

Specifying and Implementing Constraints in GIS—with Examples from a Geo-Virtual Reality System

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Abstract Constraints are important elements of every modelling process, but until now they have been treated in an ad hoc manner, depending on the specific application domain and the capabilities of the tools used. In GIS and GeoVR applications, constraints are conditions which always have to be valid (true) within the model populated with real geographic object instances. This paper argues that constraints should form a systematic part of the object class definition, similar to other aspects of the definition, viz. attributes, methods and relationships. Also, the implementation of constraints in all GIS and GeoVR subsystems (at front-end, database and exchange (I/O) level) should be derived automatically from the constraints specified by the framework. The paper therefore puts forward a framework for modelling constraints comprising (1) a classification and clarification of constraints, (2) a formal description using the unified modelling language/object constraint language (UML/OCL) and (3) implementation characteristics. The components of the framework are illustrated and applied to SALIX-2, a geo-virtual reality (GeoVR) landscape modelling system.

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1 Introduction

This paper discusses the important, but often underestimated, role of constraints when modelling geo-information and how to implement them in geographic information systems (GIS), in particular those extended to include Virtual Reality (VR) options, known as ‘GeoVR’. Constraints are conditions which must always be fulfilled by the user and the data processing functionality of the GeoVR application. So far, unfortunately, they have been treated in a very ad hoc manner, differing from one application to another, because of the lack of an adequate and extensive formal approach. They are very important in most applications, and some functions (e.g., linear programming in spatial decision support systems, least squares adjustment of survey data, cartographic generalisation) are based partially on constraints. However, they are not an integral part of a system development procedure, hence their specifications and implementation are often implicit, ‘hidden’ in the application’s source code. It will therefore be very difficult to maintain constraints and constrained objects, especially if the user of the application interactively modifies the object constraints. This is true with respect to GIS in general, but in the interactive and dynamic environment of a GeoVR system the formalised support of constraints is even more essential. Throughout this paper we provide examples from a GeoVR system to illustrate the need for such formalisation and how it can be implemented.

Certain types of constraints are already supported at present. Domain value constraints and referential integrity constraints in relational data base management systems (DBMS) [7] are standard functionality: e.g., whenever one object references another object via a foreign key the DBMS checks if the referenced object actually exists, in other words whether the primary key value occurs (otherwise the transaction/change will not be committed). Another example, specific to GIS applications, is support for topological constraints (e.g., certain types of objects must not overlap). Such topology constraints can be supported by the DBMS, based on either LaserScan Radius topology [14] or Oracle Spatial 10 g with topology [20]. They can also be supported at client/edit level, as in the ESRI ArcGIS [6] environment. Referential integrity and topological correctness are just two examples of the various constraint types, however.

Constraints can be related to properties of the object itself, and they also can be based on relationships between two or more objects. Typical examples of a constraint relating to relationships between two objects are ‘a Yucca tree must never stand in water’ and ‘the boss’s salary must always be higher than those of the other staff’. Constraints such as ‘a tree must always be green’ or ‘a staff member’s pay should be higher or equal to the minimum statutory pay’ illustrate constraints based on thematic properties of one object only. Such constraints need a formal description and definition.

Constraints can be implemented at various levels (or subsystems) of an application, e.g., at front-end or user interface level (e.g., editing, simulation), at data exchange level and at database level. Currently, in geoVR systems, many constraints are implemented as object behaviour (and thus maintained in the

application): for example, the constraint ‘two trees (objects) cannot grow at the same location’ can be implemented (hard-coded in the editing environment) by means of collision detection, a well-known computer graphics technique.

Despite the fact that support for constraints is still incomplete or fragmented in practice, there has been some research in this area. First of all, constraints have some relationship to issues such as data quality [11] and the stage and source of the errors [6]: data collection, data input, data storage, data manipulation, data output or use of results. Cockcroft [4] was one of the first researchers to put forward a taxonomy of such spatial integrity constraints. One of the things the current paper sets out to do is refine this taxonomy. Cockcroft [5] also argued that an integrated approach to handling integrity constraints entails developing a repository of data and constraints. The conclusion is that constraints should be part of the object class definition, like other aspects of the definition such as attributes, methods and relationships (generalisation/specialisation, part/whole and associations). The repository will be used by both the database and the application as a consistent source of integrity constraints. Here we continue these investigations into ways of managing constraints in an integrated system-wide manner and add the data exchange level as yet another part of the system where constraints are important. To this end we introduce a framework for object constraints based on the requirements of a GeoVR system for landscape modelling (SALIX-2).

The paper is organised in six sections. Section 2 discusses the goal and current functionality of the SALIX-2 system as an illustration of an interactive GeoVR and explains why it needs to be extended to include constraints maintenance. Sections 3 and 4 develop a conceptual framework for classifying and formally defining constraints respectively. Section 5 discusses the implementation of constraints, focusing specifically on the DBMS. The last section discusses the results and makes suggestions for further research. It should be noted that much of the material put forward is still at the conceptual stage; full implementation is still work in progress, though important parts have been completed and proven to work.

2 Constraints in GeoVR: The SALIX system

Combining GIS with Virtual Reality produces GeoVR, where the spatial extent and object properties of the VR part are based upon data provided by the GIS part. The SALIX-2 system is a GeoVR system of this kind, enabling a user to interactively manipulate (e.g., import, delete, move) new objects (trees, bushes, etc.) in a 3D landscape at will and find out how the planting objects will grow. It is designed to provide a three-dimensional digital workspace for landscape architects and students [13]. For example, SALIX-2 (Figure 1) offers functionality for basing the location of planting objects regarding attributes (e.g., height), but this is not obligatory: in fact the user is free to locate the planting objects where he likes. SALIX-2 is also used to prototype and test new findings from geo-visualisation research at Wageningen University, in particular the GeoVR framework approach [1]. Using SALIX-2 in design studios provides information on the impact of VR facilities [10] on landscape architecture students’ progress in spatial thinking and reasoning. Examples of such VR facilities are ‘1:1 scale’ navigation, simulating growing processes on demand, alternating between architectural primitives and architectural objects, and quick transition between different views and projections.

Fig. 1 3D scene in SALIX-2: an interactive landscape modelling system



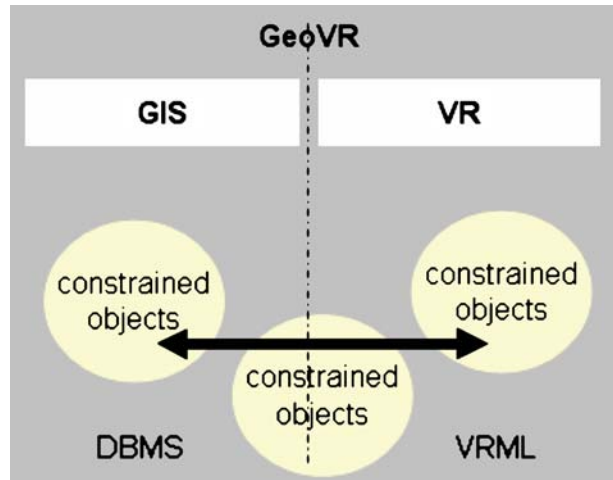
During the design practicals it was found that students defined a brief, as the starting condition, and design rules during the design process. Both types of design constraints have to be satisfied by the results. As is the case in reality, these constraints are related to planting objects (trees, bushes) that have to fulfil conditions such as (1) being at a certain distance from one another (e.g., two trees have to be planted no closer than 3 metres to and no further than 6 metres from each other), (2) having to form other objects (e.g., a number of trees in a certain pattern together forming a hedgerow), or even (3) not being allowed to be planted in a given area (e.g., no trees on a road).

As in a real world situation, a student should be restricted from planting on particular areas and objects: e.g., trees must not be planted in the middle of the road. The system therefore has to be explicitly provided with constraints relating to types of planting objects and geo-information objects which are well defined and can be maintained and changed easily through a formal procedure.

Our proposed framework for object constraints identifies three different aspects: 1. classified and clarified constraints, 2. a formal description in a modelling language, 3. implementation at front-end, interface and database level (Figure 2). Depending on the type of constraints (and the application), some constraints can be best implemented at the front end (e.g., Edit, Move), others in the DBMS, and yet others in the exchange protocol.

This paper focuses on the constraints to be implemented at database level by the DBMS. There are two reasons for this choice. The specifications of some constraints have to be easily accessible and intuitive to the user: these could be included in the object model, which needs to be as formal as possible. This makes it easier to update and change constraints. It also enables the user to be informed what kinds of constraints are available: for example, there could be a simple list of all the maintained constraints or a more sophisticated attempt-alert in the user interface. Secondly, DBMSs are based on SQL92, and since SQL92 the 'general constraints'

Fig. 2 Constraints in GeoVR: front-end (right) specific, data-base (left) specific and exchange oriented (arrow)



(assertions) have been part of this standard, they could be used to implement the OCL constraints. Assertions are not supported in the DBMSs currently available; however, developers are referred to the use of triggers and procedures. Assertions may be considered as an intermediate step between UML/OCL and the actual implementation of constraints using triggers and procedures in the DBMS. The paper illustrates the implementation of constraints for SALIX-2 in a DBMS using triggers (see Section 5).

3 Classification of constraints

Classification of the different types of spatial etc. constraints reveals a complex taxonomy. Cockcroft [4] puts forward a two-dimensional taxonomy of these constraints, where the first axis represents the static versus transitional (dynamic) distinction and the second axis the classification into topological, semantic and user constraints. While we recognise that the transitional aspect of integrity constraints (allowed and valid operations) is relevant, in this paper we regard it as the other side of the same coin. We refine the second axis of Cockcroft's taxonomy by recognising five sub-axes (different criteria) for the classification of integrity constraints:

- (1) The number of objects/classes/instances involved. Constraints can be related to:
 - a single instance (restrictions on attributes and the relationship between attribute values of a single instance)
 - two instances of same class (binary relationship)
 - multiple instances of the same class (aggregate)
 - two instances of two different classes (binary relationship)
 - multiple instances of different classes (aggregate)

- (2) The type of object *properties* and *relationships* between the objects involved:
 - metric (distance or angle between objects)
 - topological (neighbourhood or containment)
 - temporal
 - thematic (semantic)
 - complex: a combination of the above
- (3) The dimension (related to the 2nd sub-axis):
 - spatial dimension (2D, 3D)
 - temporal dimension
 - mixed time and space, i.e., 4D
 - thematic measurement scale
- (4) The manner of expression:
 - ‘must never’ (a bush must never stand in water) or
 - ‘must always’ (a tree must always be planted in open soil)
- (5) The nature of the constraint:
 - ‘theorem-based’ (e.g., physically impossible: a tree cannot float in the air)
 - ‘design-based’ (e.g., bush should be south of tree)

In practice the way constraints are expressed is only important when it comes to communication between users. Once the object and the constraints have been formally defined, the expressions ‘must never’ and ‘must always’ can be represented by a single constraint, viz. the one that is more efficient from the implementation point of view: for example, the constraint ‘a tree must never be in water, in the street or in a house’ is equivalent to the constraint ‘a tree must always be in a garden or park’, assuming there are only five possible objects on the ground, water, street, house, garden and park. The second expression would seem to be more efficient, as it requires only two classes to be considered.

Further elaboration will be given upon sub-axes 2 and 3, i.e., constraints with respect to object attributes and spatial relationships, and dimension.

3.1 Constraints derived from spatial etc. relationships between objects

The components of the proposed classification of integrity constraints based on relationships are as follows:

- (1) *Spatial*, with the following subtypes of relationship constraints:
 - *Direction*: trees should be always south of paving polygons, so people can walk in the sunshine’.
 - *Topology*: ‘no trees or bushes inside water polygons; no trees or bushes inside paving polygons’.
 - *Distance*: ‘no trees in water, except if <1 metre from edge of water bushes and >1 metre from paving (so the leaves do not overlap with the paving)’.
- (2) *Temporal*: ‘bushes may only be located after trees have been positioned’ (adjacent in time).

- (3) *Thematic* (with semantics not related to spatial or temporal relationships): ‘a parcel must always be owned by at least one person’.
- (4) *Mixed, e.g., quantity (or aggregate)*: ‘maximum of 10 planting objects in a specified area in the centre of the park’.

The formalisation of such relationship constraints is closely related to that of spatial etc. associations between the objects. We suggest using the same mechanisms for defining constraints as for describing associations between objects.

Direction constraints are based on the formalism for directional relationships [21]. A directional relationship is defined as the position of an object in relation to another object, and the directions can be stated as degrees in the range $[0^\circ, 360^\circ]$ or as verbal expressions (Northeast, North, Northwest, West, Southwest, South, Southeast, East). The second approach is in fact a generalisation of the first one, since each expression stands for an interval in degrees. Algorithms can also be written to assign the correct direction to an object.

Topological constraints are constructed using frameworks for neighbourhoods [8], [3]. The 9-intersection topology model, also recommended in the OGC/SFS standard, [17] utilises the fundamental notions of general topology for topological primitives to investigate the interactions of spatial objects. The basic criterion for distinguishing between different relationships is the detection of empty and non-empty intersections between the interior, exterior and boundary of objects. The maximum number of detectable relationships between two objects is 512 in theory, but only a small proportion of them are possible in reality. Eight relationships are given names, viz. *disjoint*, *meet*, *contains*, *covers*, *inside*, *covered by*, *equal* and *overlap*: for example, if the boundaries of the two objects intersect but the interiors do not, the conclusion is that the objects *meet*. The constraint ‘no bush in water’ can be translated into ‘no point-in-a-polygon’ (assuming a bush is represented as a point and water as a polygon), which corresponds to the topology relationship ‘not *inside*’.

Distance constraints impose a constraint on a Euclidean distance between objects. They can be expressed in linear metres or by more approximate linguistic terms such as ‘closer than’, ‘further than’ or ‘interval distance’.

Temporal constraints are specified on the basis of frameworks for describing temporal relationships between objects [22]. The temporal relationships between two time intervals are described in [12]. Given two time intervals, there are seven distinct ways in which they can be related (*before*, *meets*, *overlaps*, *finishes*, *during*, *starts*, *equals*). The relationships can relate to two time intervals or can be seen as existing between two objects with a certain time interval as the existence time (with the start and end time of existence marking the boundaries of the time interval).

Thematic constraints are similar to the relationship constraints found in business logic for non-spatio-temporal systems. Finally, it is common to mix these fundamental types of relationship constraint. Specifying a certain density of objects in a certain area by quantity (or aggregate) constraints is only implicitly related to spatial relationships. Once the distribution of objects in a certain area is known, the minimum distance between two objects can be computed and, if appropriate, the approach for metric constraints can be used. From the user’s point of view, however, a more intuitive approach will be to specify a number per given area. This constraint can be stated as a minimum, exact or maximum number of objects related to a surface area (density). Examples of density constraints are the maximum number of houses in a residential area or the minimum number of trees there. Examples of

exact number are one tower, three benches and one statue must be placed in this garden. This exact number of certain objects can be seen as a special case of a density constraint, as it can be defined as an exact number of certain objects for the whole area (i.e., the area in the 3D model).

3.2 Constraints derived from properties of objects

In this category, constraints on the value of object properties (attributes), we can make a similar distinction as in the case of relationship constraints. We shall discuss the following three categories of property constraints: thematic (non-spatial business-logic-based), temporal, and spatial (area, perimeter, length).

Thematic information about objects (with non-spatial temporal semantics) can be found in their attributes (e.g., house, road, grass). Some objects of the same type have relationships with objects of another type, e.g., all objects that are *houses* have a relationship with all objects that are *roads*. In interactive modelling, real-world thematic relationships between objects are used to formulate constraints that are understandable to the user, e.g., houses must be placed near roads so as to be accessible. The constraints in such cases are usually mixed with spatial constraints (e.g., ‘near’ in the example above).

Temporal property constraints specify allowed values for one or more of the time attributes, e.g., the start time (birth) of an object must be before the end time (death) of that same object. Other temporal property constraints may specify valid values for time attributes, e.g., the date/time associated with a historic event must be in the past.

Spatial constraints can be associated with spatial properties of an object such as size or shape. An example of a size constraint is ‘a tree should not grow higher than 30 m’ and a constraint on shape could be ‘a bush must be represented by an egg shape’.

3.3 Dimensional aspects of constraints

The last aspect to be discussed here relates to dimension. Generally speaking, all the different kinds of spatial relationship constraints can be specified for both 2D and 3D objects. Constraints can apply to the 2D ground plane or the 3D objects (bushes and trees) that could be placed on the ground plane to create a spatial configuration. The rules concerning the ground plane are based on the planning policy for a certain area and the fact that designations could conflict with one another. Policy makers lay down designations for each area and record them in plans. These designations for the ground plane can easily be stored as additional attributes of the separate polygons. The restrictions laid down by the policy makers could still conflict, however: e.g., a road can never be sited in water (except where a bridge or tunnel is built), a forest can never be sited on a major road and all houses should be accessible by a path or road. On the other hand, such conflicting constraints could also be a source of strategic spatial decision-making. The rules for 3D objects can even be more complex.

3.4 Constraints selected for implementation in SALIX-2

The SALIX-2 system currently maintains three object classes, *trees*, *bushes* and *ground surface*. The possible ground surfaces are *water*, *paving*, *soft paving*, *grass* and *bridge*. The possible types of trees and bushes for use in planning are five

(CorAve, CorMas, RosCan - bushes -, FraxExc and QueRob - trees-). Examples of rules for the positioning of objects in GeoVR environments are: ‘a tree (object a) must not overlap with water (object b)’, and ‘a tree (object a) must be covered by a polygon with the function ‘forest’ (object b)’. For these constraints it makes sense to represent a tree as a circle (an extended object) rather than a point (a centroid). Table 1 shows some examples of constraints for SALIX-2.

4 Formal description of constraints

In the second part of the proposed framework, constraints have to be included in the object model, which should be as formal as possible so that constraint implementations can be derived within the various subsystems (Edit, Store, Exchange). Formal modelling is an essential part of every large project, but it is also very helpful in small and medium-size projects. A formal model enables ideas to be communicated with other professionals as well as providing a clear, unambiguous view of implementation strategies. Surveys have shown that large software projects have a high probability of failure if formal approaches are overlooked.

Here we shall use Unified Modelling Language (UML), a standard for object-oriented modelling [18, Chapter 3]. UML is a graphic language which provides a wide range of ways of representing objects and their static and dynamic relationships. In general it can be used to model business processes, classes, objects and components, as well as for distribution and deployment modelling. UML consists of diagram elements (icons, 2D symbols, paths, strings), which can be used in nine different diagrams. The most appropriate diagram for describing static constraints is the class diagram, which provides a formalism for describing objects/classes (with their attributes and behaviour) and the relationships between these objects, such as association, generalisation and aggregation.

Dynamics of objects (temporal constraints) can be modelled using one of the interaction diagrams, i.e., a sequence or collaboration diagram. While the former

Table 1 Examples of constraints for SALIX-2.

Type of relationship	Constraints with forced relationships between objects
Direction	A bush must always be placed south of a tree (1 predicate)
Topology	Bushes must always be disjoint or meet water (2 predicates) A bush must always meet or be disjoint with paved areas (also thematic constraint) (2 predicates)
Metric	Trees must always be positioned >1 metre from paving (1 predicate)
Temporal	An oak always grows for 70 years (1 predicate)
Quantity/ aggregate (sum)	There must always be at least 10 trees on the specified ground surface (1 predicate)
Thematic	A bush must always meet or be disjoint with paved areas (note the mix topological constraint) (2 predicates)
Complex	The distance between trees in water must always be >8 m and the distance between the tree and the edge of the water must always be <0.5 metre AND the species must be a salix Trees of type 1 must always be placed west of trees of type 2 and the distance between trees of type 1 and trees of type 2 must always be 7 metres (pattern)

enables the explicit sequence of events to be described (with respect to time), the latter shows the interaction organised around the roles in the interaction and their relationships (without an explicit temporal aspect). A collaboration diagram is suitable for designing interface software (e.g., user-system communication when a user attempts to plant a tree in a forbidden area). We shall not discuss this here, as the dynamic aspect is beyond the scope of this paper.

Notwithstanding the wide range of ways of formalising objects and processes, UML class diagrams are typically not refined enough to express all the relevant aspects of constraints, which, as discussed above, are often initially described in natural language. Practice has shown that this always results in ambiguities. In order to enable unambiguous constraints to be written, UML provides a non-graphic language for the modelling of semantics (knowledge frameworks), Object Constraint Language (OCL) [18, Chapter 6]. OCL is a pure expression language. When an OCL expression is evaluated it simply returns a value. Thus evaluating an OCL expression never changes the state of the system.

The advantage of using OCL is that—as in the case of UML class diagrams—generic (i.e., not GIS-specific) tools are available to support OCL. The context of an invariant is specified by the relevant class: e.g., the object class ‘parcel’ is the context of the constraint ‘the area of a parcel must be at least 5 m²’. It is also possible for a constraint to use an association between two classes (e.g., every instance of the object class ‘parcel’ must have at least one owner, which could be depicted as an association with the class ‘person’).

OCL enables expressions and constraints on object-oriented models and other object modelling artefacts to be described formally. In this context, an *expression* is an indication or specification of a value and a *constraint* is a restriction on one or more values in an object-oriented model or system (or part of it).

OCL expressions can be used in a number of places in a UML model to specify values and roles (e.g., an initial value of an attribute (or association end), a derivation rule of an attribute, the body of an operation) in a class diagram, or to indicate instances, parameters or conditions in dynamic diagrams. Four general types of constraints can be defined in OCL:

- An *invariant* is a constraint that states a condition that must always be met by all instances of the class, type or interface. An invariant is described using an expression that evaluates to be true if the invariant is met. Invariants must be true all the time.
- A *precondition* to an operation is a restriction that must be true at the moment that the operation is going to be executed.
- A *post-condition* to an operation is a restriction that must be true at the moment that the operation has just ended its execution.
- A *guard* is a constraint that must be true before a state transition fires.

Each OCL expression has a *context definition*, which specifies the model entity for which it is defined: this is usually a class, interface, data type or component. Sometimes the model entity is an operation or attribute, or—rarely—an instance. It is always a specific element of the model, usually defined in a UML diagram. This element is called the *context* of the expression. The standard OCL data types are integer, real, string and boolean. Operations include the standard operations such as +, −, /, *, and, =, <>, but also the boolean operators *implies* and *if-then-else*, which

enable more complex constraints to be formulated. The formal representation of context is as follows:

```
context Typename::operationName(param1 : Type1, ... ): ReturnType
pre : param1 > ...
post: result = ...
```

The context of an invariant is specified by the relevant class: e.g., ‘parcel’ if the constraint was ‘the area of a parcel must be at least 5 m²’. It is also possible for a constraint to use an association between two classes (e.g., ‘parcel’ must have at least one owner, which is an association with the class ‘person’). Below are two examples in UML/OCL syntax (keywords in bold print):

```
context Parcel inv minimalArea:
self.area > 5
context Parcel inv hasOwner:
self.Owner -> notEmpty()
```

The word ‘self’ is used to specify the context and is omitted in many cases, as it is obvious what is meant by the constraint without this word.

Figure 3 shows the UML class diagram with the objects and constraints (depicted as associations) used for SALIX-2 (as introduced in Section 2 and refined in Section 3, Table 1). In principle there is little difference between a ‘data model’ relationship (association, aggregation, specialisation) and a ‘data model’ integrity relationship constraint, both of which are depicted as lines in the UML class diagram. Normal associations are often indented in subsequent implementations so as to be explicitly stored (in one or both directions), however, whereas relationship constraints should not result in such storage (but in a consistency rule in the implementation environment). In order to distinguish between the two, normal relationships are depicted in black and integrity relationship constraints in colour. Notes (written in UML, OCL or natural language text) can be used in the diagram to explain the constraints on relationships and/or properties.

5 Implementation of constraints in the DBMS

The UML/OCL models managed in a repository should form the foundation for the user interface (e.g., Edit, Simulate) application environments, the storage data models (described in the DDLs of the DBMS) and the exchange data models. We shall not discuss the editing/simulation application environment here, apart from pointing out that it is very important to incorporate the integrity constraints from the model in these applications automatically. As regards data exchange, eXtensible Markup Language (XML) can be used for models containing the class descriptions at class level (XML schema document ‘xsd’) and for data at object instance level (normal XML document with data ‘xml’). XML documents also include the geometric aspect of objects (e.g., LandXML, GML, X3D). Here too more research is needed into the best way of incorporating integrity constraints in XML schemas. The UML models (inc. OCL) with constraints should be translated into XML schemas automatically. Note that this is different to encoding a UML model in an XML document using XML Metadata Interchange (XMI). In this section we

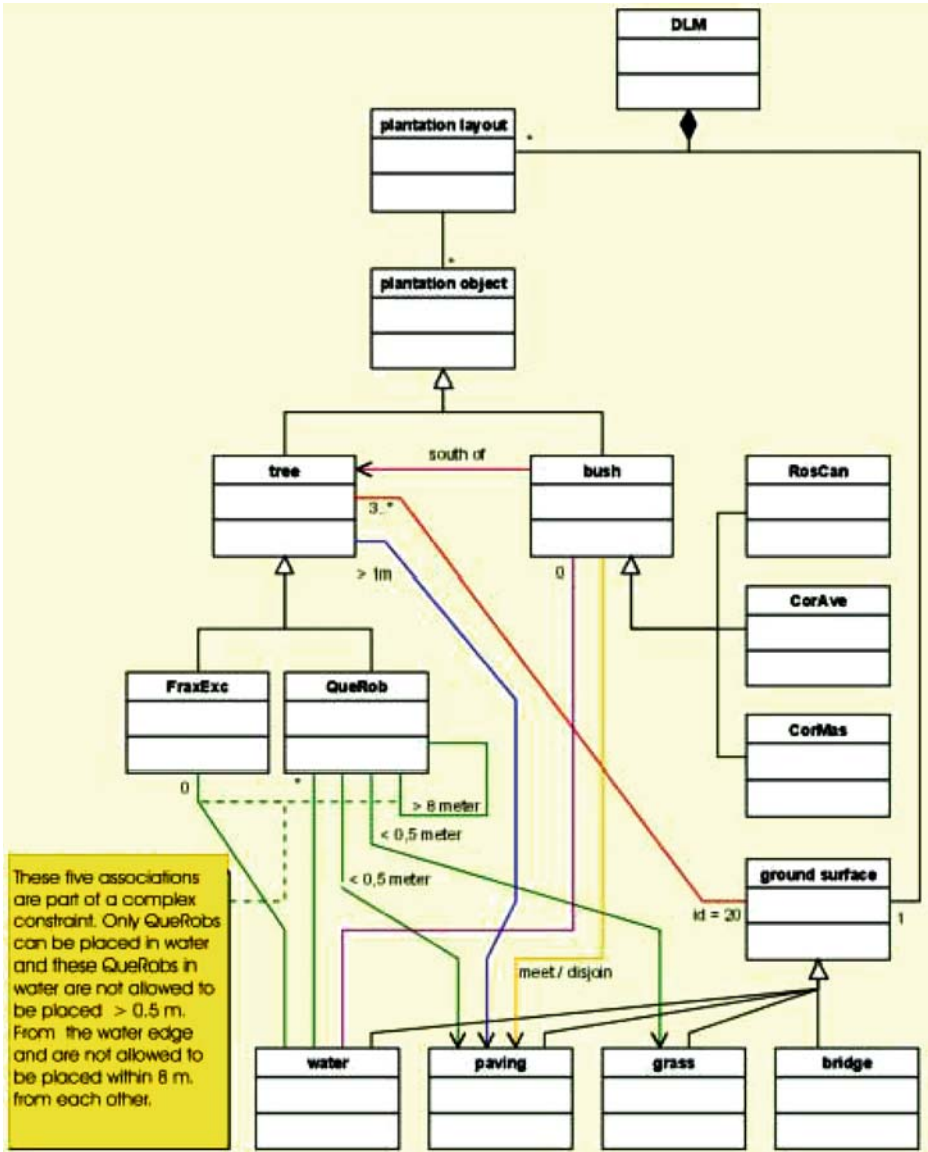


Fig. 3 UML class diagram representing the objects of interest in SALIX-2

illustrate the implementation of integrity constraints with database examples, mainly because of the relatively high flexibility when it comes to specifying integrity constraints.

The apparent benefit of front-end implementation is the direct interaction with the user (Figure 4). If a user places a planting object in the VRML scene, fast feedback on the validity of the placement can be provided if the constraints are also maintained in the visual environment (e.g., the VR component of the SALIX-2 system). Ways of changing constraints within the VR-environment are limited, however, as they are currently hard-coded in the VR application code, as they are in

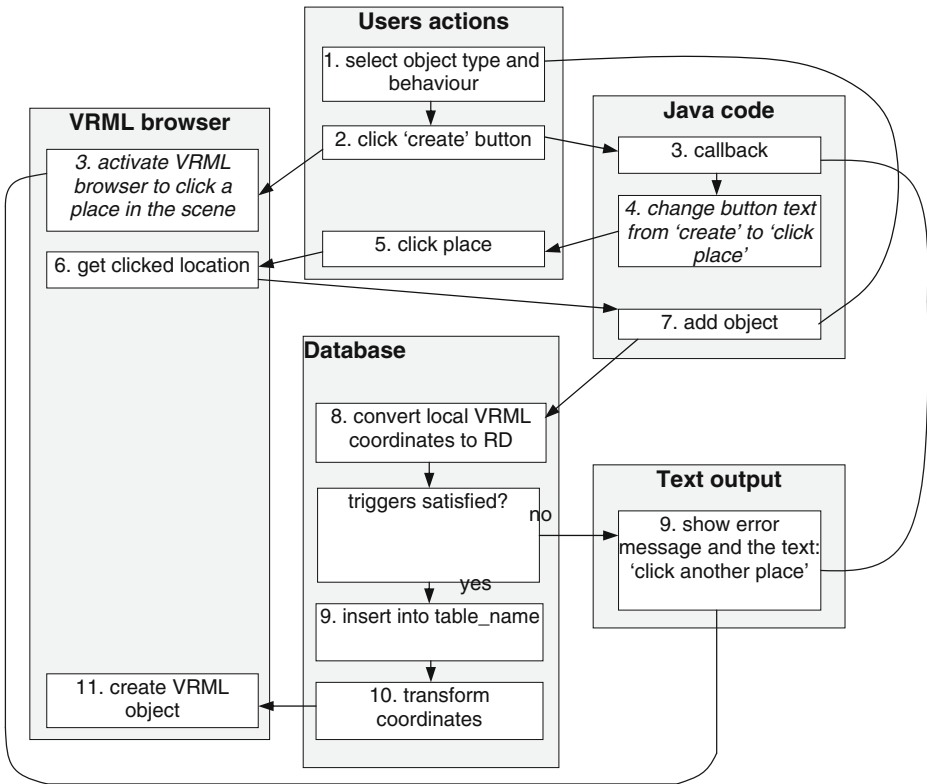


Fig. 4 Flowchart showing the interaction with the system SALIX-2 (with triggers)

many other editing/simulation environments (not managed centrally). In future development environments it should be possible to generate the part of the VR program application code that implements the constraints (as specified in UML/OCL) automatically.

Database implementation offers better management of constraints. If they are stored in a database, they are kept in a central place, easily accessible and therefore easily modifiable. As the VR application only connects to the database when saving or loading a planting plan (as with SALIX-2), however, there is no connection while the plan is being created (edited) interactively, so the user only receives feedback when the plan is saved, not when a planting object is placed. An obvious and simple improvement would be to connect to the database automatically after the user finishes a 'logical edit unit'. This would enable feedback to be provided immediately, generated by the database but displayed in the editing environment.

The ideal solution would probably be for all subsystems to support integrity constraints (especially in disconnected scenarios), i.e., storing the constraints in a database at a central location and encapsulating this information in the application code. This would significantly improve feedback from the system. The constraints are stored more than once, however, which could result in inconsistency between the subsystems. It is very important, therefore, that the implementation of the constraints in the VR environment is derived automatically so as to guarantee consistency.

5.1 Assertions in SQL92

We now discuss the possibilities of implementation at DBMS level. There are two possible ways of implementing constraints, using assertions and triggers. The syntax of an assertion ('general constraint') is as follows:

```
CREATE ASSERTION <assertion_name> CHECK <constraint_body>
```

This syntax is quite simple and straightforward. When an attempt is made to commit the changes to a database, after a set of updates, inserts, and deletes, the assertion is checked: if the expression evaluates 'true' the commit succeeds, otherwise it fails and the database remains in the old state (for which the expression was also 'true'). It is easy to imagine these assertions being generated automatically from the UML/OCL invariants, similarly to the way database table definitions (DDL) can be derived from UML class diagrams. Assertions are supported in standard SQL92, [7] but unfortunately they have not yet been implemented in any of the mainstream DBMSs (Oracle, DB2, Ingres, Informix, PostgreSQL, MySQL). Assertions are compact representations of integrity constraints in the database, however, and therefore form convenient intermediate representations of their final implementations in the database.

Let us now formulate a number of example constraints as assertions. The SALIX-2 tables used in the assertions are: `prcv_treesrd_point` (planting objects of the type trees and bushes) and `prcv_gvkrd_poly` (ground surface with the description water, paving, soft_paving, grass and bridge). We shall use the examples introduced in Section 2 and refined in Section 3, Table 1 and illustrated in Section 4, Figure 3.

Bushes must never be sited in water:

```
create assertion constraint_1 check (not exists (
  select * from prcv_treesrd_point t, prcv_gvkrd_poly g
  where t.treetype in ('CorAve', 'CorMas', 'RosCan')
  AND g.descript = 'water'
  AND sdo_relate (g.geom., t.geom., 'mask=inside, querytype=window')
  ='TRUE'))
```

A bush must always be placed south of a tree:

(This assertion requires a geometry that represents the restricted area: the geometry must first be created, which can be done using a function. Here we use the name 'fu_restricted_area' and the inputs to the function are two angles representing the direction and a maximum distance to restrict the search area. The function returns a geometry which has its basis in the location of the bush involved and can be used in the assertion.)

```
create assertion constraint_2 check (exists (
  SELECT * FROM prcv_treesrd_point t, prcv_treesrd_point b
  WHERE t.treetype IN ('FraxExc', 'QueRob')
  AND b.treetype IN ('CorAve', 'CorMas', 'RosCan')
  AND sdo_relate (t.geom,
  fu_restricted_area(first_angle, second_angle, distance, b.geom),
  'mask=ANYINTERACT, querytype=window')='TRUE'))
```

Trees must always be positioned >1 metre from paving:

```
create assertion constraint_3 check (not exists (
  SELECT * FROM prcv_treesrd_point t, prcv_gvkrd_poly g
  WHERE t.treetype IN ('FraxExc', 'QueRob')
  AND g.descript IN ('paving', 'soft_paving')
  AND sdo_within_distance (g.geom., t.geom., 'distance=1') = 'TRUE'))
```

There must always be at least three trees on the specified ground surface.
(this constraint uses the grass polygon with id 20).

```
create assertion constraint_4 check ( (
  SELECT count(t.treeid) FROM prcv_treesrd_point t, prcv_gvkrd_poly g
  WHERE t.treetype IN ('FraxExc', 'QueRob')
  AND g.id=20
  AND sdo_relate(t.geom, g.geom, 'mask=ANYINTERACT, querytype=
  window')='TRUE') >=3)
```

5.2 Triggers and procedures

The assertions look nice and are relatively easy to specify, but as mentioned above, they are not supported in the mainstream DBMSs. Triggers therefore offer the only practical way of implementing constraints at present. These can be seen as small programs that check certain conditions and give an alert with respect to them. The same effect, basically, can be achieved using triggers as by defining assertions. One functionally correct, but not very efficient, way of implementing assertions would be to combine all the boolean expressions of the individual assertions into one big boolean expression. This would be checked on each commit to the database (via a trigger and procedure) and if the result is false, the transaction fails. This is not a very efficient implementation, however, and here we shall use triggers and procedures in a more specific way. The user has to develop the specific code for the triggers (and the procedures used) himself, however: while this is more labour-intensive than specifying the higher-level assertions, it also provides additional functionality. Database triggers can be *before* triggers or *after* triggers, for example, and they can be row triggers or statement triggers. The order in which triggers are executed is critical to the DBMS. When there are two or more triggers of the same type the order in which they are executed is arbitrary. In the case of constraints it does not matter in what order they are checked, as they do not influence one another. The syntax for specifying a trigger is as follows:

```
CREATE [OR REPLACE] TRIGGER <trigger_name>
  BEFORE | AFTER
  INSERT OR UPDATE [<column(s)>] OR DELETE ON <table_name>
  [FOR EACH ROW [WHEN (condition)]]
  <trigger_body>
```

In order to avoid 'low-level' hand-coding of constraints (or business rules) Oracle provides a development tool called Custom Development Method (CDM) that generates this code for the DBMS automatically [16], [2]. The CDM RuleFrame is

the CDM's business rules implementation framework. The rules consist of three parts: [16]

- a function that indicates when the rule should be validated
- a function that performs the actual validation, if the previous function indicates that this is necessary
- a handling procedure that manages communication with the outside world

CDM RuleFrame does not check business rules at the moment the user performs insert, update or delete statements; instead it stacks the rules that have to be enforced and checks them only at the moment of commit. This stacking of rules and any business rule enforcement is done in the Transaction Management component.

5.3 Our implementation of constraints

For the time being, and for the purpose of illustration, we decided to convert and hand-code our constraints in SALIX-2 and use the Oracle *before* and *after* triggers. One *before each row* trigger is sufficient to implement the constraints. First the temporary table is updated, then constraint checking takes place. A stored procedure is used for each constraint check. The disadvantage of using only one trigger for the constraint implementation is that the user cannot enable or disable separate constraints (as database triggers). Consequently the opportunities for interaction are rather limited in our current simple prototype implementation, but using only one trigger is less complex than using more than one.

The constraint checking is organised as follows. For each insert or update statement relating to an object in the configuration table (with the trees and bushes that together form the planting plan) a *before each row* trigger is invoked. This first inserts all the new attribute values of the object involved in package variables. These attributes are easily accessible and can be used in all procedures and functions. All the procedures and functions are stored in a single package (named 'salix'). A check takes place if the object involved is a bush (first bold line in [Appendix](#)); then all the constraints concerning bushes must be checked (using functions and procedures). If the object involved is a tree, the constraints concerning bushes are of no interest and all the constraints concerning trees must be checked (also using functions and procedures). In addition, all the constraints that cannot have the object involved as a starting point are checked in the *after* statement trigger (in our case, for example, the quantity constraint relates to a specific ground surface polygon).

A partial example ('a bush must not stand in water') of a constraint implemented in a DBMS using triggers and procedures is shown in Box 1. In the front-end application a new object is created and an insert statement is sent to the DBMS. The statement is checked for integrity constraints (set of bold lines in [Appendix](#)) and feedback to the user is given through DBMS outputs. This output can be used by the front-end application. The constraint checking is done using triggers, packages, procedures and functions—all standard functionality in DBMSs. In the procedures more complex spatial etc. constraints can also be checked using PL/SQL, e.g., based on the operators available in Oracle spatial [19]. Further details of the implementation of concepts and a VR interface in SALIX-2 can be found in [15].

6 Conclusions

6.1 Results obtained

Constraints have not received much attention in GeoVR, despite the serious need for them, especially between objects. This paper proposes a classification of the constraint types relevant to a GeoVR based on five aspects: 1. the number of objects/classes involved; 2. the properties of objects and/or relationships between objects: metric, topological, temporal, quantity, thematic or mixed; 3. the dimension (2D or 3D or mixed time and space, i.e., 4D); 4. the manner of expression ‘must never’ or ‘must always’; and 5. the nature of the constraint: theorem or design-based.. We analysed and defined a number of constraints for our SALIX-2 system, a GeoVR simulator for landscape architecture.

The formalisation of spatial etc. constraints must be specified in UML/OCL. The implementation of different parts of the system should be derived automatically from this single specification (in future, as current development environments are not capable of supporting this). The constraints should be implemented in the front end (to enable users to receive immediate feedback during editing), in the database (to ensure that only valid data is stored and accepted), and during communication or data exchange in the case of loosely coupled clients and servers (to ensure that the client is aware of the constraints). Database assertions do seem to be quite close to UML/OCL invariants, so it is rather disappointing that they are not yet available in mainstream DBMSs, where constraints currently have to be implemented using triggers (and procedures). This is the approach we adopted to implementing (hand-coding) the different types of constraints for our SALIX-2 database.

6.2 Further research

The first step should be to develop a good mechanism for checking whether the constraints specified (as part of the object descriptions) conflict with one another. This study only involved a check beforehand (in the conceptual phase). If users can change the constraint definitions once the application has been created, a conflict check should also take place when constraints are changed. This aspect is also of interest in the case of existing software: for example, topology constraints can be implemented in ESRI (geodatabase) software, [9] but there is no check on whether the constraints conflict with one another (neither beforehand nor while the software is running). This can result in unwanted system behaviour, e.g., ‘an infinite loop’ correcting one error (according to rule 1) which results in another error (according to rule 2): there will never be a correct situation that satisfies both rules (integrity constraints).

In real interactive applications an end-user, i.e., a non-programmer such as a landscape designer, must be able to change, delete or make new constraints, so a way of creating constraint definitions interactively is needed. This is closely related to modelling: cf. the UML class diagram with all the relevant object classes and their-restricted-relationships.

The user should receive visual ‘feedback’ during editing, e.g., areas that turn red or green during an insert. These areas should be derived from constraints and the instance geometry in a DBMS based on spatial functionality (buffers, overlays, etc.).

Research is needed into whether these areas can be created in the DBMS (and presented as views) or using specific GIS software.

This could be extended to 2 1/2D or 3D referenced objects, the objects of interest and their-interrelated-constraints. The objects of interest are currently limited to point objects (planting objects) and polygon objects (ground surfaces), but could be extended to include volume (polyhedron) objects. Data types and operations for 2 1/2D and 3D geometry—which are indispensable to implementing 2 1/2D and 3D constraints concerning 2 1/2D or 3D objects—are not yet available in DBMSs, however.

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Appendix

1.1 Example PL/SQL code for triggers and procedures to implement constraints

```

CREATE OR REPLACE TRIGGER brt_all_salix
BEFORE INSERT ON prcv_treesrd_point
FOR EACH ROW
BEGIN
  – The treeid and the treetype of the object involved in the insert
  – statement are saved in a package.
  – These attributes can be used in the triggers, procedures and
  – functions. For the constraint checking in SALIX-2 they are
  – used to determine if the object is a tree or a bush and
  – only the corresponding constraints are checked
  pck_salix.treeid_io := :new.treeid;
  pck_salix.treetype_io := :new.treetype;
END;

CREATE OR REPLACE TRIGGER ast_salix
AFTER INSERT ON prcv_treesrd_point
BEGIN
  – constraint 1: a bush must never be placed in water; the existing
  – table with all objects has no bushes in water, so only
  – after each update or insert does a check have to take place if
  – the new location of a bush is in water. This can be
  – an after statement trigger.
IF pck_salix.treetype_io IN ('CorMas', 'RosCan', 'CorAve') THEN
  – the object is a bush, so all constraints concerning
  – bushes must be run.
  DBMS_OUTPUT.PUT_LINE('the object involved is a bush');
  pck_salix.pr_topology_c1;
  ELSE raise_application_error(-20099,'the object is a tree, no constraints have to be checked.');
```

```

CREATE OR REPLACE PACKAGE pck_salix
IS
  treeid_io NUMBER;
  treetype_io varchar2(15);
  – procedure to check constraint 1:
  – a bush can never be placed in water
  procedure pr_topology_c1;
END pck_salix;

CREATE OR REPLACE PACKAGE BODY pck_salix AS
–
– procedure pr_topology_c1: a bush can never be placed in water
–
PROCEDURE pr_topology_c1
IS
  description varchar2(15);
  xrd_io number;
  yrd_io number;
  bush_in_water EXCEPTION;
BEGIN
  SELECT g.description, t.geom.sdo_point_x, t.geom.sdo_point_y
  INTO description, xrd_io, yrd_io
  FROM prcv_gvkrd_poly g, prcv_treesrd_point t
  WHERE t.treeid = pck_salix.treeid_io
  AND sdo_relate(g.geom, t.geom, 'mask=anyinteract, querytype=window')
  = 'TRUE'
  GROUP BY g.description, t.geom.sdo_point_x, t.geom.sdo_point_y;
  IF description = 'water' THEN
    raise bush_in_water;
  ELSE DBMS_OUTPUT.PUT_LINE('1: the bush is not placed in water');
  END IF;
EXCEPTION
  WHEN bush_in_water THEN
    raise_application_error (-20001,
    '1: The bush (x='||to_char(xrd_io)||', y='||to_char(yrd_io)||') is
    placed in water (a bush must never be placed in water).
    Place the bush at another location. ');
END pr_topology_c1;
END;

```

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