithm is used for the propagation.

Finally, the criterion A1 is implemented as described in line 64 which states that if the four first constraints (previously defined) are satisfied, then the verification of the fifth one is triggered. All the other criteria are implemented in a similar way. The propagation is then performed, with the instruction `choco/propagate(pb)`.

Various results with the whole criteria of the considered norm have been obtained. The most interesting thing here is that through this simple prototype, it is shown that the detection of nonsatisfied criteria is possible with the choices: (1) extraction of data and knowledge (specific to the recyclability analysis) from textual sources with a conceptual modeling language and (2) modeling the problem of the verification of the compliance of a product with norm through CSP techniques.

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