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Structuring and modelling norms for the recyclability assessment of products during their design

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Environmental issues, such as product recyclability, are becoming a crucial social concern for manufacturers. Often formulated in natural language, the norms and standards that govern these issues can be difficult to link to the product definition. It becomes necessary to provide the designer with appropriate support tools allowing, for instance, for the compliance of products with environmental criteria to be checked. In the current paper, we show how normative knowledge, coming from textual sources (eco-labels), can be expressed through constraints, allowing checking in a semi-automated process the recyclability of a product.

Keywords: Decision support system; Knowledge-based system; Conceptual modelling; Constraints; Norm; Eco-label

1. Introduction

Owing to the sustainable development paradigm, environmental issues such as product recyclability, are becoming a crucial social concern for manufacturers. Indeed, they will increasingly have to face regulations that will lead them to respect tight environmental constraints. In particular, these constraints will cause them to consider the recyclability of their products and the associated recycling processes. However, addressing the product recyclability after its design, often leads to some basic recovery and destruction processes such as incineration, that are increasingly subjected to tight rules. It is interesting to take into account the product recyclability during the early phases of the lifecycle, particularly during the design phase, in order to improve its efficiency or make a concurrent advantage out of it.

An initial problem is that environmental norms or standards are usually formulated in natural language in a textual form, and are therefore difficult to interpret by a human or software. It can therefore be difficult to link these requirements to the product definition. It is then necessary to provide means for translating these norms and standards into an interpretable form. In order to help the designer to make use of the knowledge extracted from an environmental norm or standard, a final objective would be to make this knowledge available within the computer aided design (CAD)–computer aided manufacturing (CAM) systems, already used during the design of the product. Therefore the main problem to solve is how to model the recyclability knowledge at hand in a way that could be consistent with the product model defined in the existing design tools. To this end, we suggest adding to the usual design parameters of a product (already present in its bill of materials) those specifically concerned with the recyclability area.

Eco-labels have been chosen here as examples of recyclability requirements, because they are dedicated to types of products and therefore do not only consider generic assumptions on eco-friendly design. A sample of well-known eco-labels, among the large panel accessible, has been considered then analysed. These sources have allowed us to suggest an extended product model including the main data required for the recyclability assessment. NIAM/ORM (Halpin 1998), an ontology-based modelling language, has been used to facilitate the interpretation of the considered knowledge sources, and has allowed us to translate them into rules linking the parameters of the

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product. This approach is, for instance, close to the one suggested in Blaise *et al*. (2003) in the field of safe machines.

The rules built from the considered knowledge sources have then been expressed by constraints and propagated in the product structure in order to analyse the compliance of the design of the product with the criteria contained in a given norm or standard. The CLAIRE object language has been used to implement this knowledge-processing step.

The current paper is structured as follows: the context of the design for recyclability is first presented. The main environmental regulations to which the manufacturers are submitted will be highlighted. A brief state of the art related to the support of the design activity in the context of the sustainable development will then be presented. The proposed extended product model will then be described. The use of an appropriate modelling formalism (NIAM/ORM), allowing assisting in the interpretation of the textual sources, will be illustrated, followed by the description of the translation of an eco-label into rules, then constraints. Finally, the feasibility of the suggested methodology will be shown through the description of a software prototype, used for the test of the compliance of a product described in the literature on the Blue Angel eco-label.

2. The context of design for recyclability

2.1. *Context of the study*

This study is part of a European project, PREMI (www.premi.cf.ac.uk) (Product Recyclability and Miniaturization), aiming at transferring innovative technologies to small and medium-sized enterprises (SMEs) in the Atlantic area, and focusing on environmental issues. As part of the topic of products recyclability, our aim is to define a method allowing to extract recyclabilty knowledge from norms, and to make use of it in a decision support system (DSS) intended to facilitate the verification of the compliance of a product with a given norm or standard.

Within the framework of the PREMI project, the objective of this study is to develop a prototype of DSS with the following characteristics:

(a) online access on the designer's workstation, with an integration to CAD–CAM tools;
(b) selection of a given standard or eco-label in a database;
(c) assessment of the ongoing product design according to the selected standard.

The proposed system must allow communication 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, it has been defined according to the methodology summarized in figure 1:

1. The data on the product contained in the bill of materials, always produced during the design process, were considered as a base;
2. A set of selected norms and eco-labels was analysed for listing the data required by the recyclability analysis not present in usual bills of materials (step 1 on figure 1);
3. The consequence 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);

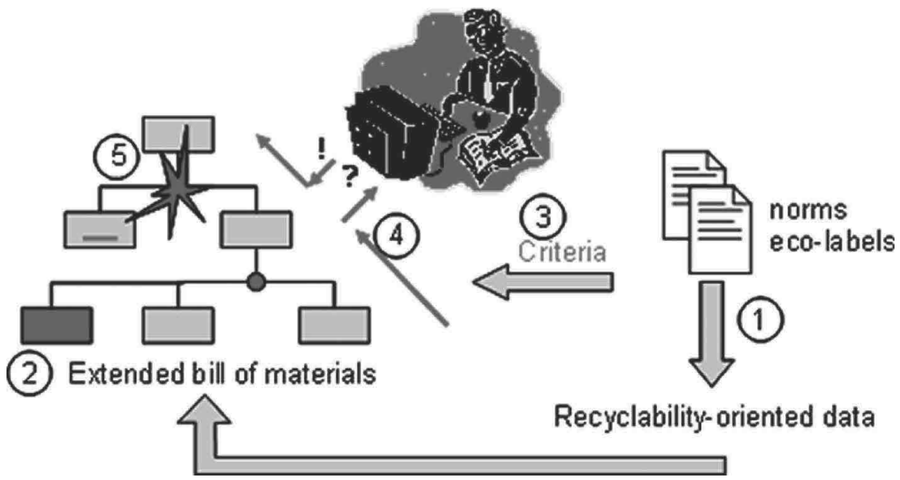

Figure 1. Principle of the suggested system.

4. The standards or eco-labels have to be modelled by '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:

1. When a standard or eco-label is selected in the database, the corresponding criteria are extracted (step 3);
2. 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 available are not sufficient for allowing to state whether a criterion is verified;
3. Data that 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).

2.2. *The legal context*

It is now clear that the design, the use and the end-of-life management of products will be increasingly governed by tight regulations. This will be the case, for instance, in the European Union area where directives have been enacted by the parliament (http://europa.eu.int/eur-lex/fr/lif/reg/fr_register_15103030.html) in order to guarantee the low environmental impact of given families of product: e.g. directives on the waste management and clean technologies such as the Directive 2002/53/EC dealing with the end-of-life vehicles, the Directive 2002/95/EC related to the restriction of the use of certain hazardous substances in Electrical and Electronic Equipments (EEE), the Directive 2002/96/EC concerning the Waste of EEE (WEEE). In the EU countries where this last directive is active, the responsibility of the manufacturers is engaged on the management and on the cost of the recycling.

With a more voluntary approach, with respect to the legal context (see the bottom right, part A of figure 2), non-compulsory agreements have also been established, intended to guarantee the compliance of some families of product with environmental criteria. These agreements are for instance presented in the form of norms or standards. Most of the environmental norms are based on the ISO 14000 family (ISO 2002). This family of norms allows defining the main principles related to the environmental impact of products. Among others discussed are (a) the description of environmental performances based on the life cycle analysis methods (cf. ISO 14040), (b) the improvement of environmental performances based on eco-design methods (cf. ISO 14062), and (c) the communication on the compliance of products with some environmental criteria. This last point is concerned with the

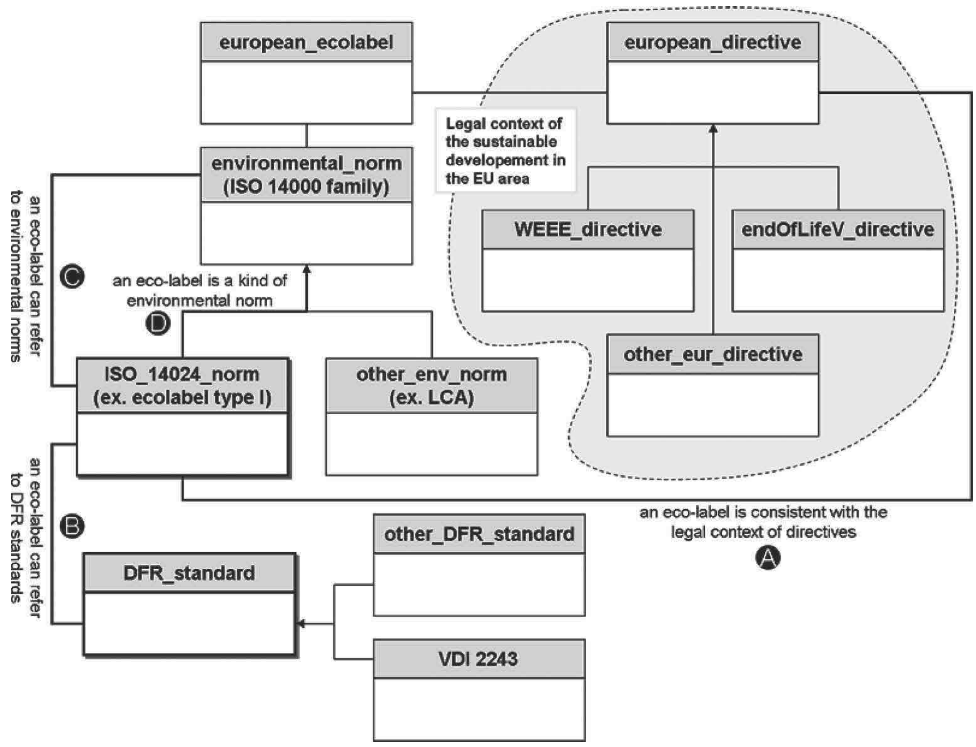

Figure 2. Consistency of eco-label with the legal context and the environmental norms.

eco-labels (cf. ISO 14020). Among them, the following can be distinguished (i) the eco-labels of type I (cf. ISO 14024) that include official labels such as Blue Angel or Nordic Swan (see left middle of figure 2), (ii) the eco-labels of type II (cf. ISO 14021) consisting of self-declarations such as '*Point Vert*' in France and (iii) the eco-labels of type III (cf. ISO 14025) dealing with eco-profiles, i.e. the guarantee that a given category of environmental criteria has been satisfied (for instance the VOLVO^{TM} eco-profile on the CO_2 emissions).

Some eco-labels apply in a geographical area (for instance, Blue Angel in Germany, Nordic Swan in the Nordic countries, Eco Mark in Japan, etc.); others apply to an industrial field or to a given family of products: for instance, Siemens Norm 36350-1 and the European Computer Manufacturers Association (ECMA) standard address respectively EEE and Personal Computers.

Although they all have the same normative purpose (see the left middle, parts C and D of figure 2), the framework of the norms and standards could be distinguished by their respective formulations. Very often, directives and norms (such as the ISO 14000 family) only address generic principles on environmental issues (i.e. the 'what' issues), without any support on the way these principles could be efficiently integrated in the designer's workstation (i.e. the 'how' issues). On the contrary, eco-labels provide various recycling rules (in addition to generic design principles) that could be more easily linked to the product definition: e.g. the VDI 2243 guideline (VDI 1993) that is often referred to in eco-labels (see the left bottom, part B of figure 2). As a consequence, these standards will be the main target of this study: as depicted in figure 2, this choice remains consistent with the legal context of the directives and with the context of environmental norms as well. Nevertheless, owing to their formulation in natural language, providing a systematic translation of these standards in order to allow automatic data processing is nothing less than an obvious task.

The next section presents the main studies available in the literature that are concerned with the support to the design activity in the context of the sustainable development.

2.3. Support to the design activity in the context of the sustainable development

Eco-design, also known as Design For Environment (DFE) (cf. ISO 14062), is the main target of studies concerned with the integration of environmental constraints in the design of products. In the literature, it aims at suggesting methods allowing the minimization of the environmental impact of a product during its lifecycle (Tukker and Eder 2000). Among the suggested tools, the eco-design strategy wheel (Brezet and Van Hemel 1997) is one of the best frameworks allowing to analyse the environmental performances of a product, including its whole lifecycle. This visual tool, based on a spider-diagram, especially allows comparing a real product to an 'ideal' version on the point of view of given environmental criteria, in order to identify the weak points of the design that should require further attention.

Concentrating more on recycling issues, the design for recycling (DFR) is concerned with studies aiming at anticipating products recyclability (Ishii 1998, Hundal 2000). Issues addressing sub-problems such as the optimization of the disassembly are for instance discussed in Dowie (1994). This kind of issue has a great interest in the context of eco-labels, the disassembly of product being one of the most important points addressed.

A complementary issue, relevant for the manufacturer, and as a consequence for the designer, is to increase the value of the product at its end-of-life, since, according to the law, the responsibility of the company is engaged on the management of the recycling activities and their associated cost (see Directive 2002/96/EC). In Mathieux (2002), four types of studies are distinguished for that purpose: (1) design for disassembly (DFD) (Dowie 1995, Johansson 1997), particularly intended to facilitate the separation of materials, the identification of parts (especially those containing hazardous substances), their accessibility, their handling while disassembling etc.; (2) the end-of-life strategies, mainly focusing on the support to the product retirement (Pnuelli and Zussman 1997, Lee and Ishii 1998); (3) the design for no-disassembly, a concept that suggests alternative approaches to manual disassembly. This concept promotes for instance methods for an appropriate choice of compatible materials which can be crushed and recycled without disassembly (Hundal 2000), or choice of separable materials, for instance materials with very low density which can be easily separated after grinding; (4) design for valorization systems (Coppens 1999), a novel method combining the previous ones in a systemic approach. The main issue considered here is the optimization of the design by maximizing the value of the end-of-life product, according to its mass and to economical criteria. In this context, a major concern is the availability of data on the economical performances of the recycling channels.

It appears that, in the context of eco-design, most of the studies addressing the support of the design activity are oriented on the definition of methods intended to decrease the environmental impact of products during their whole lifecycle, by means of optimization of the recycling activities, including issues addressing the ease of disassembly. Some of these studies suggest for instance useful design rules allowing to improve the recyclability of products, among which some are referred to in the eco-labels (VDI 1993, Dowie 1995, Simon 1996, Kärnä 1998). In this study, and in consistence with the principles of the proposed approach depicted in figure 1, our aim is clearly not to suggest another method for improving the recycling, but to focus on the integration of already suggested design rules in a decision support system. Indeed, we do believe that the major obstacle to the progress of environmental considerations in design is not so much the existence of knowledge than its access on the designer's workstation.

As stated previously, the rules allowing improving the recyclability are contained in textual sources (in our case the eco-labels), which could be difficult to interpret. The characterization of knowledge contained in these sources has been considered as a first step for translating them into an exploitable form.

3. Characterization of normative knowledge: case of eco-labels

Following the methodology depicted in figure 1, a first step for the development of the proposed system is to characterize the sources considered in order to identify the data that have to be added to those already contained in a 'usual' bill of materials. A sample of the most well-known eco-labels, among a large panel accessible in the literature, has been built for that purpose. As discussed in Houé (2006) and based on the study described in WEPSI (2001), this sample seems representative of sources containing normative knowledge allowing to assess the recyclability, although they are mostly dedicated to computers or electronics devices. The main standards considered are the following:

(a) the German Blue Angel eco-label (RAL-UZ78 2004);
(b) the Nordic Swan eco-label (Nordic Ecolabelling 2002);
(c) the TCO'99 Swedish eco-label (TCO 2000);
(d) the Japanese PC green label system (PC3R 2006);
(e) the ECMA standard (ECMA 1999);
(f) a SIEMENS standard (Siemens 1999);
(g) the DFE by the American Electronics Association – AEA (AEA 1993).

A part of the requirements contained in these standards is considered as out of the scope of this study, specifically dedicated to the design of product. It is for instance the case for requirements on the product functionality, packaging issues, etc. While performing this survey, a very encouraging point is that these sources are mostly based on a common family of data that are listed below.

After analysing these eco-labels, the suggested requirements have appeared to belong to four main categories, well known in the recycling field: (C1) Identification of materials, (C2) Homogeneity of materials, (C3) Nature of the materials and (C4) Disassembly process.

3.1. Identification of the materials

A first mandatory point for allowing recyclability is that the nature of the materials included in the product has to be easily identifiable. 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 moulded codes on plastic parts or by labels.

Example 1.

(R1) ECMA: 'The system is designed for disassembly by using marking on plastic parts over 25 g, according to ISO 11469'.

(R2) AEA: 'Materials should be identified by label (moulded on, embossed, or printed with compatible inks)'.

(R3) Blue Angel: 'Have the plastic parts been labelled according to ISO 11469?'

(R4) Siemens: 'Mark plastic components suitable for recycling'.

3.2. 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.

Example 2.

(R5) Nordic Swan: 'Single plastic parts (over 25g) in the housing and chassis must consist of one type of polymer (homopolymer or copolymer) or recyclable plastic blend'.

(R6) Nordic Swan: 'Large plastic parts (over 25g) may not be painted'.

(R7) TCO: 'All plastic components weighing more than 100 g shall be made from the same type of plastic material'.

(R8) Blue Angel: 'Large-size case parts made of plastics shall consist of a holopolymer or copolymer'.

(R9) Blue Angel: 'Avoidance of coatings and composite structure materials'.

(R10) AEA: 'Plastics should have no paint or sprayed metallic on the surfaces'.

Let us mention that the application of the rules promoted by these standards may itself lead to some problems: for instance, labels stuck on a material for its identification may result in mixing inhomogeneous materials. New rules are then designed for avoiding problems, such as the following:

Example 3.

(R11) 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'.

3.3. *Nature of the materials*

Some materials are not suitable for recycling, others may be dangerous for the people in charge of the disassembly; these elements have to be included in the product database.

Example 4.

(R12) TCO: 'Plastic containing chlorinated or brominated polymers, e.g. PVC, are not accepted in plastic components of any size'.
(R13) Siemens: 'Employ recyclable material'.
(R14) Nordic Swan: 'The housing and chassis must not contain chlorine-based plastics'.
(R15) Nordic Swan: 'Cadmium or lead must not be actively added to plastic parts (over 25 g)'.
(R16) Nordic swan: 'The flame retardants based on polybrominated organic components may not be used in the plastic parts (over 25 g)'.
(R17) AEA: 'In general, thermoset plastics should be avoided if possible, as their cross-linked structure makes recycling very difficult, if not impossible'.

3.4. *Disassembly process*

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

(i) Components should be easily separable.
Example 5.
(R18) AEA: 'Joining should allow disassembly and not mix incompatible materials – use snap fits, break or inserts, or screws; don't use adhesives'.
(R19) Siemens: 'Design all connections that require dismantling to be readily identifiable'.

(ii) Clear directions should be available for disassembly.
Example 6.
(R20) Blue Angel: 'Did the manufacturer carry out a check disassembly and prepare a disassembly report listing weak points?'

(iii) There should not be any need for special tools in the disassembly process.
Example 7.
(R21) Nordic Swan: 'It must be possible to carry out the dismantling without special tools'.
(R22) Blue Angel: 'Can disassembly be done with all-purpose tools exclusively?'

(iv) There should be enough space for inserting tools during the disassembly process.
Example 8.
(R23) Blue Angel: 'Is the product equipped with the necessary points of application and working spaces for disassembly tools?'
(R24) Siemens: 'Design all connections that require dismantling to be easily accessible'.

(v) The disassembly must require few human operators.
Example 9.
(R25) Blue Angel: 'Can the disassembly be done by a single person?'

These various examples illustrate that, in order to address the 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, etc.), 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 modelling tool.

4. Data formalization

In the previous examples of environmental criteria, it is noticeable that the translation of a normative knowledge, such as that contained in the eco-labels, is not obvious. This is mainly attributable to the textual form of the considered sources that could be difficult to interpret. As discussed in Houé (2006), the modelling of these sources at the 'knowledge level' (Newell 1982) is the most promising approach allowing to translate them into an exploitable form, for instance in order to perform the recyclability assessment. Indeed, this modelling approach has the interesting characteristic of allowing the separation between the description of a domain knowledge and the modelling of problem solving (Studer 1998). Thus, it could be possible to take into account knowledge that is not completely or that is roughly identified, which is the case in this study.

In this approach, the description of a universe of discourse consists of building an ontology of the domain knowledge, i.e. 'a specification of a representational vocabulary for a shared domain of discourse' (Gruber 1993). This kind of share interpretation of the description of a universe of discourse will provide us with a framework allowing modelling the recyclability knowledge contained in eco-labels. The choice of an appropriate modelling language is discussed in the following.

4.1. Choice of a modelling language

As stated previously, a textual source (such as an eco-label) can be difficult to translate into a form exploitable by a system. We have then chosen to build ontology of the recyclability area in order to define a precise framework of the recyclability area. This choice has for instance been suggested in Mostefai *et al.* (2005) in the field of collaborative product design.

The NIAM/ORM (Nijssen language Information Analysis Method - Object Role Modelling) modelling language has been especially designed to improve a shared understanding of the interpretation of a universe of discourse (Abrial 1974, Habrias 1998, Halpin 1998). Therefore, it seems to be appropriate in our context. As discussed in Halpin (1999), ORM has many interesting characteristics compared to the other conceptual modelling languages. One of its strengths is that constraints, i.e. relations between the concepts that represent the description of a knowledge domain, can be easily described in the models. This will be useful for representing the environmental rules to which the parameters of a product are submitted. Furthermore, the modelling is based on a readily understandable formalism, consisting of describing the considered domain knowledge through elementary facts expressed in a form close to the natural language. This corresponds to a major concern of our study. In an implementation perspective, let us also mention that a database can be automatically generated from an ORM model, allowing fast prototyping.

It is clear that many other choices could be made. In Morel *et al.* (2001) for instance, the authors have used the B language in order to perform formal specification for manufacturing systems automation, which is different from our purpose. In our case, a formal model is not strictly needed.

Other aspects of conceptual modelling can for instance be found in Dieng *et al.* (1998), Guarino (1998), Studer (1998), Bachimont *et al.* (2002) or in papers specifically dedicated to ORM previously mentioned. In the following an illustration is given of the use of the chosen modelling language for our proposed 'extended' product model.

4.2. Proposed product model

According to the conceptual schema design procedure (CSDP) suggested in Halpin (1998), the modelling with ORM follows a step-by-step methodology that can be summarized as follows: (1) describe the universe of discourse in elementary facts; (2) build a preliminary model using the ORM graphical notation; (3) add specific constraints thanks to the interpretation of the domain, and if necessary, return to (1) in order to improve the understanding of the universe of discourse.

In the context of this study, the modelling is based on the characterization suggested in section 3 of the considered textual sources, i.e. a sample of representative eco-labels. As an illustration, let us consider criterion (R1) of examples 1.

In a first step (following the CSDP method) and according to our interpretation, the term 'system' is assimilated to the 'product'. We then suggest that 'product has mass (for instance 25 g)' (f1), 'product may be identified (for instance by marking)' (f2), 'the identification of a product may refer to a norm (for instance ISO 11469)' (f3). Each of these elementary facts, i.e. (f1), (f2) and (f3), characterizes a binary constraint between concepts. Thus, in (f1) the concepts 'product' and 'mass' are linked to the relation 'has' or 'is of', depending on the concept used as the subject of the associated elementary fact ('product has mass', 'mass is of product'). The two other facts, (f2) and (f3), have been translated in the same manner: for (f2), the concepts are 'product' and 'identification mode', and the binary constraint is defined by the relation 'is identify by / is of'; for (f3), the concepts are 'identification mode' and 'identification norm', whereas the relation 'is consistent with / concerns' has been defined.

In a second step, and following the ORM graphical notation detailed in Halpin (1998), we represent concepts (also called objects in the ORM formalism) by ellipses, and relations (also called roles in the ORM formalism) by rectangles (see figure 3).

In a third step, according to the CSDP method, we have added some specific constraints that characterize our interpretation of the considered universe of discourse. We express for instance that 'each product must have a mass', which represents a *mandatory role constraint* which stipulates that each instance of the constrained object must play the role concerned by this constraint. This is depicted by a dot placed at the end of the line that links the constrained object to the role concerned by the constraint (see for instance at the top left of figure 3, the dot placed on the object 'product' that is linked to the role 'has'). We also express that 'a product has one and only one mass', which characterizes a *uniqueness constraint*, depicted by an arrow placed over the constrained role (for instance at the top left of figure 3, an arrow has been placed over the role 'has'). Many other constraints could be defined (Halpin 1998), those mentioned above being the main ones concerned with our context.

Let us add that in figure 3, the dotted ellipse (see the concept 'mass') represents a 'lexical object type', according to the NIAM/ORM terminology. This could be assimilated to the definition of an attribute in usual modelling language.

Thanks to the VisioModeler^{TM} editor, which has been used for the modelling, a 'verbalizer' box can been shown in order to check (in a pseudo natural language manner) the

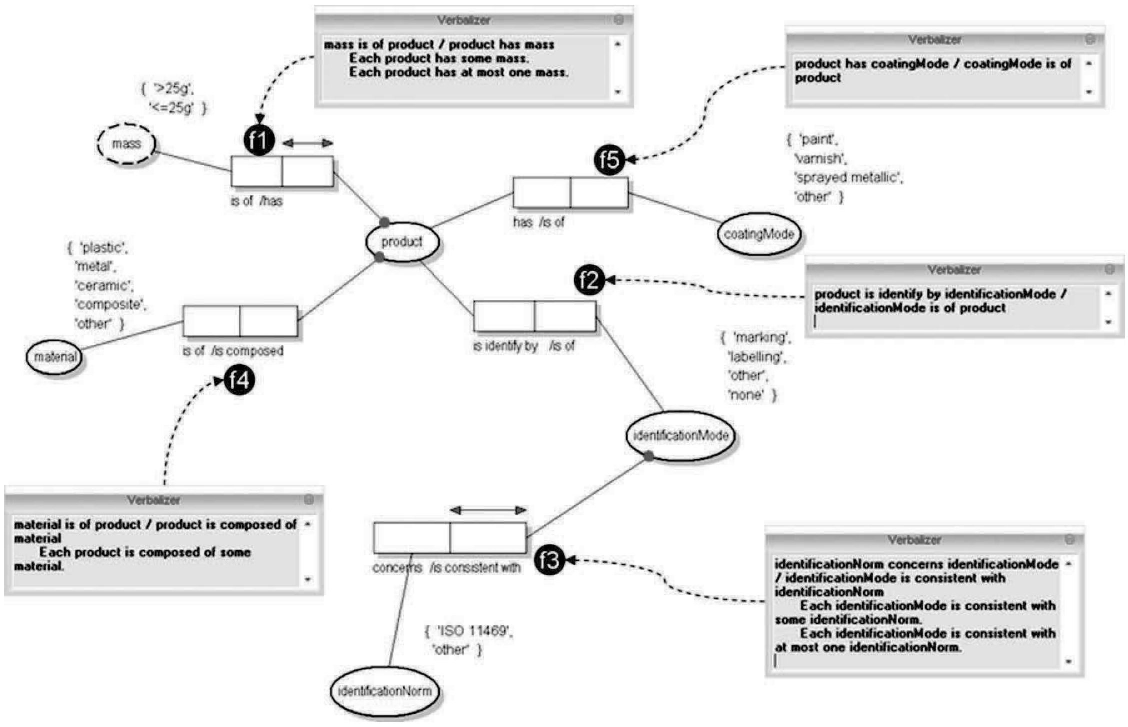

Figure 3. Excerpt of the 'recyclability view' of the proposed model.

translation of the considered sources of knowledge. Each concept (i.e. object) of the model could also be populated by some instances in order to facilitate the reading: see for instance the concept 'coatingMode' populated by the example 'paint', 'varnish', 'sprayed metallic', 'other'. This will help us to define unary constraints that characterize the possible values of each parameter required in the recyclability assessment. Being able to describe the data involved in the criteria of the eco-labels is of course not enough for assessing the compliance of a product with a norm: the modelling of the resolution process is specified later in the paper.

The other criteria of examples 1 and 2 have been modelled in the same way. Let us mention some results, according to our interpretations: (R2) is concerned with the fact (f2), and also with the new fact 'product is composed of material' (f4); (R3) is concerned with (f2), (f3) and (f4), (R4) with (f2) and (f4), (R5) with (f1) and (f4), (R6) with (f1), (f4) and also with the new fact 'product may be coated' (f5), (R7) with (f1) and (f4), (R8) also with (f1) and (f4), (R9) with (f4) and (f5), and (R10) also with (f4) and (f5).

It appears that some criteria have similar translations although they are not expressed identically, for instance (R7) and (R8). A criterion may overlap another one, for instance (R3) which has complementary information (i.e. the norm of identification) that is not mentioned in (R4). A criterion could be expressed like a typical 'if - then' rule, for instance (R11). Indeed, a part of this criterion could be formulated as follows: 'IF a product is identified by a label, THEN the material of this later must be the same as the product one', and conversely. The constraint between the set of materials that compose products and the one concerned with labels can also be modelled in ORM language, as illustrated in figure 4. However, in consistence with our approach, this kind of constraint is not necessarily needed, since we do not intend to perform any formal verification of the specification of the product from the conceptual model (as done for instance in Morel *et al.* (2001)). Furthermore, this would not allow us to choose the eco-label to which the product in design must comply, since this kind of constraint is very often tied with a specific label.

It can be shown that the rules defined in (C1), (C2) and (C3) of the above characterization of the normative knowledge contained in eco-labels are translated in a homogeneous frame described by concepts and relations similar to those depicted in figure 3. This figure represents the first view of the proposed extended product model, defined as the 'recyclability view'. Another view, based on the part (C4) of the above knowledge characterization, has been defined, the 'disassembly view'. Following the modelling method of the 'recyclability view', complementary facts have then been expressed, such as those depicted

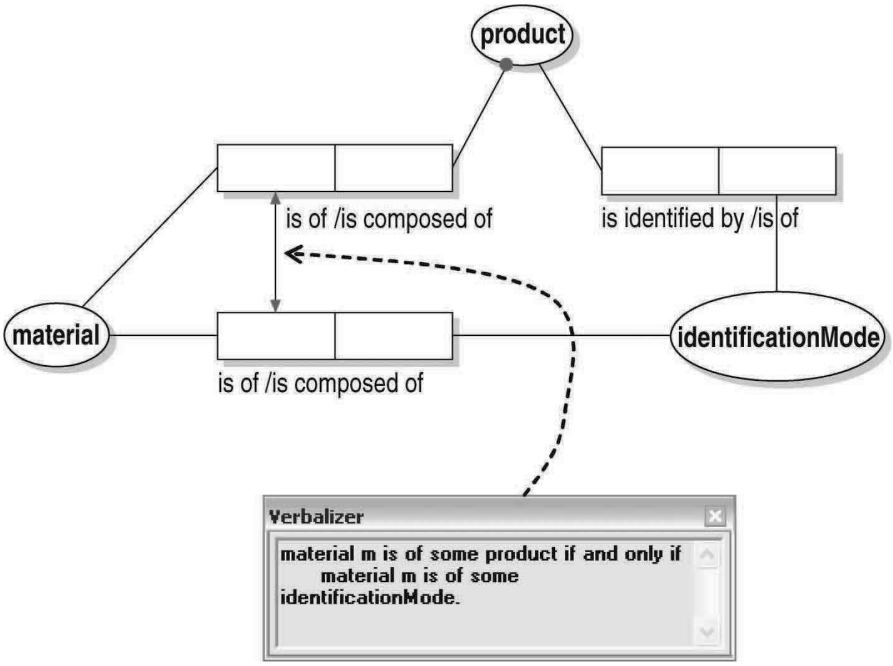

Figure 4. Modelling constraint between two sets of parameters in ORM.

in figure 5. However, the high expressiveness of the ORM modelling language can be illustrated by the following case: it is shown in figure 5 that 'an assembly may require a disassembly tool' (f7) and 'the fact that an assembly is dismantled by a tool may require enough space for the accessibility of this tool' (f8). The grammatical expression 'the fact that an assembly is dismantled by a tool' has been modelled as a concept (i.e. 'dismantlingByTool') that plays the role of requiring enough space for the accessibility of the tool (f8). This kind of translation is represented, according to the ORM graphical notation, by a rounded rectangle that illustrates the 'objectification', i.e. the way by which a role is converted into object. This allows complex grammatical expression to be modelling, which is widely recognzed as the high expressiveness of ORM.

Finally, the two views of the proposed 'extended' product model described above are those that contain the product parameters, specific to the recyclability area. These parameters (designed through objects in ORM) have then been added to those already present in the usual bill of materials: thirty different objects have been identified in the modelling in all. From the ORM formalism, the resulting product model is then automatically converted into data, thanks to a mapping process between ORM objects and the schema of a relational database.

The suggested extended data model is described with more details in Houé and Grabot (2007). In order to validate the technical feasibility of the proposed system, a prototype has been developed, based on the data model produced using the above methodology and tested on an example of product of the literature. This point is discussed in the following.

5. Validation of the method

As discussed previously, it is possible to model constraints using ORM, and so to 'incorporate' knowledge on the recycling process in the product model when the database tables are generated. Nevertheless, it was here also mandatory to separate the model from the constraints in order to be able to select the eco-label to be applied on the product model. As a consequence, an external way to verify the satisfaction of criteria based 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 in structured rules, then to choose an adequate language for their processing.

5.1. *Modelling constraints through rules*

The facts used in the criteria for recycling can be modelled according to the well-known <attribute> <object> <value> form used in logic programming. Some examples are:

<toolCategory> <disassemblyTool> <'standard'> i.e. disassembly tool has to be of a 'standard' category,

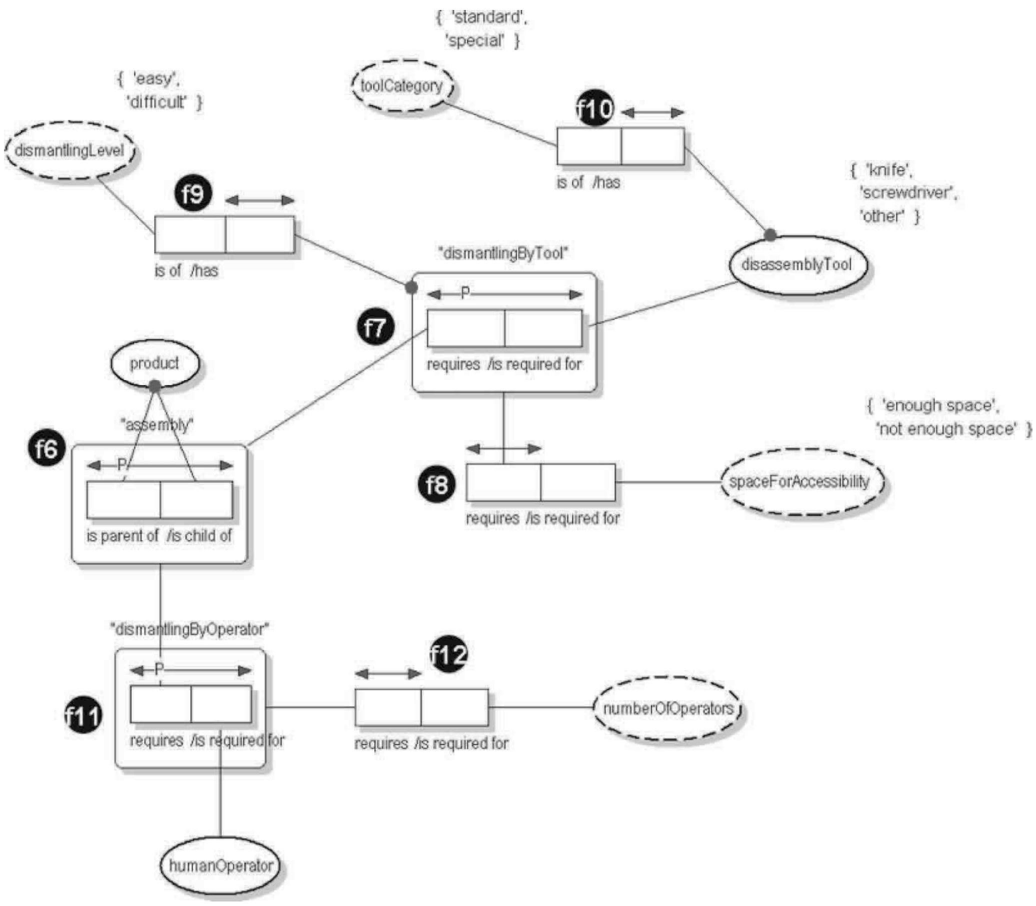

Figure 5. Excerpt of the 'disassembly view' of the proposed extended product model.

<spaceForAccessibility> <dismantlingByTool> <'enough'> i.e. there should be enough space to facilitate the accessibility of a tool during the disassembly,
<numBerOfOperators> <dismantlingByOperator> <'1'> i.e. no more than one person is needed to dismantle an assembly.

The values of some objects are numerical, for instance the number of operators required for the dismantling, others are symbolic values, for instance 'enough space'. Sometimes, being able to assess the satisfaction of a criterion would require an exaggerated increase of complexity of the data model. In that case, we have preferred to process the criterion through a question asked to the designer. It is for instance the case for (R20), which is modelled in the template <Question> <Criterion> where the question is, in this case, 'did the manufacturer carried out a check disassembly and prepared a disassembly report listing weak points?'

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 the form IF A THEN B, A and B being combinations of facts through Boolean connectors. Twenty-four rules have been extracted from the part of Blue Angel concerning recyclability, among which 75% were mandatory and 25% were advices. Eight other criteria were modelled by questions. The potential automatic processing of the Blue Angel eco-label by this modelling framework was 75%. Tests of other standards led to comparable results:

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

Some examples of rules extracted from Blue Angel are provided in table 1, 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 they generate a constraint which has to be satisfied. In other terms, ‘required facts’ are generated by the conclusion part of a rule which should be present in the fact base (for us, in the product model) in order to satisfy the criterion.

Table 1 also illustrates that some of the constraints can be verified ‘on-line’ during the design phase: for instance, the three first ones that can be checked as soon as the characteristics of the product are defined. Others, for instance the last one in table 1, require that the product has been entirely designed, since they deal with global characteristics (total number of person required to dismantle the product in (R25)).

Although the modelling of environmental criteria through constraints in the logic formalism seems to be natural and broadly satisfactory, some problems might be encountered. The management of such constraints in our context seems to be difficult, since knowledge to be modelled has to be completely specified in order to be integrated in the reasoning process. Incomplete pieces of knowledge are often considered in sources such as eco-labels, which could not be incorporated. Another major problem is concerned with the interaction required between the designer and the system: in a pure logic-based tool, ‘explanations’, aiming for instance at mentioning why a criterion has not been satisfied, are not provided in a ‘natural’ manner. The ‘trace’ of a reasoning provided by a system like PROLOG for instance could be hard to interpret for a designer.

Furthermore, the conclusion of this modelling step has shown us that the modelling of the criteria contained in the eco-labels requires:

Table 1. Examples of rules extracted from Blue Angel.

Criteria	Facts and production rules
(R3)	F1: <material> <product p> <material m> F2: <familyMaterial> <material m> <‘plastic’> F3: <identificationMode> <product p> <label l> F4: <identificationNorm> <label l> <‘ISO 11 469’> IF (F1 ∩ F2 ∩ F3) THEN F4
(R9)	F1: <material> <product p> <material m> F2*: <familyMaterial> <material m> <‘composite’> F5: <coatingMode> <product p> <‘none’> IF F1 THEN (not F2* ∩ F5)
(R22)	F6: <disassemblyTool> <assembly a> <tool t> F7: <toolCategory> <tool t> <‘standard’> IF F6 THEN F7
(R25)	F8: <numberOfOperators> <dismantlingByOperator> <‘1’> F8

(a) to manipulate lists easily (lists of forbidden materials, of required tools for the disassembly, etc.);
(b) to be able to easily model constraints;
(c) to be able to dynamically handle these constraints, since it can be seen in table 1 that the constraints to be satisfied (i.e. the ‘THEN’ part of the rules) may depend on a condition (i.e. the ‘IF’ part of the rules).

These requirements have brought us to implement the environmental rules translated from eco-labels according to the constraints satisfaction problem (CSP) paradigm. The CLAIRE (combining logical assertion, inheritance, relation and entities) language seems to be a suitable choice for that purpose, as illustrated and discussed in the following.

5.2. *Choice of the CLAIRE language*

Let us first remember that a CSP can be informally defined by:

(a) a finite set of variables (for instance the parameters of the design of product);
(b) each with a domain of possible values, often finite, which is for instance the case in our context (e.g. possible types of coating a component, possible manners of joining components, etc.);
(c) a set of constraints that limit the values the variables can take on (for instance the compatibility of the material of a label, if used, with the material of the component on which it is stuck, etc.).

A *solution* of a CSP can be defined as an assignment of a value to each variable such that the constraints are all satisfied. The user of such formalism can be interested in various results: knowing if a solution exists to a given problem, finding a solution, finding all solutions, or finding the ‘best solution’ according to some metric (for instance economical performances of the recycling). In the following, we will only try to check if the assignment of the parameters satisfies the constraints to be checked. Optimizations issues are out of the scope of our study.

According to the main requirements mentioned in the previous section, CLAIRE seems to be an appropriate implementation language for us. It is a high level free language providing a set of orientations of great interest for this study, among which object orientation, description of concrete or abstract sets, or production rules (Caseau and Laburthe 1996).

A first interest 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.

Secondly, even if CLAIRE is not a constraint propagation language on its own, it allows to easily describing constraints. Algorithms of arc-consistency checking are for instance available in the libraries of CLAIRE, especially the CHOCO solver, a library written in CLAIRE dedicated to constraint programming and including dynamic constraint satisfaction.

Indeed, arc-consistency is especially relevant in the context of this study. Among the tools of constraint propagation, arc consistency (see for instance (Dechter 2003)) allows to check whether the values of variables located on the nodes or links of a graph are consistent with a constraint, which allows to process most of the constraints identified in this work, e.g. the 33 binary constraints in the case of Blue Angel.

As a summary, it is easy to manipulate with CLAIRE both production rules such as those described in previous section and constraints using constraint propagation algorithms.

5.3. Modelling constraints in CLAIRE

Let us consider two examples, again extracted from Blue Angel:

Example 1. 'Joins to be separated must be easily traceable'.

This example can be defined in the CSP paradigm with the two following variables 'joinFamily' and 'identificationMode', each with its possible values as illustrated in figure 6. A binary constraint is defined in this CSP, which is depicted in the figure by a line that joins the value of the above variables that are consistent according to a criterion. The value 'to be separated' of the first case is here consistent with the three first values of the second variable. This means that a component has to be identified, whatever the mode of identification may be.

In CLAIRE, a CSP is defined through the following steps: 1/ create a problem, 2/ create variables, 3/ state constraints.

Step 1: The following instruction creates for instance a problem p, named 'First recyclability analysis' with at most 20 variables:

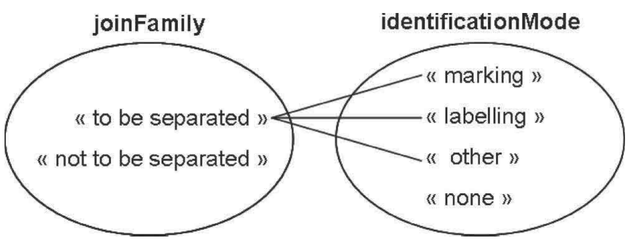

Figure 6. Traceability of separable joins.

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

Step 2: The two variables of the above example are then created as follows:
joinFamily : = makeIntVar(p, 'joinFamily', 1, 2)
identificationMode : = makeIntVar(p, 'identificationMode', 1, 4)
The numbers 1 and 2 in the first instruction respectively stand for 'to be separated' (value 1) and 'not to be separated' (value 2), whereas 1, 2, 3 and 4 stand for 'marking', 'labelling', 'other' and 'none' in the second instruction.

Step 3: A binary constraint between these two variables is then defined in two steps. A relationship is firstly defined that defines the authorized pairs of values between two domains. Secondly, a binary constraint is stated, related to the concerned relation and the problem previously defined:

identificationRel : = makeBinRelation(1,2,1,3, list(tuple (1,1), tuple(1,2), tuple(1,3)))
post(p,binConstraint(joinFamily, identificationMode, identificationRel,3)

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

Example 2. 'Join to be separated must consist of at least 50% of plug/snap join (if plastic components)'.

This criterion uses the data described in figure 7. We are here in the case of a constraint ('50% of plug/snap connections') that depends on a condition ('if plastic components') and which characterizes a dynamic CSP.

In CLAIRE, the associated problem can be described as follows:

post(p, implies(materialFamily in {1}, feasTupleConstraint (list(joinFamily, joinType, joinPercentage), list (list(1,2,1)))).

The unary constraint materialFamily in {1} is the condition that triggers the constraint ('1' standing for 'polymer'): feasTupleConstraint(list(joinFamily, joinType, joinPercentage), list(list(1,1,1))) which defines the feasible triples of values authorized between the three concerned variables.

Since a constraint has to be satisfied for all the components, all the joins, etc., we need to define a variable, for instance, wholeProduct as a list a elementary product component, then perform a loop over the whole product in

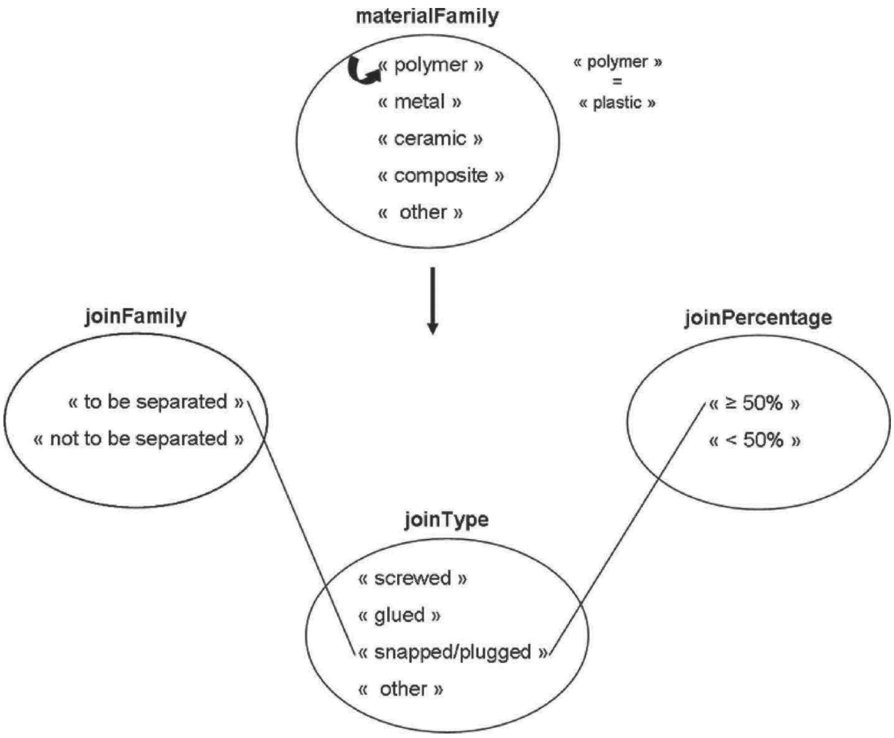

Figure 7. Characteristics of the joins.

order to propagate the constraints on all the components and joins:

```
// define constraint for each
// component of the whole
// product
...
for pr in wholeProduct (
   post(p, implies(pr.materialFamily in {1}, feasTuple-
   Constraint (list(joinFamily,joinType, joinPercentage),-
   list(list(1,2,1)))))
   ...
//propagate the constraints
propagate(p)
```

The following section shows the result of the propagation of constraints written in CLAIRE on a simple but representative example of the literature.

5.4. *Example of constraint propagation in the extended product model*

In order to perform the first tests, a case available on the internet has been chosen: the Motorola Display/Keypad Microphone already discussed by other authors on the point of view of disassembly optimization (Bras 2006). The components of this product are shown in figure 8, 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, we have only had to complete the data base with some additional features for being able to assess the compliance of this product with constraints extracted from the selected standards.

The following constraints are considered here for illustration, all extracted from Blue Angel (even if this standard is devoted to computers):

1. Electrical modules should be removable (A2);
2. Electrical modules should be traceable (A2);
3. Connection to be separated should be easily traceable (A3);
4. Disassembly should be done exclusively through multi-purpose tools (A4);
5. Connection elements to be separated for recycling purpose should be axially accessible (A6);
6. All screwed connection between modules should be separated with no more than three tools (A7);
7. At least 50% of the connections between plastic components should be separated plug/snap connections (A8);
8. Disassembly should be done by a single person (A9).

A software prototype has been developed, with the following possibilities and limitations:

1. Communication between the database and the constraint program has not yet been achieved; therefore, it is necessary to directly enter the values of the parameters in the program before checking whether the constraints are satisfied.
2. Generally speaking, parameters can be expressed as accurate values but also as intervals or sets of possible values. The CHOCO solver checks whether the defined values of the parameters are compatible with the constraint to be checked, and eventually restricts the domain of variation of the parameters to the values which satisfy the constraint.

In these first tests, all the parameters have precise values. Therefore, the solver returns that no solution has been found if the constraint is not satisfied by the present values of the parameters.

Example on rule 2:
The parameters are the followings: identification mode (IdentificationMode), product type (pType), product nature (pConNature) with:

a. identification possible values: 1 = 'marking', 2 = 'labelling', 3 = 'other', 4 = 'none';
b. product type possible values: 1 = 'electrical', 2 = 'mechanical', 3 = 'other';
c. product nature possible values: 1 = 'separable', 2 = 'none separable'.

If an electrical module is separable but not marked, this leads to the following parameters:

choco/setVal(identificationMode, 4),
choco/setVal(pType, 1),
choco/setVal(pConNature, 1),

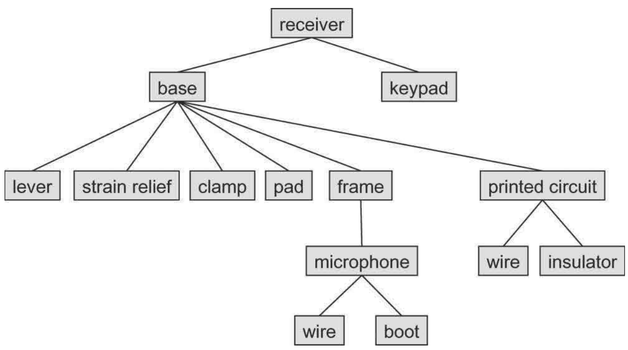

Figure 8. Components of the display/keypad microphone (from (Bras 2006)).

For entering these values, the interface shown in figure 9 has been used as a provisional step.

In that case, the CHOCO solver gives no solution since the concerned module does not comply with the rule which states that any 'electrical modules should be removable and traceable'. At the moment, no explanation is given on the reason why the constraint is not satisfied.

Let us consider the results of the application of the constraints taken as illustrations:

1. 'Electrical modules should be removable (A2)'. The only electrical modules found in the bill of materials of figure 8 are the printed circuit (25) and microphone (18), which are both removable since they are plugged without additional connector: the constraint is so satisfied.
2. 'Electrical modules should be traceable (A2)'. No mention is made in the bill of materials of labels or marks (the labels 4 and 24 only give the trademark and name of the product): the constraint is not satisfied.
3. 'Join to be separated should be easily traceable (A3)'. The joins are not specifically marked: the constraint is therefore not satisfied.
4. 'Disassembly should be done exclusively through multi-purpose tools (A4)'. The used tools mentioned are a screwdriver (#1 Philips), pliers, knife, pry, pin, saw and drill which have been included for the tests in a list of the standard tools. It would of course be necessary to define more precisely such a list for real applications.
5. 'Connection elements to be separated for recycling purpose should be axially accessible (A6)'. A question to the designer has been generated for checking this constraint, considered as impossible to check on the bill of materials which does not provide any geometrical information. It is interesting to notice that such constraint could be handled on a CAD–CAM system.
6. 'All screwed connection between modules should be separated with no more than three tools (A7)'. Only one screwdriver is necessary here: the #1 Philips: the constraint is so satisfied.

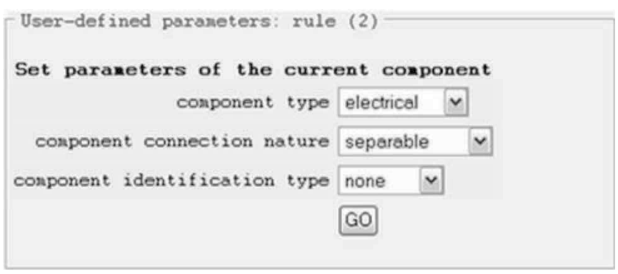

Figure 9. Provisional interface for parameters.

7. 'At least 50% of the connections between plastic components should be separated plug/snap connections (A8)'. Two connections using screws connect plastic components: (1–3) and two (9) screws in figure 8. A connection has to be disassembled with a saw, one with a drill and another with a knife, with a result of 5 non-plug/snap connections on a total of 8: the constraint is satisfied.
8. 'Disassembly should be done by a single person (A9)'. Since no information was given, we have associated the disassembly process with a single operator in the data model shown in Figure 5: the constraint is so satisfied.

6. Conclusion and perspectives

In today's sustainable development context, the number of tight environmental regulations is increasing. Companies, particularly in the area of mechanical or electronic equipments, will increasingly need to face these regulations, generally presented in the form of norms or standards. In practice, the designer has to make important efforts for the integration of these regulations, mainly because of the difficulty of interpreting the sources considered, and also owing to the lack of links between the recyclability knowledge and the product data. Eco-labels are the kind of sources that particularly contain recyclability criteria a product has to comply with.

In this study, we have considered the recyclability assessment of a product during its design stage, in the point of view of its compliance with an eco-label. Our aim is to provide a method for the extraction and structuring of recyclability knowledge, allowing to include this knowledge into a DSS dedicated to a semi-automated assessment of the compliance of a product with a norm. We have proposed a methodology of structuring data, information and knowledge contained in eco-labels sources: we have first shown the formalization of data, specific to the recyclability issues and extracted from these sources, within the product structure. The NIAM/ORM language has been used for that purpose. Based on a sample of the most well-known eco-labels, among a large panel accessible in the literature, it has then been shown how a normative knowledge (such as defined in eco-labels) could be structured into constraints that the product characteristics have to satisfy.

The CLAIRE language, thanks to the CHOCO solver, has been used in order to implement a prototype allowing performing the propagation of these constraints within the proposed product model. This implementation has shown only the feasibility of this process.

The first perspective of this work is therefore to achieve the development of a software prototype allowing to completely assess the compliance of a product with an eco-label, which should be done in the following months and based on the following requirements:

a. to provide a connection between the proposed program (in CLAIRE) and a product database system;
b. to implement explanation facilities when constraints are not satisfied. According to (McDonald and Prosser 2002), this could be done using the CHOCO solver following a procedure such the one defined in (Junker 2001);
c. to develop interfaces allowing an efficient interaction between the user and the decision support system;
d. to achieve the structuring of other eco-labels through CLAIRE programs;
e. to suggest indicators allowing to synthesize the degree of compliance of a product with an eco-label.

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References

Abrial, J.R., Data Semantics, in *Data Base Management*, edited by J. W. Klimbie and K. L. Koffeman, 1974 (North Holland: Amsterdam).
American Electronics Association, DfE Paper: The Hows and Whys of Design for the Environment, A Primer for Members of the American Electronics Association, Technical report, June, 1993.
Bachimont, B., Troncy, R. and Isaac, A., Semantic commitment for designing ontologies: a proposal. In *Proceedings of 'EKAW' Conference*, Siquenza, Spain, 2002.
Blaise, J.-C., Lhoste, P. and Ciccotelli, J., Formalisation of normative knowledge for safe design. *Safety Sci.*, 2003, **41**, 241–261.
Bras, B., Design for recycling, part 1, Georgia Institute of Technology, lecture notes, 2006. Available online at http://www.srl.gatech.edu/education/ME4171/.
Brezet, H. and Van Hemel, C., *Ecodesign: A Promising Approach to Sustainable Production and Consumption*, 1997 (United Nations Publication: New-York).
Caseau, Y. and Laburthe, F., CLAIRE: Combining objects and rules for problem solving. In *Proceedings of the JICSLP'96 Workshop on Multi-paradigm Logic Programming*, edited by M. T. Chakravarty, Y. Guo and T. Ida, 1996 (TU: Berlin).
Coppens, C., Méthode de conception en vue d'optimiser la valorisation des véhicules hors d'usage (Design method for optimising end of life vehicles recovery). PhD Thesis, ENSAM, 1999.
Dechter, R., *Constraint Processing*, 2003 (Morgan Kaufmann Publishers: San Francisco).
Dieng, R., Corby, O., Giboin, A. and Ribière, M., Methods and tools for corporate knowledge management. In *Proceedings of KAW'98*, Banff, Canada, 1998.
Dowie, T., Design for Disassembly, Technical Report, Manchester Metropolitan University, 1994.
Dowie, T., A disassembly planning and optimization methodology for design. PhD Thesis, Department of Mechanical Engineering, Design and Manufacture, Manchester Metropolitan University, Manchester, GB, 1995.

ECMA, ECMA: European Computer Manufacturers Association, 'Product-related environmental attributes', Technical Report 70, June, 1999.

Gruber, T.R., A translation approach to portable ontologies. *Knowl. Acquis.*, 1993, **5**, 199–222.

Guarino, N., Formal ontology and information systems. *Proceedings of FOIS'98*, Trento, Italy, 1998.

Habrias, H., The binary relational model, NIAM Method. Eyrolles, 1998.

Halpin, T., Object-role modelling (ORM/NIAM). *Handbok of Architectures of Information Systems*, edited by P. Bernus, K. Mertins and G. Schmidt, 1998 (Springer-Verlag: Berlin).

Halpin, T., Data modelling in UML and ORM: a comparison. *J. Database Mgmt*, 1999, **4**, 4–13.

Houé, R., Modélisation des connaissances normatives en vue de l'évaluation de la recyclabilité d'un produit en conception: des normes aux contraintes (Modelling normative knowledge for the recyclability assessment: from norms to constraints). PhD thesis, Laboratoire Génie de Production, ENI, Tarbes, 2006.

Houé, R. and Grabot, B., A decision support system for recyclability assessment: from norms to constraints. *Proceeding volume of INCOM 06*, Saint Etienne, France, 17–19 May 2006.

Houé, R. and Grabot, B., Knowledge modelling for Eco-design. *Int. J. Concurrent Engng Res. Applic.*, 2007, **15**, 7–21.

Hundal, M., Design for recycling and remanufacturing. *International Design Conference – DESIGN 2000*, Dubrovnik, 2000.

Ishii, K., Design for environment and recycling: overview of research in the united states. In *CIRP 5th International Seminar on Life-cycle Engineering*, 1998.

International Organization for Standardization, *Application of the ISO 14000 family, Environmental Management*, pp. 10–11, 2002 (ISO: Geneva).

Johansson, G., Design for disassembly: a framework. Licentiate thesis, Graduate School of Management and Industrial Engineering, Linköping University, Linköping (Suède), 1997.

Junker, U., Quickxplain: conflict detection for arbitrary constraint propagation algorithms. In *IJCA'01 Workshop on Modelling and Solving Problems with Constraints*, 2001.

Kärnä, A., *Environmentally Oriented Product Design*, 1998 (Federation of Finnish Electrical and Electronics Industry: Helsinki).

Lee, B.H. and Ishii, K., The recyclability map: application of demanufacturing complexity metrics to design for recyclability. *J. Sustainable Prod. Des.*, 1998, **5**, 38–48.

Mathieux, F., Contribution à l'intégration de la valorisation en fin de vie dès la conception d'un produit. Une méthode basée sur l'évaluation multi-critères de la recyclabilité du produit et sur l'identification de ses points faibles de conception. PhD thesis, ENSAM, Chambéry, 2002.

McDonald, K. and Prosser, P., A case study of constraint programming for configuration problems, 2002. Available online at: http://www.dcs.st-and.ac.uk/~apes-45-2002.ps.gz.

Morel, G., Petin, J.F. and Lamboley, P., Formal specification for manufacturing systems automation. *10th IFAC INCOM Symposium*, Vienna, Austria, 2001.

Mostefai, S., Bouras, A. and Batouche, M., Effective collaboration in product development via a common sharable ontology. *Int. J. Comput. Intell.*, 2005, **2**, 1304–4508.

Newell, A., The knowledge level. *Artific. Intell.*, 1982, **18**, 87–127.

Nordic Ecolabelling, Nordic Swan: 'Nordic Ecolabelling, Ecolabelling of Personal Computers, Criteria document, Version 2.1', 2002.

PC3R, PC Green Label System, 2006. Available online at: http://www.pc3r.jp/pdf/gl2006_e.pdf (2006).

Pnuelli, Y. and Zussman, E., Evaluating the end-of-life value of a product and improving it by redesign. *Int. J. Prod. Res.*, 1997, **35**, 921–942.

RAL-UZ78, Blue Angel. Basic Criteria for Award of the Environmental Label – Workstation Computers, February edition, 2004.

Siemens, SN 36350-1, Environmentally Compatible Products, 1999.

Simon, M., Feasibility of a Common Indexing System for Recycling of Electronic Products. Technical Report, Manchester Metropolitan University, 1996.

Studer, R., Knowledge engineering, principles and methods. *Data Knowledge Engng*, 1998, **25**, 161–197.

TCO, TCO '99 Certification requirements and test methods for environmental labeling. *Ecology for Displays, Portable Computers, System Units, and Keyboards*. Report No.5, Edition 2, June 20, 2000.

Tukker, A. and Eder, P., Eco-design: European State of the art. Part II: Specific Studies, IPTS Report, Seville, 2000.

VDI, *VDI 2243 – Konstruiren Recyclinggerechter Technischer Produckte*, 1993 (VDI: Düsseldorf).

WEPSI, Overview of DfE Assessment Standards, 12/24/01.