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MAPPING DESIGN INFORMATION BY MANIPULATING REPRESENTATIONAL STRUCTURES

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Abstract. Design problems require a multiplicity of viewpoints each distinguished by particular interests and emphases. Alternative viewpoints necessitate different representations of the same entity, albeit a building or a building part, a shape or other complex attribute. We argue that the exploration of alternative design views can be supported by providing access to the representational structure and by allowing the structure to be manipulated through incremental changes. Hereto, we briefly describe the representational framework of *sorts* and present its support for comparing representational structures and mapping design information according to it. We illustrate the creation and manipulation of structures and their comparison. We consider the specification of design queries through the integration of data functions into representational structures. We conclude with a presentation of future work.

1 Introduction

Computational design relies on effective information models, for the creation of design artifacts and for the querying of the characteristics of such artifacts. Mäntylä stated in 1988 that these (geometric) representations must adequately answer "arbitrary geometric questions algorithmically." Without emphasis on the geometric aspects, this remains as important today. However, current computational design applications tend to focus on the tools and operations for the creation and manipulation of design artifacts. Techniques for querying receive less attention and are often constrained by the data representation system and methods. Nevertheless, querying a design is as much an intricate aspect of the design process as is creation and manipulation.

Design is also a multi-disciplinary process, involving participants, knowledge, and information from various domains. As such, design

problems require a multiplicity of viewpoints, each distinguished by particular interests and emphases. For instance, an architect is concerned with aesthetic and configurational aspects of a design; a structural engineer is engaged by the structural members and their relationships; and a building performance engineer is interested in the thermal, lighting, or acoustical performance of the eventual design. Each of these views — derived from an understanding of current problem solution techniques in these respective domains — requires a different representation of the same (abstract) entity. Even within the same task and by the same person, various representations may serve different purposes defined within the problem context and the selected approach. Especially in architectural design, the exploratory nature of the design process invites a variety of approaches and representations.

Design views facilitate a visual inspection of design data and information. Design queries support the analysis of existing design information in order to derive new information that is not explicitly available in the information structure. Design views can be understood to be discrete and domain-specific; design queries on the other hand seem to indicate small incremental steps transcending common, domain-specific views in search of information that does not naturally form part of the design view. At the same time, the result of a design query, possibly presented in the context of other design information, may be seen to define a design view and, similarly, design views may be expressed through design queries.

The distinction between discrete and incremental views can also be related to the development of integrated data models. Integrated data models span multiple disciplines and support different views. These allow for various representations in support of different disciplines or methodologies and enable information exchange between representations and collaboration across disciplines. Examples are, among others, the ISO STEP standard for the definition of product models (ISO, 1994) and the Industry Foundation Classes (IFCs) of the International Alliance for Interoperability (IAI), an object-oriented data model for product information sharing (Bazjanac, 1998). These efforts characterize an *a priori* and top-down approach: an attempt is made at establishing an agreement on the concepts and relationships which offer a complete and uniform description of the project data, independent of any project specifics (Stouffs and Krishnamurti, 2001). These efforts also mainly target software developers who can ensure compatibility of their own representation corresponding to a particular design view with the integrated data model.

Alternative modeling techniques consider a bottom-up, constructive approach. These provide a more extensive degree of flexibility that allows for the development of information models that are context, and thus project specific. This flexibility may also enable incremental changes to existing

representations supporting alternative design views. Woodbury et al. (1999) adopt typed feature structures in order to represent partial information models and use unification-based algorithms to support an incremental modeling approach. Concept modeling (van Leeuwen and Fridqvist, 2003) allows for the extensibility of conceptual schemas and for flexibility in modeling information structures that differ from the conceptual schemas these derive from. The SPROUT modeling language (Snyder and Flemming, 1999) allows for the specification of schematic descriptions that can be used to generate computer programs that provably map data between different applications.

This suggests that support can be provided for exploring alternative design views by providing access to the representational structure and by allowing the structure to be manipulated through incremental changes. In this paper, we briefly describe the representational framework of *sorts* (Stouffs and Krishnamurti 2002) and present its support for comparing representational structures and mapping design information according to it. We illustrate the creation and manipulation of structures and their comparison. We consider the specification of design queries through the integration of data functions into representational structures. We conclude with a presentation of future work.

2 Defining *sorts*

Sorts (Stouffs and Krishnamurti, 2002) offer a constructive approach to defining representational structures that enables these to be compared with respect to scope and coverage and that presents a uniform approach to dealing with and manipulating data constructs. *Sorts* are class structures identified by compositions of properties (or attributes) (Stouffs et al, 1996). *Properties* are named entities identified by a type specifying the set of possible values. Exemplar types are labels and numeric values, and spatial types such as points, line segments, plane segments, and volumes. Properties are composed or grouped using one or more constructors; *constructors* are devices for relating properties together. At this time, we consider two constructors, resulting in either a subordinate composition of properties or a disjunctively co-ordinate composition (see further for examples). Others may be defined, as needed.

In the construction of sorts, every composition of properties is considered a *sort*. Even a single property defines a *sort*. Thus, a *sort* is typically a composition of other *sorts*. Comparing different *sorts*, therefore, requires a comparison of the respective properties and their constructive relationships. We denote a *sort* identified by a single property a *primitive sort* and all other *sorts composite sorts*. A primitive *sort* necessarily has a name that is the name assigned to the property. A composite *sort* can also have a name

assigned. Named *sorts* can be conceived to define object classes. However, in contrast to the traditional product modeling approach, the collection of properties of a class is not predefined. This allows class structures easily to be modified, both by adding and removing properties, and by altering the constructive relationships (see also Van Leeuwen et al, 2001). For this purpose, we consider even property relationships and numeric data functions as properties, such that these can be dealt with in the same way.

The *attribute* constructor, denoted '^', specifies a subordinate composition of *sorts*, under an attribute relationship. For example, a *sort* of labeled plane segments is specified as a *sort* of plane segments, with one or more labels assigned as attribute to each plane segment. Figure 1 illustrates three alternative *sorts* derived from the same *sort* by composing this *sort* with another *sort* under the attribute constructor. Consider a *sort* to represent a drawing, denoted *drawings*. Consider a new *sort* with the purpose of representing a collection of drawings where each drawing is distinguished by some attribute information. If the distinguishing aspect is a name, we can define the new *sort named_drawings* as follows:

labels : [Label]
named_drawings : *drawings* ^ *labels* (1)

Here, ':' denotes the operation of semantic identification, i.e., assigning a name to a *sort*, and '[Label]' defines the type of the primitive *sort*. If the distinguishing aspect is a point of reference for the respective drawing, the resulting *sort layouts* can be defined as follows:

points : [Point]
layouts : *drawings* ^ *points* (2)

We may also combine both distinguishing aspects, for example, by assigning the labels as attribute to the respective reference point, as follows:

named_layouts : *drawings* ^ *points* ^ *labels* (3)

The *sum* constructor, denoted '+', allows for disjunctively co-ordinate compositions of *sorts*. For example, a *sort* of spatial elements may be defined as the sum of a *sort* of points, a *sort* of line segments, a *sort* of plane segments and a *sort* of volumes; then, a spatial element can be either a point, line segment, plane segment or volume. Figure 2 illustrates a *sort* representing a hierarchical tree structure of architectural concepts or keywords. The representation is conceived as a tree structure in which each keyword can have zero, one or more subordinate keywords. The *sort concepts*, a *sort* of labels, represents the individual keywords:

concepts : [Label] (4)

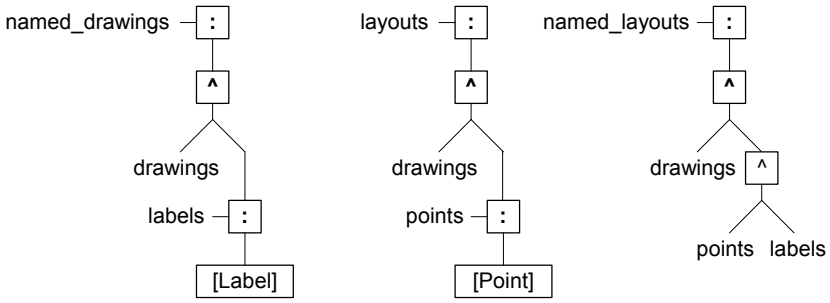


Figure 1: *Diagrammatic definition of three sorts, named_drawings, layouts and named_layouts, each derived from the sort drawings by combining this sort with another sort under the attribute relationship*

The subordinate relationship between keywords is expressed by the attribute constructor on *sorts*. The resulting *sort*, named *conceptstree*, is defined recursively:

$$conceptstree : concepts + concepts \text{ ^ } conceptstree \tag{5}$$

The attribute constructor relates to each individual keyword (*concepts*) a non-empty data form of subordinate keywords (*conceptstree*). The sum constructor ('+') allows for the combination of keywords with (*concepts* ^ *conceptstree*) and without (*concepts*) attribute keywords. Thus, individual keywords are assigned either to the *sort concepts*, or with an attribute data form to the *sort concepts* ^ *conceptstree*. Figure 2 also presents an exemplar data form corresponding to the *sort conceptstree* and expressed using the Sorts Description Language; individual concepts, i.e., labels, are assigned either to the *sort concepts*, or with an attribute form to the *sort concepts* ^ *conceptstree*.

An alternative view of a semantic structure (or architectural typology) is in the form of a network or (semantic) map. A network structure distinguishes itself from a simple hierarchical structure in that a subordinate keyword may be shared by more than one keyword. Such a structure can be extended from the structure in Figure 2 by allowing references to be specified to keywords that are already defined elsewhere in the structure. Such references can be represented using a property relationship *sort* that is defined over the *sort concepts* and an equivalent *sort conceptrefs*:

$$conceptrefs : concepts \tag{6}$$

The property relationship *sort* distinguishes two named *aspects*, *hasrefs* and *isrefs*, respectively corresponding to the relationship from *concepts* to *conceptrefs* and vice versa:

$$(hasrefs, isrefs) : [\text{Property}]\ (concepts, conceptrefs) \tag{7}$$

```
form $concepts = conceptstree:
{ (concepts ^ conceptstree):
   { "theater"
      { concepts:
         { "infrastructure" },
        (concepts ^ conceptstree):
         { "construction"
            { concepts:
               { "load bearing structure",
                 "material" },
              (concepts ^ conceptstree):
               { "enclosure"
                  { concepts:
                     { "roof",
                       "facades" } } } },
          "format"
           { concepts:
              { "photo",
                "scale model",
                "text" },
             (concepts ^ conceptstree):
              { "view"
                 { concepts:
                    { "elevation",
                      "axonometric view",
                      "diagram",
                      "section",
                      "perspective",
                      "plan",
                      "site plan" } } } },
        ... } } } };
```

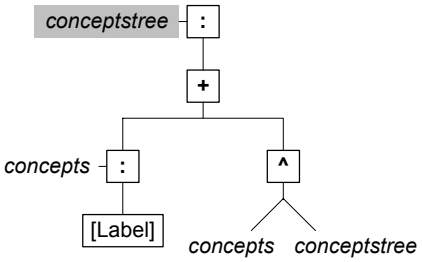


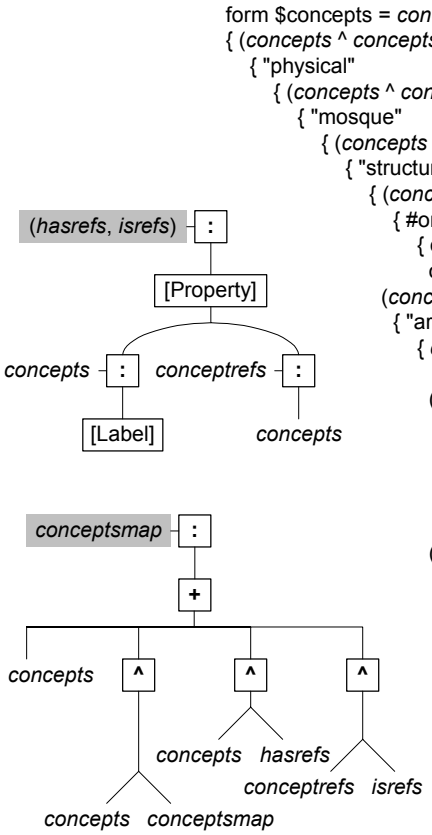
Figure 2*: Diagrammatic definition of a recursive sort conceptstree representing a hierarchical structure of architectural concepts, and the (partial) description of an exemplar data form*

These two aspects can be considered as two different views of the same *sort*. Each aspect, however, is considered a distinct *sort* if used in the definition of other *sorts*. In order to maintain consistency, each aspect must be specified as an attribute to its respective *sort* of origin under the property relationship, e.g., *concepts* ^ *hasrefs* and *conceptrefs* ^ *isrefs*. The first attribute *sort*, *concepts* ^ *hasrefs*, allows for the specification of keywords with one or more references to (subordinate) keywords that are elsewhere defined. The second attribute *sort*, *conceptrefs* ^ *isrefs*, allows for the retrieval of all keywords this subordinate keyword is referenced from. Both attribute *sorts*, together with the *sorts concepts* and *concepts* ^ *conceptsmap*, recursively define the *sort conceptsmap* under the sum constructor (Figure 3):

$$\begin{aligned} &\textit{conceptsmap} : \textit{concepts} + \textit{concepts} \wedge \textit{conceptsmap} + \\ &\quad \textit{concepts} \wedge \textit{hasrefs} + \textit{conceptrefs} \wedge \textit{isrefs} \end{aligned} \tag{6}$$

Thus, individual keywords are assigned to the *sort concepts*, with an attribute data form (that is recursively defined) to the *sort concepts ^ conceptsmap*, or with an attribute data form of references to the *sort concepts ^ hasrefs*. If a keyword has subordinate keywords of which some but not all are defined elsewhere (and thus referenced here), then, this keyword will be assigned to both the *sorts concepts ^ conceptsmap* and *concepts ^ hasrefs*.

Figure 3 also presents an exemplar data form considering an architectural typology for Ottoman mosques (Tunçer et al, 2002). Note that the data form does not specify any data to the *sort conceptrefs ^ isrefs*, these are automatically derived from the data to the *sort concepts ^ hasrefs*.




```
form $concepts = conceptsmap:
{ (concepts ^ conceptsmap):
   { "physical"
      { (concepts ^ conceptsmap):
         { "mosque"
            { (concepts ^ conceptsmap):
               { "structural"
                  { (concepts ^ hasrefs):
                     { #om-concepts-26 "arcade"
                        { om-conceptrefs-5, om-conceptrefs-14,
                          om-conceptrefs-19 } },
                    (concepts ^ conceptsmap):
                     { "arcade"
                        { concepts:
                          { "spandrel" },
                         (concepts ^ hasrefs):
                          { #om-concepts-11 "arch"
                             { om-conceptrefs-2, om-conceptrefs-6,
                               om-conceptrefs-16, om-conceptrefs-23 },
                            #om-concepts-13 "dome"
                             { om-conceptrefs-3, om-conceptrefs-7 } },
                         (concepts ^ conceptsmap):
                          { "arch"
                             { concepts:
                                { "tympanum" } },
                            "column"
                             { concepts:
                                { "column base",
                                  "column capital" } },
                            "dome"
                             { (concepts ^ hasrefs):
                                { #om-concepts-5 "crescent"
                                   { om-conceptrefs-1, om-conceptrefs-4,
                                     om-conceptrefs-29 } } } } },
... } } } } } } } };
```

Figure 3: *Diagrammatic definition of a recursive sort conceptsmap representing a (semantic) map of architectural concepts, and the (partial) description of an exemplar data form*

3 Mapping *sorts*

Sorts can be compared by matching their primitive *sorts* and constructive relationships. Matches can be identified, roughly, as equivalent, similar and convertible (Stouffs and Krishnamurti, 2002). This classification is considered from the perspective of possible data loss and on the basis of syntactic and semantic similarity. Two *sorts* are *equivalent* if these are related under semantic identification, e.g., one is semantically derived from the other. For example, the *sorts concepts* and *conceptrefs* (5) are equivalent. Equivalent sorts are syntactically identical; this guarantees the exchange of data without data loss, except for the loss of semantic identity. Two *sorts* are denoted *similar* if these are similarly constructed from equivalent *sorts*. For example, the *sorts conceptstree* (4) and *concepts* + *concepts* ^ *conceptsmap* would be considered similar, if only the *sorts conceptstree* and *conceptsmap* were similar. However, comparing the *sorts conceptstree* and *conceptsmap* only results in a partial match: the *sort conceptstree* matches a part of the *sort conceptsmap*, where the corresponding parts are similar under this partial match.

The similarity of *sorts* relies on the existence of a semi-canonical form, specifying a composition over sum of one or more *sorts*, each of which is a composition over the attribute constructor of one or more primitive *sorts*. Associative and distributive rules with respect to the constructors of sum and attribute allow for a syntactical reduction of *sorts* to this semi-canonical form (Stouffs and Krishnamurti, 2002), e.g.:

$$\begin{aligned} &a \wedge (b \wedge c) = a \wedge b \wedge c = (a \wedge b) \wedge c \\ &a + (b + c) = a + b + c = (a + b) + c \\ &a \wedge (b + c) = a \wedge b + a \wedge c \\ &(a + b) \wedge c = a \wedge c + b \wedge c \end{aligned} \tag{7}$$

The rules above are automatically applied to any *sort* structure; the respective *sorts* are considered identical. However, these rules do not take into account the operation of semantic identification. Consider, for example, the following associative rules over the attribute constructor:

$$\begin{aligned} &a \wedge (d : b \wedge c) \rightarrow a \wedge b \wedge c \\ &(d : a \wedge b) \wedge c \rightarrow a \wedge b \wedge c \end{aligned} \tag{8}$$

Though syntactically identical, these *sorts* cannot be considered identical; converting the left-hand-side into the right-hand-side would induce a loss of semantic information. These rules are not automatically applied to the specification of a *sort*, but only when comparing *sorts* based on their semi-canonical form. Similarly, the following distributive rules serve the reduction of *sorts* to their semi-canonical form for the comparison of *sorts*:

$$a \wedge (d : b + c) \rightarrow a \wedge b + a \wedge c$$
$$(d : a + b) \wedge c \rightarrow a \wedge b + a \wedge c \quad (9)$$

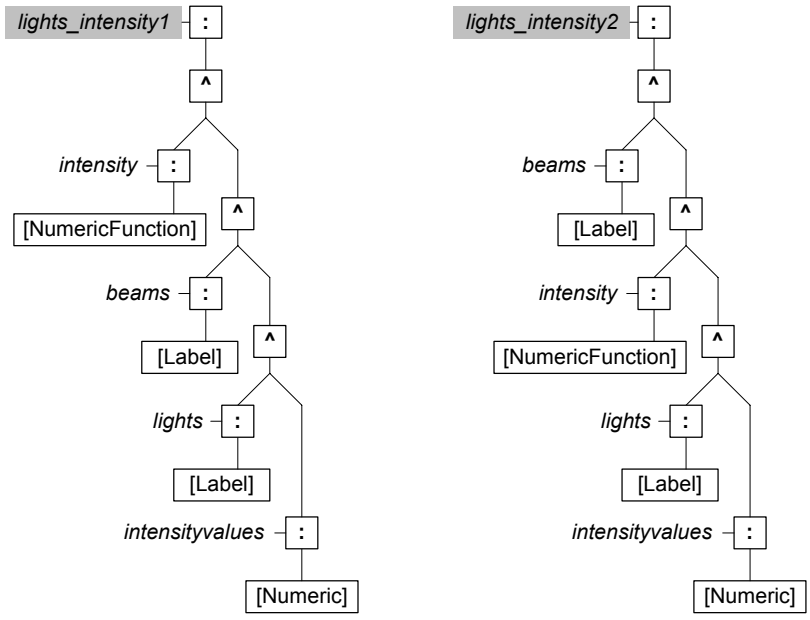
In general, if two *sorts* can be reduced to the same semi-canonical form, then these *sorts* are considered similar. No data loss, except for the loss of semantic identity, occurs when exchanging data between similar *sorts*. In the case of a partial match, data exchange without data loss will apply from the part to the whole if the parts are similar. In the opposite direction, the occurrence of data loss is dependent on the actual data that is exchanged. For example, converting data from *conceptstree* to *conceptsmap* involves no data loss; a tree structure is a special instance of a network or map structure. Converting data in the other way may involve data loss; the data lost in this case is the identification of shared concepts even if each copy of these concepts is fully expanded in a depth-first traversal.

If two *sorts* are constructed from the same equivalent *sorts* but cannot be reduced to the same semi-canonical form, then, these are considered *convertible*. For example, *points* ^ *labels* and *labels* ^ *points* are considered convertible. Whether data loss occurs when data between convertible *sorts* is exchanged depends on the specifics of the primitive *sort*s, in particular, their behavioral specification (Stouffs and Krishnamurti, 2002).

Figure 4 illustrates two *sorts* built from the same primitive *sorts* using only the attribute constructor, but considering the primitive *sorts* in a different order. These primitive *sorts* are the *sorts lights* and *beams*, both of labels, *intensityvalues* of numeric values, and *intensity* of numeric functions:

lights : [Label]
beams : [Label]
intensityvalues : [Numeric]
intensity : [NumericFunction] (10)

Consider lighting design for a stage or TV studio: a number of lights are selected and positioned, and placed on a stand or attached to a beam. Next, electrical cables are strung in order to power the lights. When laying out these cables, the intensity (wattage) of the lights on each beam has to be considered. The use of numeric functions as a data type enables numeric functional behavior to be integrated into data constructs. Numeric functions specify both a functional description, a *sort*'s property attribute as argument, and a result value. The result value is automatically recomputed using the functional description over the *sort*'s property attribute each time the data form is traversed, e.g., when visualizing the data. In the lighting example, this property attribute is the numeric value of the *intensityvalues* entities (see the exemplar data forms in Figure 4).




```
form $lights = lights_intensity1:
{ sum(intensityvalues.value)
   { "beam1"
      { "light1"
         { 100 },
        "light2"
         { 150 } },
    "beam2"
      { "light3"
         { 70 } } } };
```

```
form $lights = lights_intensity2:
{ "beam1"
   { sum(intensityvalues.value)
      { "light1"
         { 100 },
        "light2"
         { 150 } } },
  "beam2"
   { sum(intensityvalues.value)
      { "light3"
         { 70 } } } };
```

Figure 4: *Diagrammatic definition of two sorts that are considered convertible, and the description of corresponding data forms. Each data form is the result of converting the other data form to this form's sort*

The *sort lights_intensity1* represents numeric functions that apply to beams that have lights that have an intensity value; the *sort lights_intensity2* represents beams that consider numeric functions that apply to lights that have an intensity value:

$$\begin{aligned} &\textit{lights\_intensity1} : \textit{intensity} \wedge \textit{beams} \wedge \textit{lights} \wedge \textit{intensityvalues} \\ &\textit{lights\_intensity2} : \textit{beams} \wedge \textit{intensity} \wedge \textit{lights} \wedge \textit{intensityvalues} \end{aligned} \tag{11}$$

The position of the numeric function in the structure defines its scope. Consider the two data forms presented in Figure 4. On first inspection, these seem to contain the same data, even if their organization is slightly different. The design consists of two beams. The first one has two lights with intensity values of 100 and 150, and the second has one light with an intensity value

of 70. The numeric function is in both cases the sum function applied to the numeric value of the *intensityvalues* entities, i.e., 100, 150 and 70. However, in the first example, the scope of the single sum function is the entire design, and the result of the function will be the sum of all three values, thus, 320. In the second example, each beam possesses a sum function, the scope of which is only the lights attached to this beam. The respective results will be 250 and 70.

Since the two *sorts lights_intensity1* and *lights_intensity2* are constructed from the same primitive *sorts*, they are considered convertible. Converting each data form according to the *sort* of the other data form will result in the other form. Therefore, when converting data between the *sorts lights_intensity1* and *lights_intensity2*, data loss as such does not occur because reconverting the data to the first *sort* results in the original data form. At the same time, the data in both views is not identical.

4 Manipulating *sorts*

All examples considered above illustrate how incremental changes to representational structures can yield alternative design views that offer new functionality or answer design queries. Figure 1 presents three alternative examples of how adding a new *sort* to an existing *sort* can expand the functionality of this *sort*. In these examples, a collection of named drawings or a layout of drawings is represented using a *sort* that is a composition of a given *sort* for a single drawing and a *sort* of labels, points, or labeled points, under the attribute constructor. The opposite action of removing a *sort* can similarly be considered to support a different design view, in the case of the examples, one drawing out of a collection of drawings. Figures 2 and 3 similarly illustrate two *sorts* where one can be considered as an extension of the other. These *sorts*, *conceptstree* and *conceptsmap*, support related data structures, the one hierarchical, the other a hierarchical structure with shared nodes. This extension of *conceptstree* to *conceptsmap* requires the specification of one new primitive *sort*, with the *aspects hasrefs* and *isrefs*, as well as the semantic derivation of *conceptrefs* from *concepts*. Finally, Figure 4 shows how a small change in the compositional structure, in this case switching the position of two adjacent *sorts* in a series of attribute relationships, can yield two different design views that answer two different queries.

The same actions can also lead to more far-reaching changes. Merging two *sorts* together under a sum or attribute relationship, selecting, and extracting a part of a *sort* as a new *sort*, and altering the compositional structure by redefining the hierarchical order, all can be considered as incremental changes. The effect and reach of such change is very much dependent on the complexity of the *sorts* involved. We still consider the

change incremental if it involves only a single action by the user. Merging a *sort* into another requires the *sort* and its intended location in the other *sort* to be identified. Depending on the compositional structure of both *sorts* near the point of merging, changes in these respective structures may be necessary in order to achieve a new structure that complies with the definition and representation of a *sort*. Extracting a part of a *sort* requires this part to be selected. The exact boundaries of this selection can be made dependent on the need to minimize data loss through maximal compatibility.

Altering the compositional structure by redefining the hierarchical order can be achieved by selecting an entity from the representational or data structure in order to bring this to the top of the structure. We consider this action to be an expression of focus. For example, object-oriented models often adopt a hierarchical structure of functional objects at various levels of detail, reflecting upon an increasingly narrower information focus. Similarly, architectural design models are commonly organized by a hierarchical classification of functional areas, such as buildings, floors, and zones, in that order. The attribute relationship serves as a prime example, leading the focus onto the object of the relationship, while the attribute expresses a qualifier with respect to this object. For example, in an architectural design description, spatial information is commonly considered more important such that other information entities are assigned as properties to the relevant spatial entities. Thus, expressing a focus onto the representational or data structure can result in a transformation of the hierarchical structure that raises the entity under focus towards the top of the structure.

Such a transformation can be achieved automatically by reversing attribute relationships. For example, consider a primitive *sort b* in a composition with *sorts a* and *c* under the attribute constructor. Then, the following rule specifies a transformation that raises the entity *b* to the focus:

$$a \wedge b \wedge c = (a \wedge b) \wedge c \rightarrow (b \wedge a) \wedge c = b \wedge a \wedge c \tag{12}$$

Since semantic identity cannot be maintained under such transformation, reduction rules for the syntactical reduction of *sorts* to their semi-canonical form can be used to assist in the above transformation.

From this, we can derive that incremental manipulations of representational structures can support the exploration of alternative design views. While each action may yield only a small step, a series of incremental changes may lead the user from one desired design view to another and enable design information to be mapped accordingly. Furthermore, these incremental changes may give the user insight into the composition of the representational structure and its data and into the potential for alternative design views. We are currently developing a graphical interface to *sorts* that allows for the creation of representational structures as *sorts* and of

corresponding data forms. We envision its extension to support the manipulations here described.

5 Conclusion

Both support of alternative design views and an expression of arbitrary design questions require flexible design information models and representations that can be modified and geared to the kinds of views and queries. Then, exploring design views and design queries may be achieved by manipulating the representational structure through incremental changes. Such actions may also lead to a conceptual understanding of the representational structure. Effective visualizations of the data structure, combined with intuitive ways of manipulating this structure, can further support such understanding.

Sorts enable the development of alternative representations of a same entity or design; the comparison of representations with respect to scope and coverage; and the mapping of data between representations, even if their scopes are not identical. Alternative design representations can be defined as variations on a given *sort*, by altering the constructive entities or the composition. Comparing sorts not only yields a possible mapping but also uncovers the potential for data loss when moving data from less restrictive to more restrictive representations. As such, reorganizations can be guided in order to maximize compatibility with the original representation and minimize data loss.

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References

Bazjanac V (1998) Industry Foundation Classes: bringing software interoperability to the building industry, *The Construction Specifier* 6/98, 47-54.

Groth, DP, and EL Robertson (1998) Architectural support for database visualization, *Proceedings of the 1998 Workshop on New Paradigms in Information Visualization and Manipulation*, ACM Press, New York, NY, 53-55.

ISO (1994) *ISO 10303-1, overview and fundamental principles*, International Standardization Organization, Geneva.

Mäntylä, M (1988) *An Introduction to Solid Modeling*, Computer Science Press, Rockville, Md.

Snyder J, and U Flemming (1999) Information sharing in building design *in* G Augenbroe, C Eastman (eds), *Computers in Building*, Kluwer Academic, Boston, 165-183.

Stouffs R, and R Krishnamurti (2001) On the road to standardization *in* B de Vries, J van Leeuwen, H Achten (eds), *Computer Aided Architectural Design Futures 2001*, Kluwer Academic, Dordrecht, The Netherlands, 75-88.

Stouffs R and R Krishnamurti (2002) Representational flexibility for design *in* JS Gero (ed), *Artificial Intelligence in Design '02*, Kluwer Academic, Dordrecht, The Netherlands, 105-128.

Stouffs R, R Krishnamurti and CM Eastman (1996) A formal structure for nonequivalent solid representations *in* S Finger, M Mäntylä and T Tomiyama (eds), Proceedings of *IFIP WG 5.2 Workshop on Knowledge Intensive CAD II*, International Federation for Information Processing, Working Group 5.2, 269-289.

Tunçer B, R Stouffs and S Sariyildiz (2002) Document decomposition by content as a means for structuring building project information, *Construction Innovation* **2**(4), 229-248.

van Leeuwen JP, and S Fridqvist (2003) Object version control for collaborative design *in* B Tunçer, S Özsariyildiz, S Sariyildiz (eds), *E-Activities in Building Design and Construction*, Europia Productions, Paris, 129-139.

van Leeuwen J, A Hendrickx and S Fridqvist (2001) Towards dynamic information modeling in architectural design, *Proceedings of the CIB-W78 International Conference IT in Construction in Africa*, CSIR, Pretoria, South Africa, 19.1-19.14.

Woodbury R, A Burrow, S Datta and T Chang (1999) Typed feature structures and design space exploration, *Artificial Intelligence in Design, Engineering and Manufacturing* **13**(4), 287-302.