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ISO/CD 10303-52

Product data representation and exchange: Integrated generic resource: Mesh-based topology

ABSTRACT:

This document provides general and application independent means of representing structured and unstructured meshes, and mathematical functions and numeric data defined over such meshes.

KEYWORDS: Mesh, Topology

COMMENTS TO READER:

Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation. The formal modeling uses EXPRESS edition 2. This document has been reviewed using the internal review checklist (see WG12 N2167), the project leader checklist (see WG12 N2168), and the convenor checklist (see WG12 N2169).

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75% of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 10303–52 was prepared by Technical Committee ISO/TC 184, *Industrial automation systems and integration*, Subcommittee SC4, *Industrial data*.

This International Standard is organized as a series of parts, each published separately. The structure of this International Standard is described in ISO 10303–1.

Each part of this International Standard is a member of one of the following series: description methods, implementation methods, conformance testing methodology and framework, integrated generic resources, integrated application resources, application protocols, abstract test suites, application interpreted constructs, and application modules. This part is a member of the integrated generic resource series. The integrated generic resources and the integrated application resources specify a single conceptual product data model.

A complete list of parts of ISO 10303 is available from the Internet:
`<http://www.nist.gov/sc4/editing/step/titles/>`

Annexes A and B form a normative part of this part of ISO 10303. Annexes C, D, and E are for information only.

Introduction

ISO 10303 is an International Standard for the computer-interpretable representation of product information and for the exchange of product data. The objective is to provide a neutral mechanism capable of describing products throughout their life cycle. This mechanism is suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases, and as a basis for archiving.

This part of ISO 10303 is a member of the integrated resources series. Major subdivisions of this part of ISO 10303 are:

— **mesh_topology_schema**;

— **mesh_connectivity_schema**.

— **mesh_function_schema**.

The relationships of the schemas in this part of ISO 10303 to other schemas that define the integrated resources of this International Standard are illustrated in Figure 1 using the EXPRESS-G notation. EXPRESS-G is defined in annex D of ISO 10303-11. The schemas identified in the bold boxes are specified in this part of ISO 10303. The **support_resource_schema** is specified in part 41 of ISO 10303. The **topology_schema** is specified in part 42 of ISO 10303. The **mathematical_constructs_schema** and the **mathematical_functions_schema** are specified in part 50 of ISO 10303. The **mathematical_description_of_distribution_schema** is specified in part 51 of ISO 10303. The **structural_response_representation_schema** is specified in part 104 of ISO 10303. The **ISO13584_generic_expressions_schema** is specified in part 20 of ISO 13584. Except for **ISO13584_generic_expressions_schema**, the schemas illustrated in Figure 1 are components of the integrated resources.

There are many applications that have to deal with massive amounts of data, which is normally numerical in nature. The quantity of data may be measured in gigabytes and in some cases terabytes. Examples include computational fluid dynamics, dynamic simulation of vehicle behaviour, and experimental data of many kinds ranging from high energy physics to global weather measurements.

A major concern in dealing with such data is to optimise the data representation and structure with respect to data transmission and storage. As part of the optimisation, the data tends to be maintained in large arrays where any particular data element can be referenced by a simple index into the array. When the data is part of a computer simulation the data is usually associated with a mesh of some kind — either structured or unstructured. The data may be bound to the vertices of the mesh or to the cells of the mesh. In any case, it is also possible to represent the simpler kinds of meshes by an indexing scheme. Within this part illustrative examples have been principally taken from the field of computational fluid dynamics.

This part of ISO 10303 provides general, application independent, means of representing indexible data and meshes.

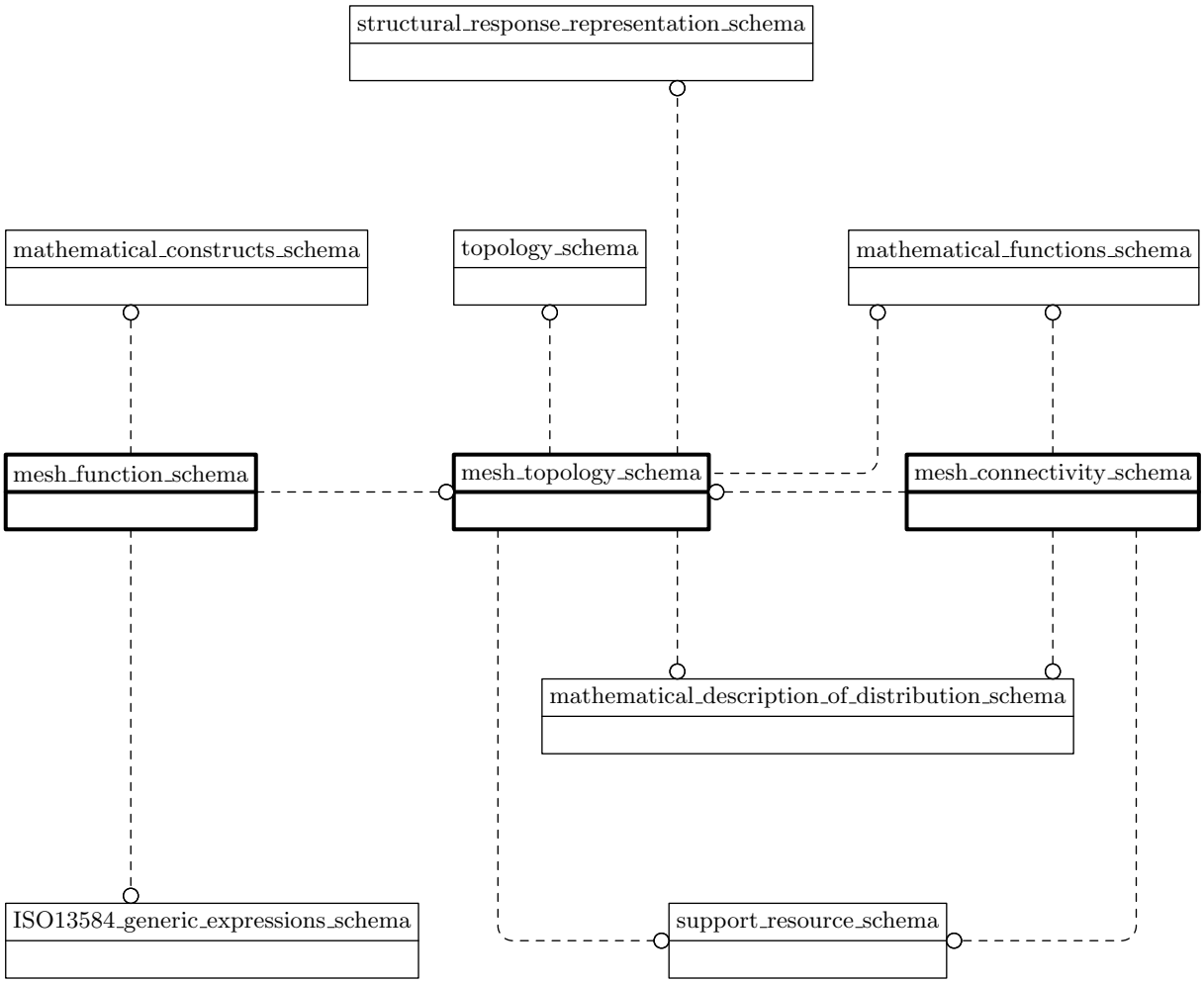


Figure 1 – Schema relationships

Industrial automation systems and integration — Product data representation and exchange — Part 52 : Integrated generic resource: Mesh-based topology

1 Scope

The following are within the scope of this part of ISO 10303:

— Mesh-based topologies;

— Cell connectivity and multiblock mesh interfaces;

— Mathematical functions defined over meshes;

— The association of numeric data with the cells, faces, edges, and vertices of a mesh.

The following are outside the scope of this part of ISO 10303:

— Applications of mesh topologies;

— Applications of mesh interfaces;

— The semantics of data associated with a mesh.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this international standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this international standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 10303-1:1994, *Industrial automation systems and integration — Product data representation and exchange — Part 1: Overview and fundamental principles.*

ISO 10303-11:2003, *Industrial automation systems and integration — Product data representation and exchange — Part 11: Description method: The EXPRESS language reference manual.*

ISO 10303-41:2000, *Industrial automation systems and integration — Product data representation and exchange — Part 41: Integrated generic resource: Fundamentals of product description and support.*

ISO 10303-42:2003, *Industrial automation systems and integration — Product data representation and exchange — Part 42: Integrated generic resource: Geometric and topological representation.*

ISO 10303-50:2002, *Industrial automation systems and integration — Product data representation and exchange — Part 50: Integrated generic resource: Mathematical constructs.*

ISO 10303-51:—[1)], *Industrial automation systems and integration — Product data representation and exchange — Part 51: Integrated generic resource: Mathematical description.*

ISO 10303-104:2000, *Industrial automation systems and integration — Product data representation and exchange — Part 104: Integrated application resource: Finite element analysis.*

ISO 13584-20:2000, *Industrial automation systems and integration — Parts library — Part 20: Logical resource: Logical model of expressions.*

ISO/IEC 8824-1:1998, *Information technology — Abstract Syntax Notation One (ASN.1): Specification of basic notation.*

3 Terms, definitions, and abbreviations

3.1 Terms defined in ISO 10303-1

For the purposes of this part of ISO 10303, the following terms defined in ISO 10303-1 apply.

— application protocol (AP)

— integrated resource

— product

3.2 Other terms and definitions

For the purposes of this part of ISO 10303, the following definitions apply.

3.2.1
edge
a topological curve (a connected region of dimensionality one) joining two vertices of a cell.

3.2.2
cell
a connected topological region of dimensionality one or higher that is a part of, or the whole of, the domain of a mesh.

3.2.3
face
a topological surface (a connected region of dimensionality two) that is enclosed by one or more edges.

3.2.4

[1)] To be published.

mesh
an arrangement of topological regions of zero or higher dimensionality with connectivity between the topological regions defined by the possession of common faces, edges or bounds.

3.2.5
node
a location in a cell or on the cell boundary that is not a (bounding) vertex.

3.2.6
topological region
a point set with a single topological dimension.

3.2.7
vertex
a topological region of dimensionality zero which is a bound of a cell.

3.3 Abbreviations

CFD	computational fluid dynamics
URL	Universal Resource Locator

4 Mesh topology

The following EXPRESS declaration begins the **mesh_topology_schema** and identifies the necessary external references.

EXPRESS specification:

```
*)
SCHEMA mesh_topology_schema;
  REFERENCE FROM mathematical_description_of_distribution_schema  -- ISO 10303-51
    (property_distribution_description);
  REFERENCE FROM mathematical_functions_schema                    -- ISO 10303-50
    (maths_space);
  REFERENCE FROM structural_response_representation_schema        -- ISO 10303-104
    (element_order,
     element_representation,
     fea_model);
  REFERENCE FROM support_resource_schema                          -- ISO 10303-41
    (identifier,
     label,
     text);
  REFERENCE FROM topology_schema                                  -- ISO 10303-42
    (topological_representation_item,
     vertex);
(*
```

NOTE The schemas referenced above can be found in the following parts of ISO 10303:

mathematical_description_of_distribution_schema	ISO 10303-51
mathematical_functions_schema	ISO 10303-50
structural_response_representation_schema	ISO 10303-104
support_resource_schema	ISO 10303-41
topology_schema	ISO 10303-42

4.1 Introduction

This schema defines and describes the structure types for describing mesh topologies.

4.2 Fundamental concepts and assumptions

A mesh is defined by its vertices and the connections between the vertices. A mesh is a connected graph.

4.2.1 Structured mesh

In a structured mesh the cells are arranged in a regular pattern and their shapes are implied by the particular kind of mesh.

A 3–D rectangular mesh is topologically hexahedral. Each cell is a dimensionality 3 topologically hexahedral region defined by eight vertices forming the corners of the hexahedron. Each cell is bounded by six faces, where each face is the quadrilateral defined by four vertices. A face is limited by the four edges that connect the four vertices.

A 2–D rectangular mesh is topologically quadrilateral. Each cell is a dimensionality two topologically quadrilateral region defined by four vertices forming the corners of the quadrilateral.

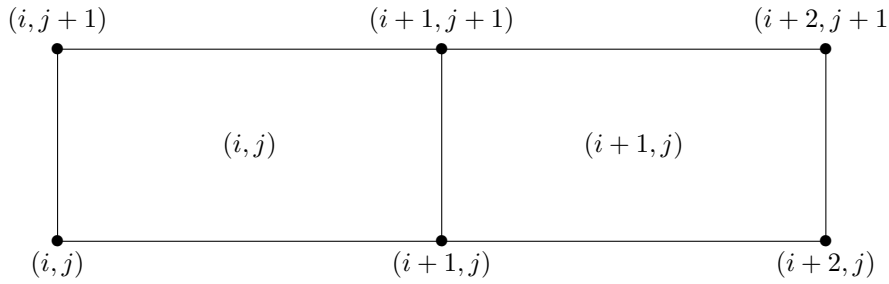


Figure 2 – Example convention for a 2-D cell center

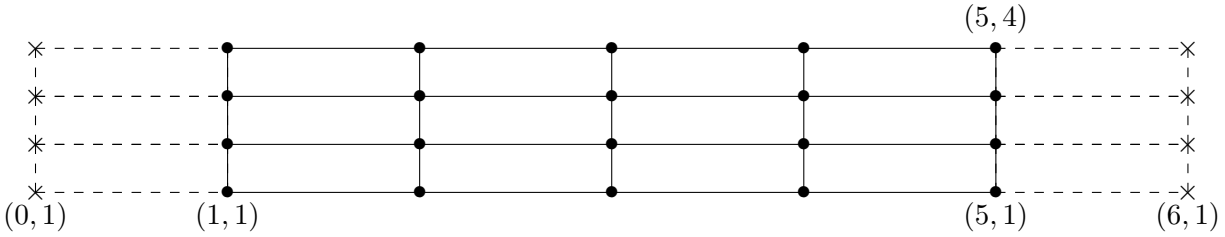


Figure 3 – Example mesh with rind vertices

Each cell is limited by the four edges that connect the four vertices.

A 1–D mesh is topologically linear. Each cell is a dimensionality one topologically linear region bounded by two vertices.

Indices describing a structured mesh are ordered: for 3–D (i, j, k); (i, j) is used for 2–D; and (i) for 1–D.

Cell centers, face centers, and edge centers are indexed by the minimum of the connecting vertices.

EXAMPLE 1 For example a 2-D cell center (or face center on a 3-D mesh) would have the conventions shown in Figure 2.

In addition, the default beginning vertex for a regular mesh is $(1, 1, 1)$; this means the default beginning cell center of a regular mesh is also $(1, 1, 1)$.

There may be locations outside the mesh itself. These are referred to as 'rind' or ghost points and may be associated with fictitious vertices or cell centers. They are distinguished from the vertices and cells making up the mesh (including its boundary vertices), which are referred to as 'core' points.

EXAMPLE 2 Figure 3 shows a 2–D mesh with a single row of 'rind' vertices at the minimum and maximum i-faces. The mesh size (i.e., the number of 'core' vertices in each direction) is 5×4. 'Core' vertices are designated by '•', and 'rind' vertices by '×'. Default indexing is also shown for the vertices.

For a mesh, the minimum faces in each coordinate direction are denoted i-min, j-min and k-min; the maximum faces are denoted i-max, j-max and k-max. These are the minimum and maximum 'core' faces.

EXAMPLE 3 $i-$min is the face or grid plane whose core vertices have minimum i index (which if using default indexing is 1).

4.2.2 Unstructured mesh

An unstructured mesh is composed of vertices and cells, where the cells need not form a regular pattern and the shape of the cells is not restricted to be uniform throughout the mesh. Cells have vertices at their corners and may also have vertices (nodes) on the edges, faces, and interior of the cell.

Each cell in an irregular mesh has at least one vertex in common with at least one other cell in the mesh. The connectivity and adjacency of the cells may be determined from the common vertices.

Each cell in an unstructured mesh is explicitly represented in terms of its shape and an ordered list of its vertices. The vertices are implied rather than being explicitly represented. Essentially all the vertices in a mesh can be mapped to a sequential list, and reference to a vertex is then equivalent to specifying the particular position in the list.

4.3 mesh_topology_schema type definitions

4.3.1 cell_shape

A **cell_shape** is an identifier of an unstructured mesh cell shape.

EXPRESS specification:

```
*)
TYPE cell_shape = EXTENSIBLE SELECT
    (cell_shape_0D,
     cell_shape_1D,
     cell_shape_2D,
     cell_shape_3D);
END_TYPE;
(*
```

4.3.2 cell_shape_0D

A **cell_shape_0D** is an identifier of a topologically 0–D unstructured mesh cell shape.

EXPRESS specification:

```
*)
TYPE cell_shape_0D = EXTENSIBLE ENUMERATION OF
    (single);
END_TYPE;
(*
```

Enumerated item definitions:

single: singleton vertex.

4.3.3 cell_shape_1D

A **cell_shape_1D** is an identifier of a topologically 1–D unstructured mesh cell shape.

EXPRESS specification:

```
*)
TYPE cell_shape_1D = EXTENSIBLE ENUMERATION OF
    (line);
END_TYPE;
(*
```

Enumerated item definitions:

line: a topological line requiring 2 vertices.

4.3.4 cell_shape_2D

A **cell_shape_2D** is an identifier of a topologically 2–D unstructured mesh cell shape.

EXPRESS specification:

```
*)
TYPE cell_shape_2D = EXTENSIBLE ENUMERATION OF
    (quadrilateral,
     triangle,
     polygon);
END_TYPE;
(*
```

Enumerated item definitions:

quadrilateral: topologically quadrilateral (four sided) requiring 4 vertices;

triangle: topologically triangular (three sided) requiring 3 vertices;

polygon: topologically polygonal (n-sided) requiring a minimum of 3 vertices;

4.3.5 cell_shape_3D

A **cell_shape_3D** is an identifier of a topologically 3–D unstructured mesh cell shape.

EXPRESS specification:

```
*)
TYPE cell_shape_3D = EXTENSIBLE ENUMERATION OF
    (hexahedron,
     wedge,
     tetrahedron,
```



```
     pyramid);
END_TYPE;
(*
```

Enumerated item definitions:

hexahedron: topologically hexahedral (six quadrilateral faces) requiring 8 vertices.

wedge: topologically pentahedral (three quadrilateral faces and two triangular faces) requiring 6 vertices;

tetrahedron: topologically tetrahedral (four triangular faces) requiring 4 vertices;

pyramid: topologically pyramidal (one quadrilateral face and four triangular faces) requiring 5 vertices;

4.3.6 indices_group

An **indices_group** is a selection of a group of indices into a multi-dimensional array.

EXPRESS specification:

```
*)
TYPE indices_group = SELECT
     (indices_list,
      indices_range);
END_TYPE;
(*
```

4.3.7 mesh_location

A **mesh_location** is an enumeration of locations with respect to a mesh.

EXPRESS specification:

```
*)
TYPE mesh_location = EXTENSIBLE ENUMERATION OF
     (unspecified,
      application_defined,
      vertices,
      cell_center,
      face_center,
      iface_center,
      jface_center,
      kface_center,
      edge_center);
END_TYPE;
(*
```


Enumerated item definitions:

unspecified: not specified;

application_defined: specified via an external agreement between the data creator and the data user;

vertices: coincident with the mesh vertices;

cell_center: the center of a cell; this is also appropriate for entities associated with cells but not necessarily with a given location in a cell;

face_center: the center of a generic face which can point in any coordinate direction;

iface_center: the center of a face in 3-D whose computational normal points in the i direction;

jface_center: the center of a face in 3-D whose computational normal points in the j direction;

kface_center: the center of a face in 3-D whose computational normal points in the k direction;

edge_center: the center of an edge.

4.3.8 mesh_maths_space_type

A **mesh_maths_space_type** is an enumeration of the kinds of associations of a **mesh_derived_maths_space** and a **mesh**.

EXPRESS specification:

```
*)
TYPE mesh_maths_space_type = EXTENSIBLE ENUMERATION OF
     (cells,
      vertices);
END_TYPE;
(*
```

Enumerated item definitions:

cells: data is associated with mesh cells;

vertices: data is associated with mesh vertices.

4.3.9 structured_mesh_type

A **structured_mesh_type** is an enumeration of the kinds of structured meshes.

EXPRESS specification:

```
*)
TYPE structured_mesh_type = EXTENSIBLE ENUMERATION OF
    (rectangular,
     pentahedral,
     pyramidal,
     tetrahedral);
```

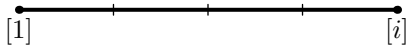



Figure 4 – A 1-D rectangular_mesh or pentahedral_mesh or pyramidal_mesh or tetrahedral_mesh (with $i = 5$)

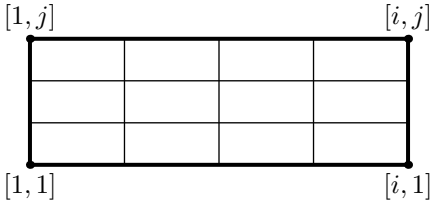


Figure 5 – A 2-D rectangular_mesh (with $i = 5$, $j = 4$)

```
END_TYPE;
(*
```

Enumerated item definitions:

rectangular: a structured mesh that is topologically linear in 1–D, quadrilateral in 2–D, hexahedral in 3–D, etc.

In 2–D the cells are all quadrilateral. In 3–D the cells are all hexahedral.

NOTE 1 Illustrations of rectangular mesh topologies are shown in Figure 4, Figure 5 and Figure 6.

pentahedral: a structured mesh that is topologically linear in 1–D, triangular in 2–D, and pentahedral, with 2 triangular and 3 quadrilateral faces forming a wedge-like shape, in 3–D. (where one of the edges between a pair of rectangular faces is analagous to the axis of a sector of a cylinder).

It is convenient to think of this kind of mesh as like a sector of a circle in 2–D where one apex point is analagous to the centre point of the circle, and like a sector of a cylinder in 3–D where one of the edges between a pair of rectangular faces is analagous to the axis of the cylinder.

In 2–D the cells adjacent to the apex are triangular; the rest are quadrilateral.

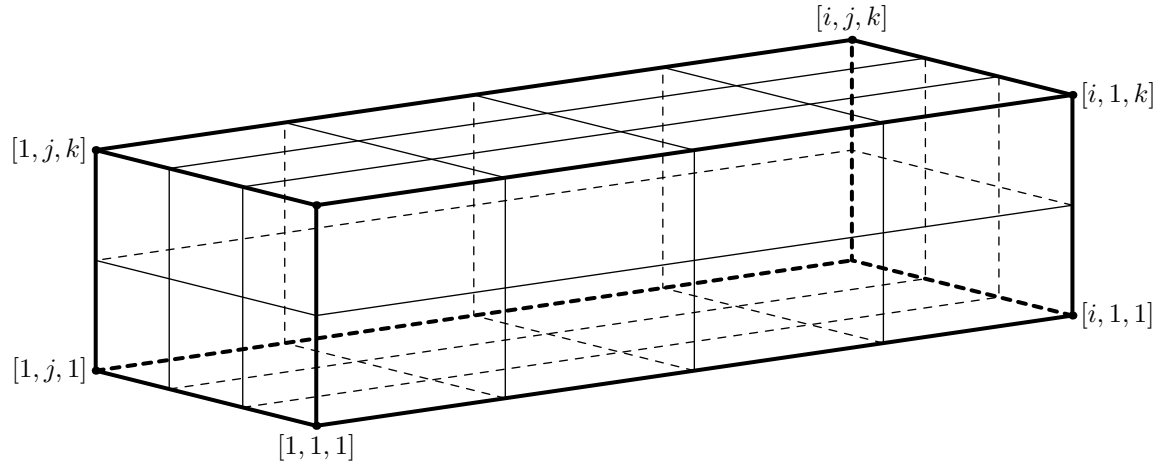


Figure 6 – A 3-D rectangular_mesh (with $i = 5$, $j = 4$, $k = 3$)

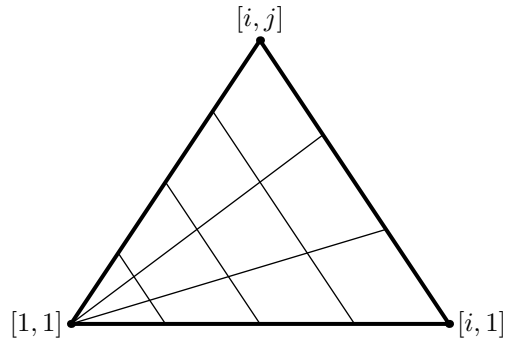


Figure 7 – A 2-D pentahedral_mesh or pyramidal_mesh or tetrahedral_mesh (with $i = 5$, $j = 4$)

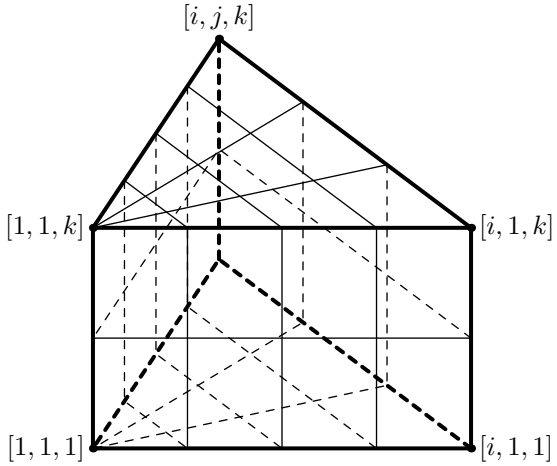


Figure 8 – A 3-D pentahedral_mesh (with $i = 5$, $j = 4$, $k = 3$)

In 3–D the cells adjacent to the axis edge are pentahedral; the rest are hexahedral.

NOTE 2 Illustrations of pentahedral mesh topologies are shown in Figure 4, Figure 7 and Figure 8.

pyramidal: a structured mesh that is topologically linear in 1–D, triangular in 2–D, and pyramidal in 3–D.

It is convenient to think of this kind of mesh as like a sector of a circle in 2–D where one apex point is analagous to the centre point of the circle, and like a sector of a sphere in 3–D where the apex point is analagous to the centre point of a sector of the sphere.

In 2–D the cells adjacent to the apex are triangular; the rest are quadrilateral.

In 3–D the cells adjacent to the apex are pyrimidal; the rest are hexahedral.

NOTE 3 Illustrations of pyramidal mesh topologies are shown in Figure 4, Figure 7 and Figure 9.

tetrahedral: a structured mesh that is topologically linear in 1–D, triangular in 2–D, and tetrahedral in 3–D.

It is convenient to think of this kind of mesh as like a sector of a circle in 2–D where one apex point is analagous to the centre point of the circle, and like

In 2–D the cells adjacent to the apex are triangular; the remainder are quadrilateral.

In 3–D the cells adjacent to the apex are tetrahedral and the cells adjacent to one edge from the apex are pentahedral; the remainder are hexahedral.

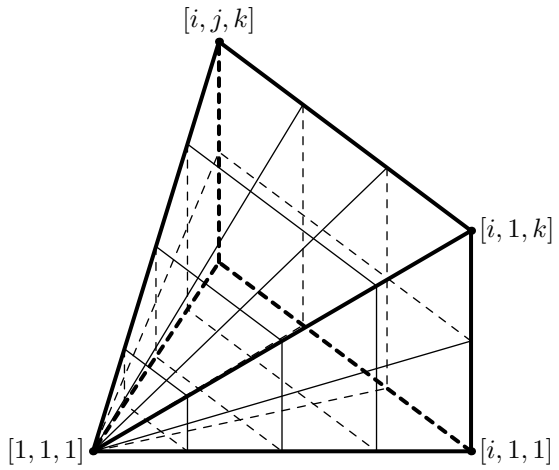


Figure 9 – A 3-D pyramidal_mesh (with $i = 5$, $j = 4$, $k = 3$)

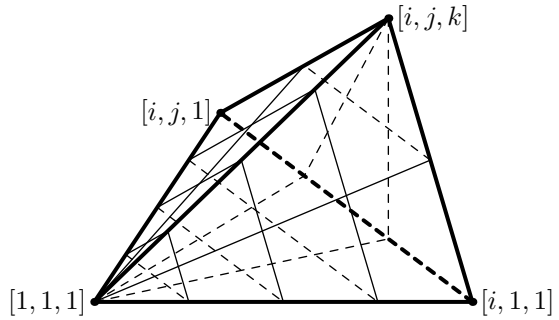


Figure 10 – A 3-D tetrahedral_mesh (with $i = 5$, $j = 4$, $k = 3$)

NOTE 4 Illustrations of tetrahedral mesh topologies are shown in Figure 4, Figure 7 and Figure 10.

4.4 mesh_topology_schema entity definitions

4.4.1 array_based_unstructured_mesh

An **array_based_structured_mesh** is a representation of an **unstructured_mesh** designed to minimise the amount of data by not requiring explicit identification of the vertices of the cells in the mesh.

EXPRESS specification:

```
*)
ENTITY array_based_unstructured_mesh
  SUBTYPE OF (unstructured_mesh);
  cells        : ARRAY [1:cell_count] OF vertex_defined_cell;
WHERE
  wr1 : SELF\mesh.index_count = 1;
END_ENTITY;
(*
```


Attribute definitions:

cells: the **vertex_defined_cell**s forming the mesh.

cell_count: (inherited) the number of cells in the mesh;

index_count: (inherited) the number of indices required to uniquely identify a vertex or cell in the mesh;

Formal propositions:

wr1: the value of **index_count** shall be 1.

4.4.2 array_based_unstructured_mesh_and_vertices

An **array_based_structured_mesh_and_vertices** is a kind of **array_based_unstructured_mesh** where the vertices of the mesh are explicity identified and ordered.

EXPRESS specification:

```
*)
ENTITY array_based_unstructured_mesh_and_vertices
  SUBTYPE OF (array_based_unstructured_mesh);
  vertex_count : INTEGER;
  vertices     : ARRAY [1:vertex_count] OF UNIQUE vertex;
WHERE
  wr1 : all_mesh_vertices(SELF);
END_ENTITY;
(*
```

Attribute definitions:

vertex_count: the number of unique **vertex** in the mesh;

vertices: an array of the unique **vertex** in the mesh.

Formal propositions:

wr1: the elements of **vertices** shall be all and only the unique vertices in the mesh.

4.4.3 cell_of_structured_mesh

A **cell_of_structured_mesh** is an identified cell of a **structured_mesh**.

EXPRESS specification:

```
*)
ENTITY cell_of_structured_mesh
  SUBTYPE OF (topological_region);
```



```
  the_mesh : structured_mesh;
  cell_identifier : ARRAY [1:index_count] OF INTEGER;
DERIVE
  index_count : INTEGER := the_mesh\mesh.index_count;
END_ENTITY;
(*
```

Attribute definitions:

the_mesh: the **structured_mesh**;

cell_identifier: the indices of the cell;

index_count: the number of indices required to uniquely identify a vertex or cell in the mesh;

4.4.4 composition_of_structured_mesh

A **composition_of_structured_mesh** is a relationship between two **structured_mesh**es that indicates one is part of the other.

EXPRESS specification:

```
*)
ENTITY composition_of_structured_mesh;
  part         : structured_mesh;
  whole        : structured_mesh;
  lower_vertex : ARRAY [1:whole_indices] OF INTEGER;
  lower_face   : ARRAY [1:whole_indices] OF OPTIONAL BOOLEAN;
  used_indices : ARRAY [1:part_indices] OF INTEGER;
  used_senses  : ARRAY [1:part_indices] OF BOOLEAN;
DERIVE
  whole_indices : INTEGER := whole\mesh.index_count;
  part_indices  : INTEGER := part\mesh.index_count;
END_ENTITY;
(*
```

Attribute definitions:

part: the **structured_mesh** that is part of the **whole**;

whole: the **structured_mesh** that contains the **part**;

lower_vertex: the position of the **vertex** in the **whole** that is the origin of the **part**. This is specified with respect to each index of the **whole**.

used_indices: the indices of the **whole** that are also indices of the **part** in the order that they are used in the **part**;

used_senses: the sense for each index of **part** as:

— TRUE if the **part** uses the index of the **whole** in the same direction;

— FALSE if the **part** uses the index of the **whole** in the reverse direction;

whole_indices: the number of indices required to uniquely identify a vertex or cell in the **whole**;

part_indices: the number of indices required to uniquely identify a vertex or cell in the **part**;

4.4.5 explicit_unstructured_mesh

An **explicit_unstructured_mesh** is a representation of an **unstructured_mesh** that is similar, but not entirely identical to, that specified in ISO 10303-104.

EXPRESS specification:

```
*)
ENTITY explicit_unstructured_mesh
  SUBTYPE OF (unstructured_mesh);
  explicit_model : fea_model;
  cells          : ARRAY [1:cell_count] OF UNIQUE element_representation;
END_ENTITY;
(*
```

Attribute definitions:

explicit_model: the finite element model;

cell_count: (inherited) the number of **element_representations**;

cells: the set of **element_representation**s comprising the mesh.

Informal propositions:

ip1: every **element_representation** in the **cells** shall belong to the **explicit_model**.

4.4.6 explicitly_defined_cell_patch

An **explicitly_defined_cell_patch** is a **patch** that consists of cells and that is defined by listing them.

EXPRESS specification:

```
*)
ENTITY explicitly_defined_cell_patch
  SUBTYPE OF (patch);
  cells : LIST [1:?] OF vertex_defined_cell;
END_ENTITY;
(*
```

Attribute definitions:

cells: the collection of **vertex_defined_cells**.

4.4.7 explicitly_defined_vertex_patch

An **explicitly_defined_vertex_patch** is a **patch** that consists of vertices and that is defined by listing them.

EXPRESS specification:

```
*)
ENTITY explicitly_defined_vertex_patch
  SUBTYPE OF (patch);
  vertices : LIST [1:?] OF vertex;
END_ENTITY;
(*
```

Attribute definitions:

vertices: the collection of **vertex**.

4.4.8 indices_list

An **indices_list** specifies a list of indices into a multi-dimensional array.

EXPRESS specification:

```
*)
ENTITY indices_list;
  nindices : INTEGER;
  indices  : LIST [1:?] OF ARRAY [1:nindices] OF INTEGER;
END_ENTITY;
(*
```

Attribute definitions:

nindices: the number of indices required to map to a unique array location;

indices: the indices.

4.4.9 indices_range

An **indices_range** specifies the beginning and ending indices of a subrange in a multi-dimensional array.

EXPRESS specification:

```
*)
ENTITY indices_range;
  nindices : INTEGER;
  start    : ARRAY [1:nindices] OF INTEGER;
```



```
  finish   : ARRAY [1:nindices] OF INTEGER;
END_ENTITY;
(*
```

Attribute definitions:

nindices: the number of indices required to map to a unique array location;

start: the indices of the minimal corner of the subrange;

finish: the indices of the maximal corner of the subrange.

4.4.10 mesh

A **mesh** is a **topological_representation_item** consisting of one or more cells. The **mesh** is the basis of all mesh topology representations. There are several ways of representing a mesh.

EXPRESS specification:

```
*)
ENTITY mesh
  SUBTYPE OF (topological_representation_item);
  description : text;
  index_count : INTEGER;
END_ENTITY;

SUBTYPE_CONSTRAINT sc1_mesh FOR mesh;
  ABSTRACT SUPERTYPE;
  ONEOF(patch,
        structured_mesh,
        unstructured_mesh);
END_SUBTYPE_CONSTRAINT;
(*
```

Attribute definitions:

description: annotation;

index_count: the number of indices required to identify uniquely a vertex or cell in the mesh.

NOTE 1 It inherits a **name** attribute of type **label** via its **topological_representation_item** supertype.

4.4.11 mesh_derived_maths_space

A **mesh_derived_maths_space** associates data values and a **mesh**.

NOTE The association commences with the **property_distribution_description** entity whose **abstract_function** attribute is of type **math_function** (a table function in this case) whose **range** and **domain** are of type **maths_space**, and hence to a **mesh**.

EXPRESS specification:

```
*)
ENTITY mesh_derived_maths_space
  SUBTYPE OF (maths_space);
  description : text;
  name        : label;
  id          : identifier;
  the_mesh    : mesh;
  kind        : mesh_maths_space_type;
END_ENTITY;
(*
```

Attribute definitions:

description: annotation;

name: a user interpretable identifier;

id: an identifier;

the_mesh: the **mesh**;

kind: the kind of association.

4.4.12 patch

A **patch** is a collection of one or more cells or one or more vertices. The cells are not necessarily connected.

EXPRESS specification:

```
*)
ENTITY patch
  SUBTYPE OF (mesh);
END_ENTITY;

SUBTYPE_CONSTRAINT sc1_patch FOR patch;
  ABSTRACT SUPERTYPE;
END_SUBTYPE_CONSTRAINT;
(*
```

4.4.13 product_of_mesh

A **product_of_mesh** is a relationship that is between:

— two operands that are a 1-dimensional **mesh** and an n-dimensional **mesh**; and

— a product that is an $(n+1)$-dimensional **mesh**,

that indicates the $(n+1)$-dimensional **mesh** is the Cartesian product of the operands.

The ordering of cells and vertices of the product **mesh** is:

— cell $i + n(j - 1)$ of the product mesh corresponds to cell i of the first operand and cell j of the second operand, where n is the total number of cells of the first operand;

— vertex $i + m(j - 1)$ of the product mesh corresponds to vertex i of the first operand and vertex j of the second operand, where m is the total number of vertices of the first operand.

EXPRESS specification:

```
*)
ENTITY product_of_mesh;
  operands : LIST [2:2] OF mesh;
  product  : mesh;
WHERE
  wr1 : (this_schema+'.STRUCTURED_MESH' IN TYPEOF(operands[1])) AND
        (this_schema+'.STRUCTURED_MESH' IN TYPEOF(operands[2])) AND
        (this_schema+'.STRUCTURED_MESH' IN TYPEOF(product));
  wr2 : operands[1].index_count = 1;
  wr3 : operands[1].index_count + operands[2].index_count
        = product.index_count;
END_ENTITY;
(*
```

Attribute definitions:

operands: the two **mesh**es that define the **product**;

product: the **mesh** that is the Cartesian product of the **operands**.

Formal propositions:

wr1: all meshes shall be **structured_mesh**es;

wr2: the first operand shall have an **index_count** of one;

wr3: the **index_count** of the **product** shall equal the sum of the **index_count**s of the **operands**.

4.4.14 rind

A **rind** describes the number of rind planes associated with a structured mesh.

EXPRESS specification:

```
*)
ENTITY rind;
  index_count : INTEGER;
  planes      : ARRAY [1:2*index_count] OF INTEGER;
END_ENTITY;
(*
```

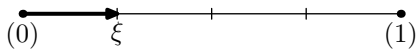



Figure 11 – Parametric coordinate system for a 1-D structured mesh

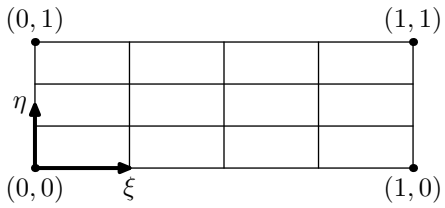


Figure 12 – Parametric coordinate system for a 2-D structured mesh

Attribute definitions:

index_count: the number of indices required to reference a vertex;

planes: contains the number of rind planes attached to the minimum and maximum faces of a structured mesh. The face corresponding to each index n of **planes** in 3-D is:

$$\begin{aligned} n = 1 &\rightarrow i\text{-min} & n = 2 &\rightarrow i\text{-max} \\ n = 3 &\rightarrow j\text{-min} & n = 4 &\rightarrow j\text{-max} \\ n = 5 &\rightarrow k\text{-min} & n = 6 &\rightarrow k\text{-max} \end{aligned}$$

EXAMPLE 1 For a 3-D grid whose 'core' size is `II`×`JJ`×`KK`, a value of **planes** = `[a,b,c,d,e,f]` indicates that the range of indices for the grid with this rind is:

i: `(1 - a, II + b)`
j: `(1 - c, JJ + d)`
k: `(1 - e, KK + f)`

4.4.15 structured_mesh

A **structured_mesh** has a regular topology. A **structured_mesh** has a parametric coordinate system; the parametric coordinate systems for one- two-, and three-dimensional structured meshes are shown in Figure 11 through Figure 13.

For each cell within a **structured_mesh**, the parametric coordinate system for that cell is identical to the parametric coordinate system for the mesh, except for an origin shift. The parametric coordinates of vertex (i, j, k) in a 3-D mesh with n, m and p cells in the 3 dimensions are:

$$((i-1)/n, (j-1)/m, (k-1)/p)$$

EXPRESS specification:

```
*)
ENTITY structured_mesh
  SUBTYPE OF (mesh);
  vertex_counts : ARRAY [1:SELF\mesh.index_count] OF INTEGER;
  cell_counts   : ARRAY [1:SELF\mesh.index_count] OF INTEGER;
  kind          : structured_mesh_type;
```

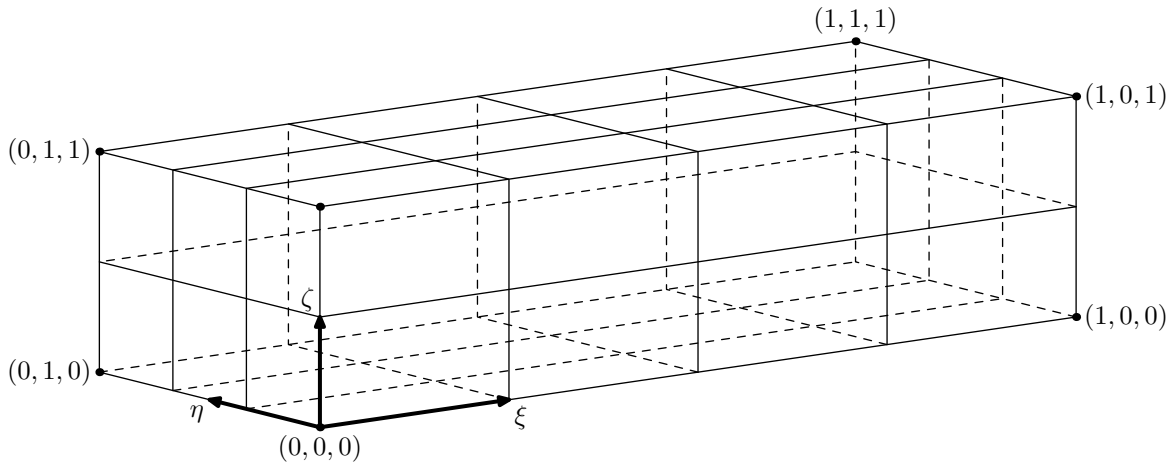



Figure 13 – Parametric coordinate system for a 3-D structured mesh

Table 1 – Number of vertices in a structured_mesh

Index_count	Rectangular	Pentahedral	Pyramidal	Tetrahedral
1	i	i	i	i
2	ij	$j(i-1)+1$	$j(i-1)+1$	$j(i-1)+1$
3	ijk	$jk(i-1)+k$	$jk(i-1)+1$	$jk(i-1)-(i-2)(j-1)$

```
END_ENTITY;
(*
```

Attribute definitions:

vertex_counts: the number of vertices in each dimension of the mesh. The product of the array elements is the number of vertices defining the mesh (i.e., excluding any rind points). The number of vertices in one- two- and three-dimensional regular mesh topologies is given in Table 1, where i, j and k correspond to the array elements `vertex_counts[1]`, `vertex_counts[2]` and `vertex_counts[3]`, respectively.

cell_counts: the number of cells in each dimension of the mesh. The product of the array elements is the number of cells on the interior of the mesh;

kind: the kind of mesh;

index_count: (inherited) the number of indices required to identify uniquely a vertex or cell in the mesh is the same as the topological dimensionality (e.g., 1–D, 3–D) of the mesh.

4.4.16 structured_mesh_with_rind

A **structured_mesh_with_rind** is a **structured_mesh** with specified **rind** planes.

EXPRESS specification:

```
*)
ENTITY structured_mesh_with_rind
  SUBTYPE OF (structured_mesh);
```



```
  rind_planes : rind;
END_ENTITY;
(*
```

Attribute definitions:

rind_planes: the **rind** planes associated with the mesh.

4.4.17 topological_region

A **topological_region** is a **topological_representation_item** that is a continuous point set with a single topological dimension.

EXPRESS specification:

```
*)
ENTITY topological_region
  SUBTYPE OF (topological_representation_item);
  description : text;
  dimension   : INTEGER;
END_ENTITY;

SUBTYPE_CONSTRAINT sc1_topological_region FOR topological_region;
  ONEOF(cell_of_structured_mesh,
        vertex_defined_cell);
END_SUBTYPE_CONSTRAINT;
(*
```

Attribute definitions:

description: annotation;

dimension: the topological dimension of the region.

4.4.18 topological_region_with_boundary

A **topological_region_with_boundary** is a **topological_region** that has a specified boundary.

EXPRESS specification:

```
*)
ENTITY topological_region_with_boundary
  SUBTYPE OF (topological_region);
  boundary : SET [1:?] OF topological_representation_item;
END_ENTITY;
(*
```

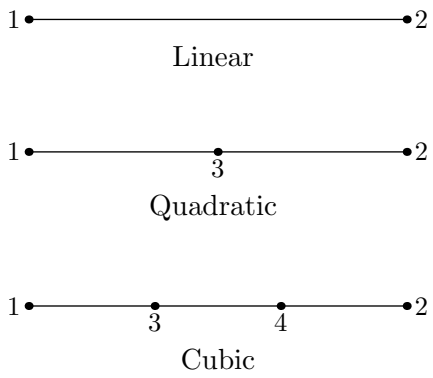



Figure 14 – Linear, quadratic and cubic line cells

Attribute definitions:

boundary: the elements forming the boundary of the region.

4.4.19 unstructured_mesh

An **unstructured_mesh** is a mesh where the topology need not be regular and the cell shapes are not restrained. It conceptually consists of the vertices of the mesh and the cells forming the volume of the mesh. The cells shall all be connected by each cell having at least one vertex in common with another cell. The shape of each cell in an unstructured mesh is explicitly specified.

EXPRESS specification:

```
*)
ENTITY unstructured_mesh
  SUBTYPE OF (mesh);
  cell_count   : INTEGER;
END_ENTITY;

SUBTYPE_CONSTRAINT sc1_unstructured_mesh FOR unstructured_mesh;
  ABSTRACT SUPERTYPE;
  ONEOF(array_based_unstructured_mesh,
        explicit_unstructured_mesh);
END_SUBTYPE_CONSTRAINT;
(*
```

Attribute definitions:

cell_count: the number of cells in the mesh.

4.4.20 vertex_defined_cell

A **vertex_defined_cell** is a **topological_region** that is bounded by vertices; the number of vertices depends on the topological shape of the cell. The cell may have interior nodes; the maximum number of interior nodes depends on both the shape and the order of the cell.

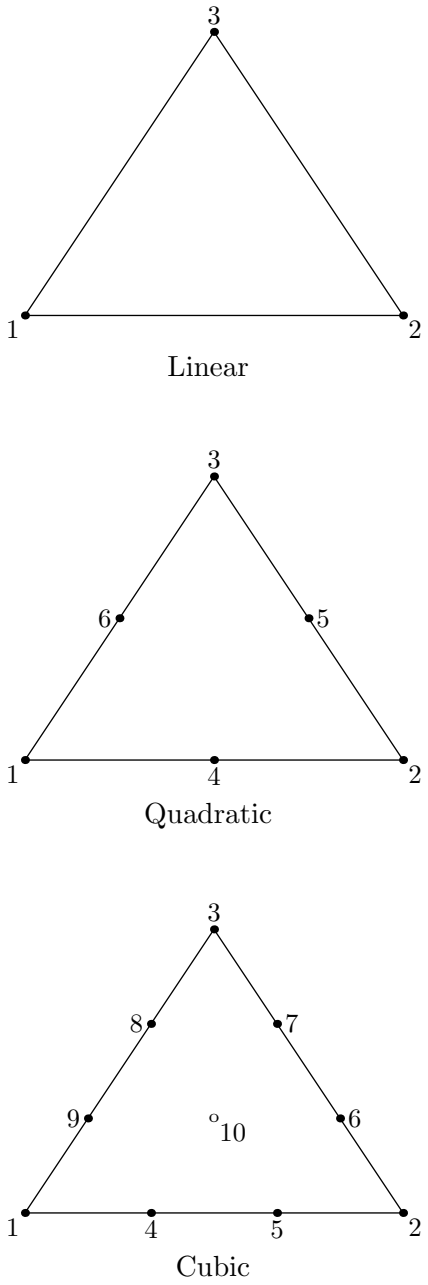


Figure 15 – Linear, quadratic and cubic triangle cells

Table 2 – Edges of triangle, quadrilateral and polygon cells

triangle		**quadrilateral**		**n-sided polygon**	
edge	**vertices**	**edge**	**vertices**	**edge**	**vertices**
1	1, 2	1	1, 2	1	1, 2
2	2, 3	2	2, 3	2	2, 3
3	3, 1	3	3, 4	3	3, 4
		4	4, 1	n	n, 1

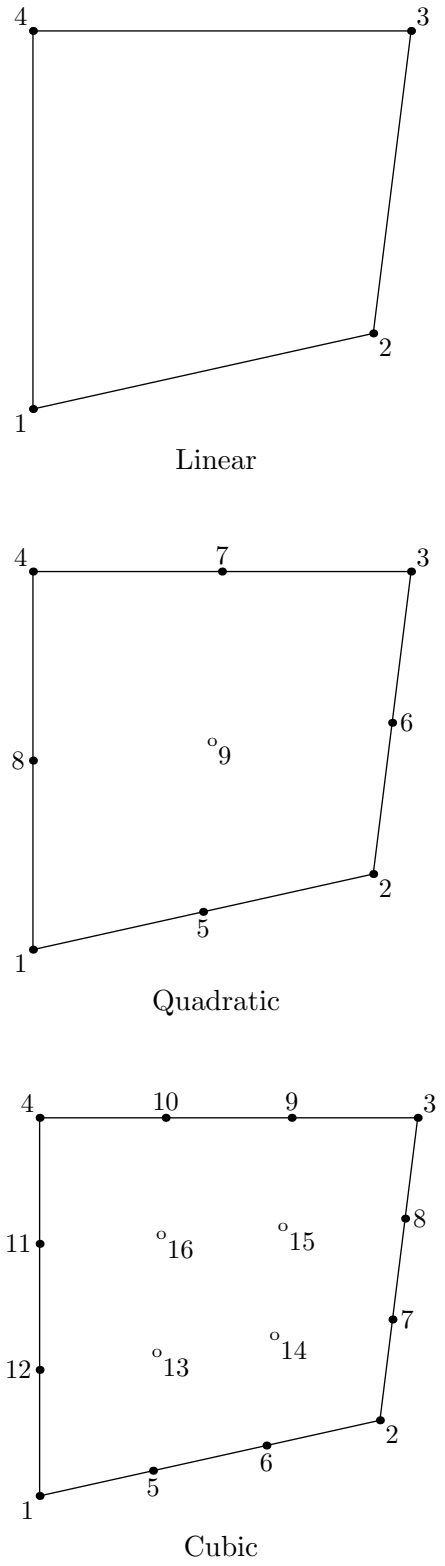
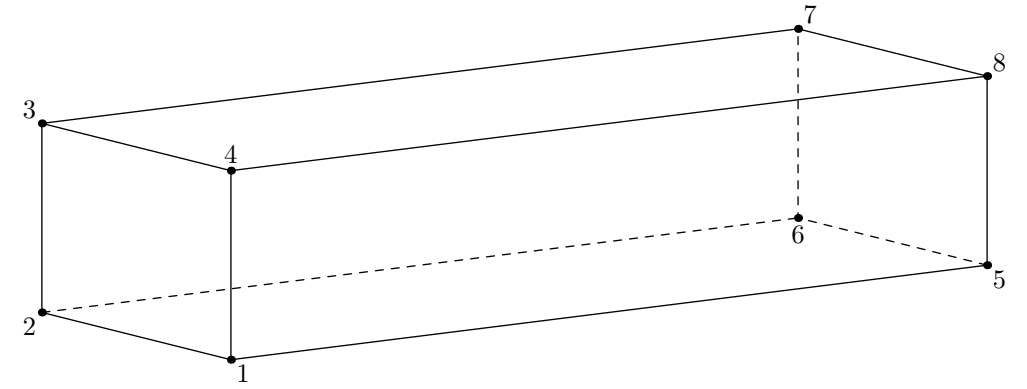
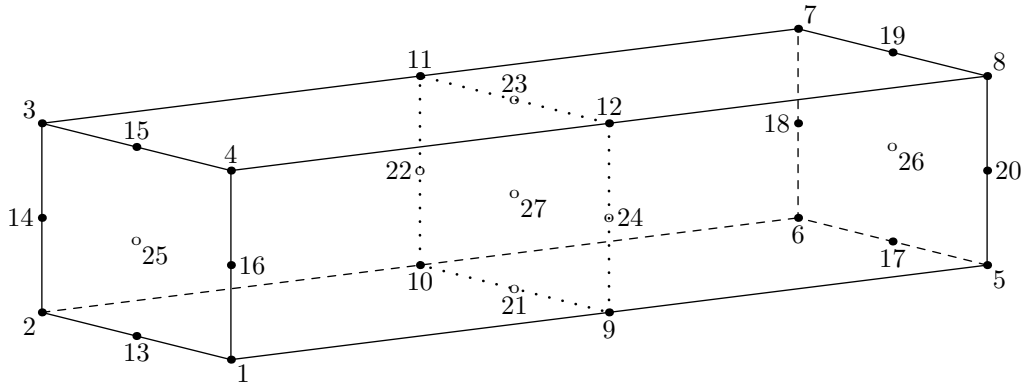


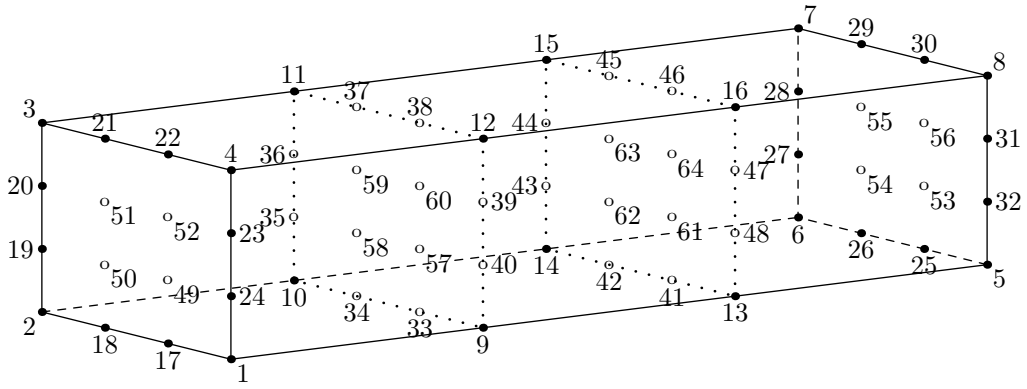
Figure 16 – Linear, quadratic and cubic quadrilateral cells



Linear

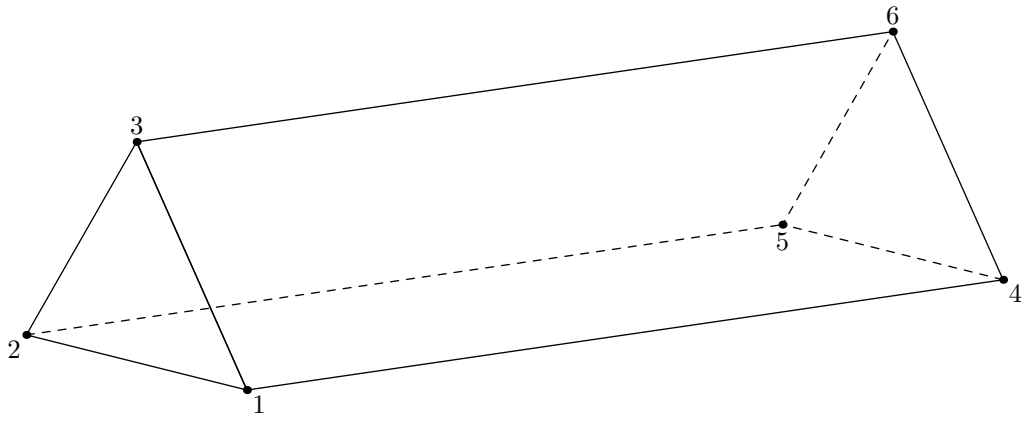


Quadratic

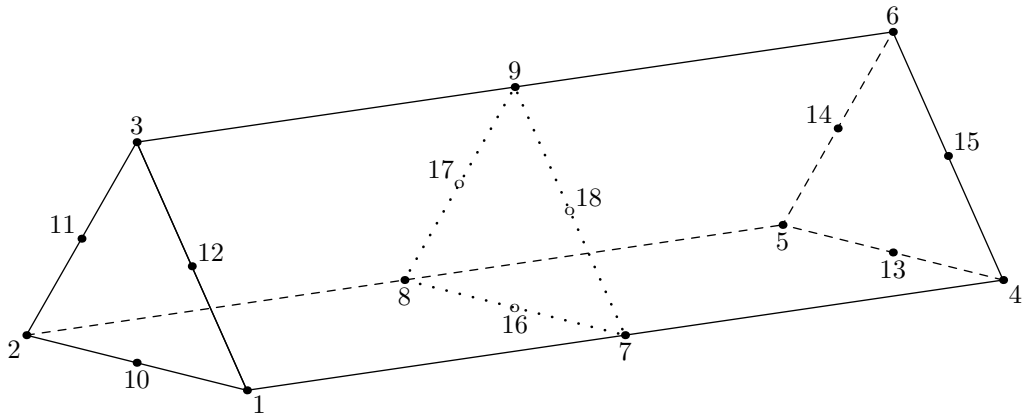


Cubic

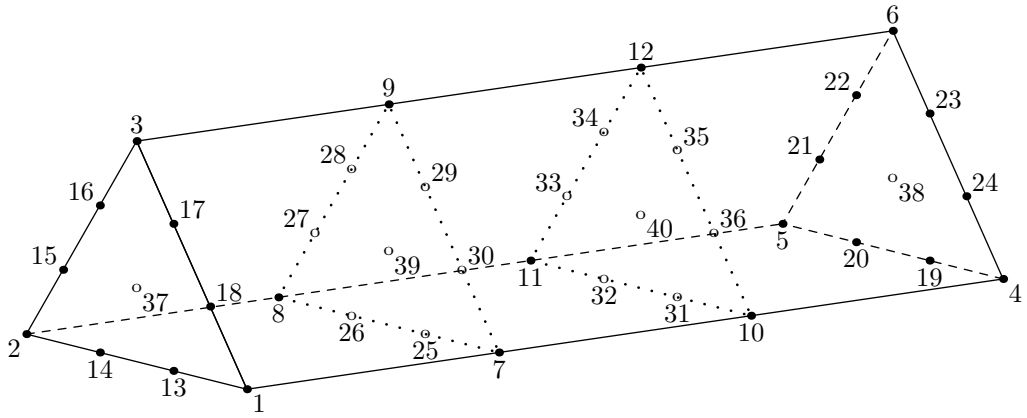
Figure 17 – Linear, quadratic and cubic hexahedron cells



Linear

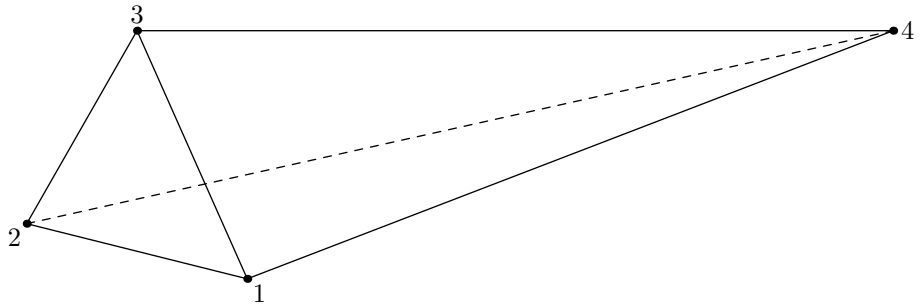


Quadratic

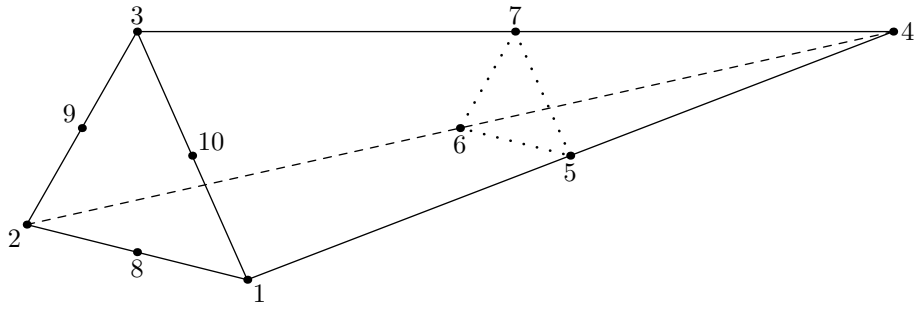


Cubic

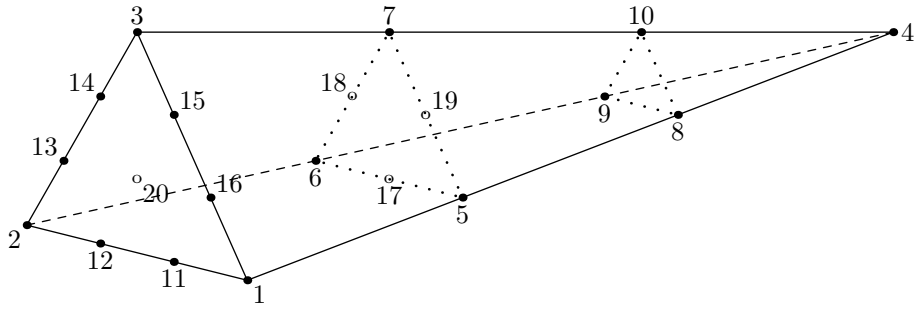
Figure 18 – Linear, quadratic and cubic wedge cells



Linear



Quadratic



Cubic

Figure 19 – Linear, quadratic and cubic tetrahedron cells

Table 3 – Edges of hexahedron, wedge, tetrahedron and pyramid cells

hexahedron		**wedge**		**tetrahedron**		**pyramid**	
edge	**vertices**	**edge**	**vertices**	**edge**	**vertices**	**edge**	**vertices**
1	1, 2	1	1, 2	1	1, 2	1	1, 2
2	2, 3	2	2, 3	2	2, 3	2	2, 3
3	3, 4	3	3, 1	3	3, 1	3	3, 4
4	4, 1	4	4, 5	4	1, 4	4	4, 1
5	5, 6	5	5, 6	5	2, 4	5	1, 5
6	6, 7	6	6, 4	6	3, 4	6	2, 5
7	7, 8	7	1, 4			7	3, 5
8	8, 5	8	2, 5			8	4, 5
9	1, 5	9	3, 6				
10	2, 6						
11	3, 7						
12	4, 8						

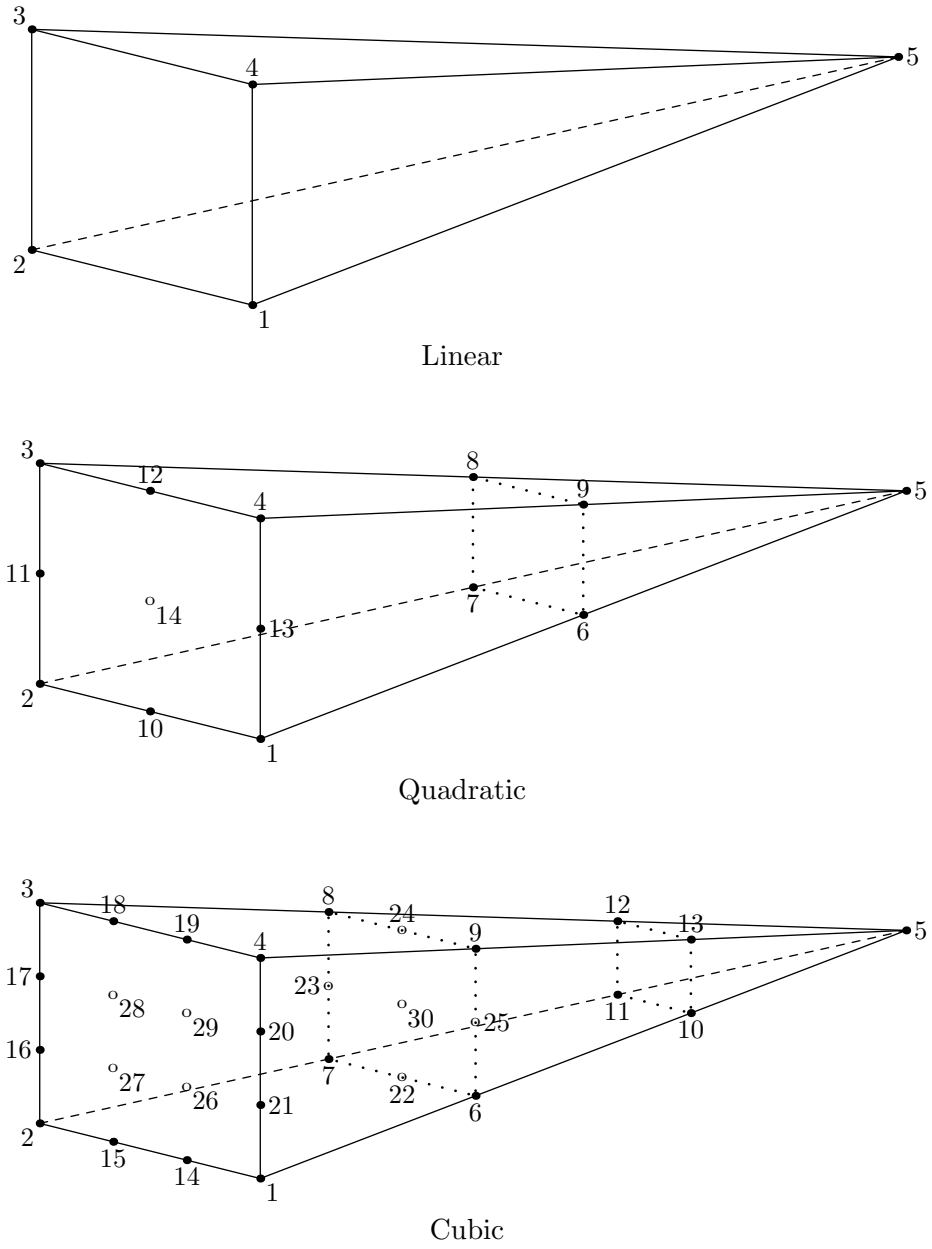


Figure 20 – Linear, quadratic and cubic pyramid cells

Table 4 – Faces of hexahedron, wedge, tetrahedron and pyramid cells

hexahedron		wedge		tetrahedron		pyramid	
face	vertices	face	vertices	face	vertices	face	vertices
1	1, 4, 3, 2	1	1, 3, 2	1	1, 2, 3	1	1, 4, 3, 2
2	5, 6, 7, 8	2	4, 5, 6	2	1, 4, 2	2	1, 2, 5
3	1, 2, 6, 5	3	1, 2, 4, 5	3	2, 4, 3	3	2, 3, 5
4	3, 7, 6, 2	4	2, 3, 6, 5	4	3, 4, 1	4	3, 4, 5
5	3, 4, 8, 7	5	1, 4, 6, 3			5	4, 1, 5
6	1, 5, 8, 4						

EXPRESS specification:

```
*)
ENTITY vertex_defined_cell
  SUBTYPE OF (topological_region);
  shape       : cell_shape;
  order       : element_order;
  vertices    : ARRAY [1:vn_count] OF OPTIONAL vertex;
DERIVE
  bound_count       : INTEGER := cell_counts(SELF)[1];
  edge_node_count   : INTEGER := cell_counts(SELF)[2];
  opt_node_count    : INTEGER := cell_counts(SELF)[3];
  required_count    : INTEGER := bound_count + edge_node_count;
  vn_count          : INTEGER := required_count + opt_node_count;
  required_vertices : ARRAY [1:required_count] OF vertex
                              := vertices[1:required_count];
END_ENTITY;
(*
```

Attribute definitions:

shape: the topological shape of the cell;

order: the order of the cell geometric interpolation;

vertices: the the cell vertices and edge nodes. The position of a vertex or an edge node in the array depends on the shape of the cell as established graphically in Figures 10 through 39 in ISO 10303-104, noting that a **polygon** cell is a generalisation of the **triangle** and **quadrilateral** cells.

NOTE 1 For convenience, most of the ISO 10303-104 Figures have been redrawn in this part of ISO 10303 as Figure 14 to Figure 20, where a vertex or edge node is indicated by a dot. The vertex labelled '1' is the first index in the array, that labelled '2' is the second index in the array, and so on. Edge and face information from ISO 10303-104 is given in Table 2 to Table 4.

bound_count: the number of cell bounding vertices; it is determined by the value of **shape**;

edge_node_count: the number of interior cell nodes located on the cell edges; it is determined by the combination of the values of **shape** and **order**;

opt_node_count: the potential number of interior cell nodes which are not located on the cell edges; it is determined by the combination of the values of **shape** and **order**;

NOTE 2 In Figure 14 to Figure 20 the non-edge interior nodes are indicated by circles.

required_count: the total number of bounding vertices plus the number of edge nodes;

vn_count: the total number of bounding vertices plus the number of nodes (both edge and non-dege nodes);

required_vertices: the vertices and nodes excluding any non-edge interior nodes. There shall be **required_count** of these.

4.4.21 vertex_range_defined_patch

A **vertex_range_defined_patch** is a **patch** that consists of cells and that is defined by specifying a vertex range within a structured mesh.

EXPRESS specification:

```
*)
ENTITY vertex_range_defined_patch
  SUBTYPE OF (patch);
  base_mesh : structured_mesh;
  range     : indices_range;
END_ENTITY;
(*
```

Attribute definitions:

base_mesh: the **structured_mesh**;

range: the vertex range.

4.5 mesh_topology_schema function definitions

4.5.1 all_mesh_vertices

The function **all_mesh_vertices** takes an **array_based_unstructured_mesh_and_vertices** as its argument and returns TRUE if the members of the **vertices** attribute are exactly the vertices in the mesh.

EXPRESS specification:

```
*)
FUNCTION all_mesh_vertices(arg : array_based_unstructured_mesh_and_vertices)
         : BOOLEAN;
LOCAL
  vertex_set : SET OF vertex := [];
  cell : vertex_defined_cell;
END_LOCAL;
  REPEAT i := 1 TO arg.cell_count;
    cell := arg.cells[i];
    REPEAT j := 1 TO cell.vn_count;
      vertex_set := vertex_set + cell.vertices[j];
    END_REPEAT;
  END_REPEAT;
  IF (SIZEOF(vertex_set) <> arg.index_count) THEN
    RETURN(FALSE);
  END_IF;
  REPEAT i := 1 TO arg.index_count;
    IF (NOT (arg.vertices[i] IN vertex_set) ) THEN
      RETURN(FALSE);
    END_IF;
  END_REPEAT;
  RETURN(TRUE);
END_FUNCTION;
(*
```


Argument definitions:

arg: an **array_based_unstructured_mesh_and_vertices**;

RETURNS: TRUE if the members of the **vertices** attribute of **arg** are exactly the vertices in the mesh, otherwise FALSE.

4.5.2 cell_counts

The function **cell_counts** takes a **vertex_defined_cell** as its argument and returns the numbers of vertices and nodes required to define the cell.

EXPRESS specification:

```
*)
FUNCTION cell_counts(arg : vertex_defined_cell) : ARRAY[1:3] OF INTEGER;
LOCAL
  om1    : INTEGER := 0;      -- (order - 1)
  om1sq  : INTEGER := om1**2; -- (order - 1) squared
  vts    : INTEGER;           -- number of bounding vertices
  eds    : INTEGER;           -- number of edges
  qf     : INTEGER := 0;      -- number of quadrilateral faces
  tf     : INTEGER := 0;      -- number of triangular faces
  result : ARRAY [1:3] OF INTEGER := [0,0,0];
END_LOCAL;
  CASE arg.order OF
    linear    : om1 := 0;
    quadratic : om1 := 1;
    cubic     : om1 := 2;
    OTHERWISE : RETURN(result);
  END_CASE;
  om1sq := om1**2;
  CASE arg.shape OF
    single :
        BEGIN
          vts := 1; eds := 0; qf := 0; tf := 0;
          result[1] := vts;
          result[2] := om1*eds;                  -- 0, 0, 0
          result[3] := 0;                        -- 0, 0, 0
        END;
    line :
        BEGIN
          vts := 2; eds := 1; qf := 0; tf := 0;
          result[1] := vts;
          result[2] := om1*eds;                  -- 0, 1, 2
          result[3] := 0;                        -- 0, 0, 0
        END;
    quadrilateral :
        BEGIN
          vts := 4; eds := 4; qf := 1; tf := 0;
          result[1] := vts;
          result[2] := om1*eds;                  -- 0, 4, 8
          result[3] := om1sq*qf;                 -- 0, 1, 4
        END;
    triangle :
        BEGIN
```



```
          vts := 3; eds := 3; qf := 0; tf := 1;
          result[1] := vts;
          result[2] := om1*eds;                    -- 0, 3, 6
          result[3] := (om1-1)*tf;                 --    0, 1
          CASE arg.order OF
            linear : result[3] := 0;               -- 0
          END_CASE;
        END;
    polygon :
        BEGIN
          vts := arg.vn_count; eds := arg.vn_count;
          result[1] := vts;
          result[2] := 0;
          result[3] := 0;
        END;
    hexahedron :
        BEGIN
          vts := 8; eds := 12; qf := 6; tf := 0;
          result[1] := vts;
          result[2] := om1*eds;                    -- 0, 12, 24
          result[3] := om1sq*(qf+om1);             -- 0, 7, 32
        END;
    wedge :
        BEGIN
          vts := 6; eds := 9; qf := 3; tf := 2;
          result[1] := vts;
          result[2] := om1*eds;                    -- 0, 9,  18
          result[3] := om1sq*qf + om1*tf;          -- 0, 3, 16
        END;
    tetrahedron :
        BEGIN
          vts := 4; eds := 6; qf := 0; tf := 4;
          result[1] := vts;
          result[2] := om1*eds;                    -- 0, 6, 12
          result[3] := (om1-1)*tf;                 --    0, 4
          CASE arg.order OF
            linear : result[3] := 0;               -- 0
          END_CASE;
        END;
    pyramid :
        BEGIN
          vts := 5; eds := 8; qf := 1; tf := 4;
          result[1] := vts;
          result[2] := om1*eds;                    -- 0, 8, 16
          result[3] := om1sq*qf + (om1-1)*tf;      --    1, 9
          CASE arg.order OF
            linear : result[3] := 0;               -- 0
          END_CASE;
        END;
  END_CASE;
RETURN(result);
END_FUNCTION;
(*
```

Argument definitions:

arg: a **cell**;

RETURNS: a 3 element array of INTEGER, where the first element is the number of vertices defining the bounds of the cell, the second is the number of interior nodes located on an edge, and the third is the maximum number of (potential) interior nodes not located on an edge.

4.5.3 this_schema

The function **this_schema** returns a STRING containing the name of the schema.

EXPRESS specification:

```
*)
FUNCTION this_schema : STRING;
  RETURN('MESH_TOPOLOGY_SCHEMA');
END_FUNCTION;
(*
```

Argument definitions:

RETURNS: the uppercase name of the schema.

EXPRESS specification:

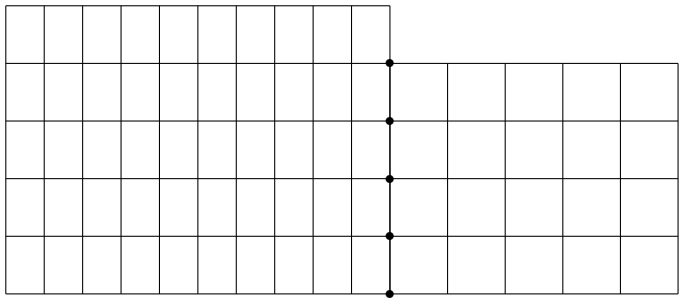
```
*)
END_SCHEMA;  -- end of mesh_topology_schema
(*
```

5 Mesh connectivity

The following EXPRESS declaration begins the **mesh_connectivity_schema** and identifies the necessary external references.

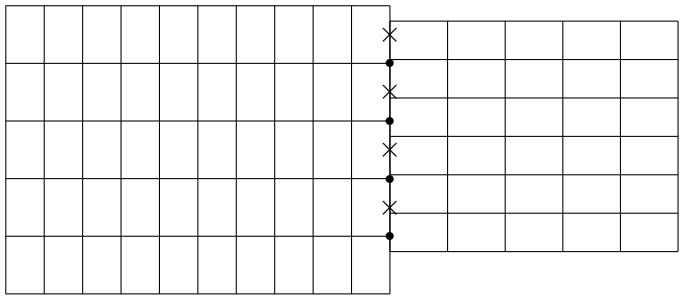
EXPRESS specification:

```
*)
SCHEMA mesh_connectivity_schema;
  REFERENCE FROM mesh_topology_schema                              -- ISO 10303-52
    (mesh,
     unstructured_mesh,
     structured_mesh,
     mesh_location,
     indices_group,
     indices_range);
  REFERENCE FROM mathematical_description_of_distribution_schema -- ISO 10303-51
    (property_distribution_description);
  REFERENCE FROM mathematical_functions_schema                     -- ISO 10303-50
    (listed_real_data);
  REFERENCE FROM support_resource_schema                           -- ISO 10303-41
    (identifier,
```

• left-mesh vertices on interface

Figure 21 – A 1-to-1 abutting interface



• left-mesh vertices on interface
× left-mesh face-centers on interface

Figure 22 – A mismatched abutting interface

```
    label,
    text);
(*
```

NOTE The schemas referenced above can be found in the following parts of ISO 10303:

mesh_topology_schema	Clause 4 of this part of ISO 10303
mathematical_description_of_distribution_schema	ISO 10303-51
mathematical_functions_schema	ISO 10303-50
support_resource_schema	ISO 10303-41

5.1 Introduction

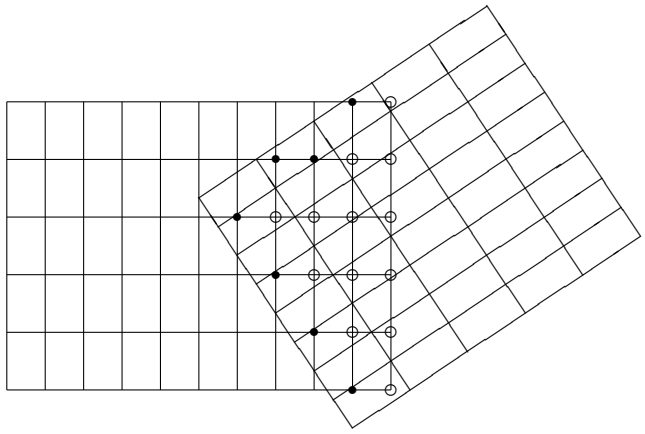
This schema defines and describes the structures for describing interface connectivity between meshes.

5.2 Fundamental concepts and assumptions

Figures 21 to Figure 23 show three types of mesh interfaces.

Figure 21 illustrates a 1-to-1 abutting interface, also referred to as matching or C0 continuous. The interface is a plane of vertices that are physically coincident (i.e., they have identical coordinate values) between the adjacent meshes; grid-coordinate lines perpendicular to the interface are continuous from one mesh to the next. In 3-D, a 1-to-1 abutting interface is always a logically rectangular region.

The second type of interface, is mismatched abutting, where two meshes touch but do not overlap (except for vertices and cell faces on the grid plane of the interface). Vertices on the interface need not be physically concident between the two meshes. Figure 22 indentifies the vertices and face centers of the left mesh that lie on the interface. In 3-D, the vertices of a mesh that constitute an interface patch may not form a logically rectangular region.



- left-mesh fringe points (vertices)
- left-mesh overset-hole points (vertices)

Figure 23 – An overset interface

The third type of interface is called overset and occurs when two meshes overlap; in 3-D, the overlap is a 3-D region. For overset interfaces, one of the two meshes takes precedence over the other; this establishes which solution in the overlap region to retain and which one to discard. The region in a given mesh where the solution is discarded is called an overset hole and the mesh vertices outlining the hole are called fringe points.

Figure 23 depicts an overlap region between two meshes, where the right mesh takes precedence over the left mesh. The points identified in Figure 23 are the fringe points and overset-hole points for the left mesh. In addition, for the mesh taking precedence, any bounding points (i.e., vertices on the bounding faces) of the mesh that lies within the overlap must also be identified.

Overset interfaces may include multiple layers of fringe points outlining holes and at mesh boundaries.

For the mismatched abutting and overset interfaces in Figure 22 and Figure 23, the left mesh plays the role of receiver mesh and the right plays the role of donor mesh.

Mesh vertices that are included in a mesh interface are, in general, termed interface points.

5.3 mesh_connectivity_schema type definitions

5.3.1 mismatched_region_type

A **mismatched_region_type** is an enumeration of the kinds of mismatched mesh regions.

EXPRESS specification:

```
*)
TYPE mismatched_region_type = EXTENSIBLE ENUMERATION OF
    (abutting,
     overset);
END_TYPE;
(*
```


Enumerated item definitions:

abutting: abutting region;

overset: overset region.

5.4 mesh_connectivity_schema entity definitions

5.4.1 matched_mesh_connection

A **matched_mesh_connection** contains connectivity information for a mesh interface patch that is abutting with 1-to-1 matching between adjacent structured mesh indices (also referred to as C0 connectivity). An interface patch is the subrange of the face of a mesh that touches one and only one other mesh. This structure identifies the subrange of indices for the two adjacent meshes that make up the interface and gives an index transformation from one mesh to the other. It also identifies the adjacent mesh.

EXPRESS specification:

```
*)
ENTITY matched_mesh_connection
  SUBTYPE OF (mesh_connectivity);
  SELF\mesh_connectivity.current : structured_mesh;
  range       : indices_range;
  donor       : structured_mesh;
  donor_range : indices_range;
  transform   : ARRAY [1:index_count] OF INTEGER;
WHERE
  wr1 : current :<>: donor;
  wr2 : donor.index_count = index_count;
  wr3 : range.nindices = index_count;
  wr4 : donor_range.nindices = index_count;
END_ENTITY;
(*
```

Attribute definitions:

current: (inherited) the current mesh;

index_count: (inherited) the number of indices required to reference a vertex.

range: contains the subrange of indices that makes up the interface patch in the **block**;

donor: the adjacent mesh;

donor_range: contains the interface patch subrange of indices for the **donor**;

transform: contains a shorthand notation for the transformation matrix describing the relationship between indices of the two adjacent meshes (see below).

Formal propositions:

wr1: **current** and **donor** shall be different;

wr2: the **index_count**s of **current** and **donor** shall have the same value;

wr3: the **index_count**s of **current** and **range** shall have the same value;

wr4: the **index_count**s of **donor** and **donor_range** shall have the same value.

The shorthand matrix notation used in **transform** has the following properties. The matrix itself has rank **index_count** and contains elements +1, 0, and −1; it is orthonormal and its inverse is its transpose. The transformation matrix (`T`) works as follows: If `Index1` and `Index2` are the indices of a given point on the interface, where `Index1` is in the current mesh and `Index2` is in the adjacent mesh, then their relationship is,

```
Index2 = T.(Index1 - Start1) + Start2
Index1 = Transpose[T].(Index2 - Start2) + Start1
```

where the '`.`' notation indicates matrix-vector multiply, `Start1` and `Finish1` are the subrange indices contained in **range**, and `Start2` and `Finish2` are the subrange indices contained in **donor_range**.

The short-hand notation used in **transform** is as follows. Each element shows the image in the adjacent mesh's face of a positive index increment in the current mesh's face. The first element is the image of a positive increment in i; the second element is the image of an increment in j; and the third (in 3-D) is the image of an increment in k in the current mesh's face. For 3-D, the transformation matrix T is constructed from **transform** $= [\pm a, \pm b, \pm c]$ as follows:

$$\mathtt{T} = \begin{bmatrix} \mathrm{sgn}(a)\mathrm{del}(a-1) & \mathrm{sgn}(b)\mathrm{del}(b-1) & \mathrm{sgn}(c)\mathrm{del}(c-1) \\ \mathrm{sgn}(a)\mathrm{del}(a-2) & \mathrm{sgn}(b)\mathrm{del}(b-2) & \mathrm{sgn}(c)\mathrm{del}(c-2) \\ \mathrm{sgn}(a)\mathrm{del}(a-3) & \mathrm{sgn}(b)\mathrm{del}(b-3) & \mathrm{sgn}(c)\mathrm{del}(c-3) \end{bmatrix},$$

where,

$$\mathrm{sgn}(x) \equiv \begin{cases} +1, \text{ if } x \geq 0 \\ -1, \text{ if } x < 0 \end{cases} \qquad \mathrm{del}(x-y) \equiv \begin{cases} 1, \text{ if } \mathrm{abs}(x) = \mathrm{abs}(y) \\ 0, \text{ otherwise} \end{cases}$$

EXAMPLE 1 **transform** `= [-2, +3, +1]` gives the transformation matrix,

$$\mathtt{T} = \begin{bmatrix} 0 & 0 & +1 \\ -1 & 0 & 0 \\ 0 & +1 & 0 \end{bmatrix}$$

NOTE 1 For establishing relationships between adjacent and current mesh indices lying on the interface itself, one of the elements of **transform** is superfluous since one component of both interface indices remains constant.

NOTE 2 The transform matrix and the two index pairs overspecify the interface patch. For example, `Finish2` can be obtained from **transform**, `Start1`, `Finish1` and `Start2`.

5.4.2 mesh_connectivity

A **mesh_connectivity** specifies the connectivity of a mesh interface.

EXPRESS specification:

```
*)
```



```
ENTITY mesh_connectivity;
  name        : label;
  description : text;
  id          : identifier;
  current     : mesh;
DERIVE
  index_count : INTEGER := current.index_count;
END_ENTITY;

SUBTYPE_CONSTRAINT sc1_mesh_connectivity FOR mesh_connectivity;
  ABSTRACT SUPERTYPE;
  ONEOF(matched_mesh_connection,
        mismatched_mesh_connection);
END_SUBTYPE_CONSTRAINT;
(*
```

Attribute definitions:

name: user-specified instance identifier;

description: annotation;

id: an identifier;

current: the current (receiver) mesh;

index_count: the number of indices required to identify uniquely a vertex or cell in the block.

5.4.3 mesh_overset_hole

An **overset_hole** is a hole, or holes, in an overset mesh.

Grid connectivity for overset meshes may also include 'holes' within meshes, where any mesh data is ignored or 'turned off', because the data in some other overlapping mesh applies instead.

EXPRESS specification:

```
*)
ENTITY mesh_overset_hole
  SUBTYPE OF (mismatched_mesh_connection);
END_ENTITY;
(*
```

NOTE 1 The interface points making up a hole within a mesh may be specified by an element in the **range** list if they constitute a logically rectangular region. Likewise further elements in the list may be used for further logically rectangular holes. The more general alternative is to use **vertices** to list all interface points making up the holes within a mesh. Using the list of **range** specifications, or using **range** in combination with **vertices**, may result in a given hole being specified more than once.

5.4.4 mismatched_donor_mesh

A **mismatched_donor_mesh** is a mesh that acts as a donor for a **mismatched_mesh_region**.

EXPRESS specification:

```
*)
ENTITY mismatched_donor_mesh;
INVERSE
  connect : mismatched_mesh_region FOR donor;
END_ENTITY;

SUBTYPE_CONSTRAINT sc1_mismatched_donor_mesh FOR
                   mismatched_donor_mesh;
  ABSTRACT SUPERTYPE;
  ONEOF(structured_donor_mesh,
        unstructured_donor_mesh);
END_SUBTYPE_CONSTRAINT;
(*
```

Attribute definitions:

connect: the **mismatched_mesh_region** for which this is the **donor**.

5.4.5 mismatched_mesh_connection

A **mismatched_mesh_connection** contains conectivity information for generalized mesh interfaces. Its purpose is to describe mismatched-abutting and overset interfaces for both structured and unstructured meshes, and can also be used for 1-to-1 abutting interfaces.

For abutting interfaces, also referred to as patched or mismatched, an interface patch is the subrange of the face of a mesh that touches one and only one other mesh. This structure identifies the subrange of indices (or array of indices) that make up the interface and gives their image in the adjacent (donor) mesh. It also identifies the adjacent mesh. If a given face of a mesh touches several (say N) adjacent meshes, then N different instances of **mismatched_mesh_connection** are needed to describe all the interfaces. For a single abutting interface, two instances of **mismatched_mesh_connection** are needed — one for each adjacent mesh.

For overset interfaces, this structure identifies the fringe points of a given mesh that lie in one and only one other mesh. If the fringe points of a mesh lie in several (say N) overlapping meshes, then N different instances of **mismatched_mesh_connection** are needed to describe the overlaps. It is possible with overset meshes that a single fringe point may actually lie in several overlapping meshes (though in typical usage, linkage to only one of the overlapping meshes is kept). There is no restriction against a given fringe point being contained within multiple instances of **mismatched_mesh_connection**; therefore, this structure allows the description of a single fringe point lying in several overlapping meshes.

EXPRESS specification:

```
*)
ENTITY mismatched_mesh_connection
  SUBTYPE OF (mesh_connectivity);
  points   : indices_group;
  gridloc  : mesh_location;
END_ENTITY;
```



```
SUBTYPE_CONSTRAINT sc1_mismatched_mesh_connection FOR
                   mismatched_mesh_connection;
  ABSTRACT SUPERTYPE;
  ONEOF(mismatched_mesh_region,
        mesh_overset_hole);
END_SUBTYPE_CONSTRAINT;
(*
```

Attribute definitions:

current: (inherited) the current mesh (the receiver mesh);

index_count: (inherited) the number of indices required to reference a vertex.

points: the indices of the interface points within the current mesh;

gridloc: the location of indices within the current mesh described by **points**. It also identifies the location of indices described by an **index_range** in a donor mesh. This allows the flexibility to describe overset interfaces for cell-centered quantities.

5.4.6 mismatched_mesh_region

A **mismatched_mesh_region** is a mismatched connection that is abutting or overset.

EXPRESS specification:

```
*)
ENTITY mismatched_mesh_region
  SUBTYPE OF (mismatched_mesh_connection);
  donor : mismatched_donor_mesh;
  kind  : mismatched_region_type;
WHERE
  wr1 : donor :<>: SELF\mesh_connectivity.current;
END_ENTITY;
(*
```

Attribute definitions:

donor: an adjacent structured or unstructured donor mesh;

kind: the kind of connection.

Formal propositions:

wr1: the **donor** shall not be the same as the **current**.

Informal propositions:

ip1: when the **kind** is **abutting** the **range** or **vertices** shall describe a face subrange (i.e., points in a single computational grid plane);

ip2: when the **kind** is **abutting** the **structured_donor** shall also describe a face subrange;

5.4.7 multiple_mesh_block

A **multiple_mesh_block** is a grouping of connected meshes. All mesh connectivity information pertaining to the group is contained in the **multiple_mesh_block** structure. This includes abutting interfaces (general mismatched and 1-to-1), overset-grid interfaces, and overset-grid holes.

All the interface patches for a given mesh in the group are contained in the **multiple_mesh_block** entity for that group. If a face of a mesh touches several other meshes (say N), the N different instances of the **mesh_connectivity** structure must be included in the **multiple_mesh_block** to describe each interface patch.

NOTE 1 This convention requires that a single interface patch be described twice — once for each adjacent mesh. It also means that the **multiple_mesh_block** is symmetrical with regard to interface patches.

EXPRESS specification:

```
*)
ENTITY multiple_mesh_block;
  name           : label;
  description    : text;
  id             : identifier;
  connectivities : LIST OF mesh_connectivity;
END_ENTITY;
(*
```

Attribute definitions:

name: user-specified instance identifier;

description: annotation;

id: an identifier;

connectivities: the connectivity information.

5.4.8 structured_donor_mesh

A **structured_donor_mesh** is a **mismatched_donor_mesh** that is structured.

EXPRESS specification:

```
*)
ENTITY structured_donor_mesh
  SUBTYPE OF (mismatched_donor_mesh);
  donor  : structured_mesh;
  points : listed_real_data;
  vsize  : INTEGER;
DERIVE
```



```
  index_count : INTEGER := donor.index_count;
END_ENTITY;
(*
```

Attribute definitions:

donor: the structured donor mesh;

points: the image of the receiver mesh interface points in the donor mesh. These may be thought of as bi- or tri-linear interpolants (depending on **dimension**) in the computational grid of the donor mesh. FORTRAN multidimensional array ordering shall be used;

vsize: the size of the data array necessary to contain the interface points;

index_count: the number of indices required to reference a vertex.

5.4.9 unstructured_donor_mesh

An **unstructured_donor_mesh** is a **mismatched_donor_mesh** that is unstructured.

EXPRESS specification:

```
*)
ENTITY unstructured_donor_mesh
  SUBTYPE OF (mismatched_donor_mesh);
  donor       : unstructured_mesh;
  cells       : indices_group;
  interpolant : property_distribution_description;
  vsize       : INTEGER;
DERIVE
  index_count : INTEGER := donor.index_count;
  cell_dim    : INTEGER := donor.cell_dim;
END_ENTITY;
(*
```

Attribute definitions:

donor: the unstructured donor mesh;

cells: contains the donor cell where the node is located.

interpolants: contains the interpolation factors to locate the node in the donor cell.

vsize: the size of the data array necessary;

index_count: the number of indices required to reference a vertex;

cell_dim: the dimension of a cell in the mesh.

EXPRESS specification:

```
*)
END_SCHEMA;  -- end of mesh_connectivity_schema
(*
```


6 Mesh function

The following EXPRESS declaration begins the **mesh_function_schema** and identifies the necessary external references.

EXPRESS specification:

```
*)
SCHEMA mesh_function_schema;
  REFERENCE FROM mathematical_constructs_schema       -- ISO 10303-50
    (application_defined_function,
     maths_function,
     unary_generic_function,
     function_is_table);
  REFERENCE FROM mesh_topology_schema                 -- ISO 10303-52
    (mesh);
  REFERENCE FROM ISO13584_generic_expressions_schema  -- ISO 13584-20
    (generic_expression,
     unary_generic_expression);
(*
```

NOTE The schemas referenced above can be found in the following parts of ISO 10303:

mathematical_constructs_schema	ISO 10303-50
mesh_topology_schema	Clause 4 of this part of ISO 10303
ISO13584_generic_expressions_schema	ISO 13584-20

6.1 Introduction

This schema defines and describes the structure types for describing mathematical functions defined over meshes.

6.2 Fundamental concepts and assumptions

6.3 mesh_function_schema entity definitions

6.3.1 mesh_function

A **mesh_function** is an **application_defined_function** that:

— has a domain that consists of a table of real tuple spaces;

  The table is a one dimensional array for an unstructured mesh, but can be a rectangular array of any dimension for a structured mesh.

  The real tuples can have different dimensions, if the mesh contains cells of different dimensions.

  The real tuple spaces can have different bounds, if the mesh contains cells of different shape, such as wedges and hexhedra.

— has a set of control values, such that the function within each cell is determined by a subset of the control values and basis for that cell.

The assignment of control values to cells is determined by the topology of the mesh. A control value is usually, but not necessarily, the value of the function at a position within the mesh.

— interpolates or extrapolates separately within each cell from the control values assigned to that cell.

EXPRESS specification:

```
*)
ENTITY mesh_function
  SUBTYPE OF (application_defined_function,
              unary_generic_expression);
  mesh          : mesh;
  basis         : LIST OF mesh_function_basis;
  uniform       : BOOLEAN;
  vertex_values : BOOLEAN;
DERIVE
  control_values : maths_function := SELF\unary_generic_function.operand;
WHERE
  wr1 : function_is_table(control_values);
  wr2 : (uniform AND (SIZEOF(basis) = 1)) XOR
        (NOT uniform);
END_ENTITY;
(*
```

Attribute definitions:

mesh: the **mesh** for the **mesh_function**;

basis: the **mesh_function_basis** specifying the methods of interpolation or extraction for use within each cell of the **mesh**;

uniform: a flag which indicates whether or not the the **mesh_function** has a uniform basis, as follows:

— if **uniform** is true, then each cell of the mesh has the same **mesh_function_basis**;

— if **uniform** is false, then a **mesh_function_basis** is specified separately for each cell of the **mesh**.

vertex_values: a flag that indicates whether or not the **control_values** are specified for the vertices or the cells of the **mesh**, as follows:

— if **vertex_values** is true, then the **control_values** are specified for the vertices of the **mesh**;

— if **vertex_values** is false, then the **control_values** are specified for a separate pattern of discretisation points for each cell of the **mesh**.

control_values: the table that specifies the control values at the vertices of the cells of the **mesh** or at the discretisation points of each cell.

The table shall be a function with:

Table 5 – Domain of the control values table for a mesh_function

mesh	location	domain
unstructured	values at vertices	i where: — i is the position in the vertex array specified for the unstructured mesh.
unstructured	discretisation points for each cell	$j_1, j_2, \ldots j_m, i$ where: — $j_1, j_2, \ldots j_m$ is the position in the pattern of discretisation points, for the cell basis; — i is the position in the cell array specified for the unstructured mesh.
structured	values at vertices	$i_1, i_2, \ldots i_n$ where: — $i_1, i_2, \ldots i_n$ is the index of the vertex in the structured mesh.
structured	discretisation points for each cell	$j_1, j_2, \ldots j_m, i_1, i_2, \ldots i_n$ where: — $j_1, j_2, \ldots j_m$ is the position in the pattern of discretisation points, for the cell basis; — $i_1, i_2, \ldots i_n$ is the index of the vertex the structured mesh.

domain: integer tuple space that identifies the vertices or discretisation points of the **mesh_function**;

range: that is the same as the range of the **mesh_function**.

The components of the integer tuple space domain are shown in Table 5.

Formal propositions:

wr1: the control values shall be a table;

wr2: if **uniform_basis** is true, then the length of the basis list shall be 1.

6.3.2 mesh_function_basis

A **mesh_function_basis** is an **application_defined_function** that has:

— a domain that is a real tuple space; and

— a range that is a space of table functions.

NOTE 1 A **mesh_function_basis** is used such that the domain is a parametric space that identifies points within a cell of a mesh. Hence the dimension of the real tuple space is the same as the topological dimension of the cell.

Each table function in the range of a **mesh_function_basis** has:

— a domain that is a subscript space; and

— a range that is the reals.

NOTE 2 A **mesh_function_basis** is used such that:

— the domain of each table function in its range is a parametric space that identifies the control values for a cell;

— the range of each table function is a weighting for a control value.

Each table function specifies the weightings for control values that define the value of a **mesh_function** at a point in a cell.

NOTE 3 An Application Module can define a subtype of **mesh_function_basis** and **externally_defined_item** to record a standard instance of a function such as the 'serendipity' function commonly used in finite element analysis.

EXPRESS specification:

```
*)
ENTITY mesh_function_basis
  SUBTYPE OF (application_defined_function,
              unary_generic_expression);
  cell_topological_dimension : INTEGER;
  value_array_dimension      : INTEGER;
  value_array_order          : ARRAY [1:value_array_dimension] OF INTEGER;
DERIVE
  value_positions : maths_function := SELF\unary_generic_function.operand;
WHERE
  value_positions_as_table : function_is_table(value_positions);
END_ENTITY;
(*
```

Attribute definitions:

cell_topological_dimension: the dimension of the real tuple space that is the domain of the **mesh_function_basis**;

value_array_dimension: the dimension of the subscript space for each table function in the range of the **mesh_function_basis**;

value_array_order: the number of control values less one, for each value array direction;

value_positions: the table that specifies the 'positions' of the control values within the domain of the **mesh_function_basis**. The 'position' of a control value is the point within the domain that has a weighting of 1.0 for that control value and a weighting of 0.0 for all other control values.

The **value_positions** table shall be a function that has:

— a domain that is an integer tuple space that identifies discretisation points for a cell; and

— a range that is a real tuple space that identifies positions in a cell.

A control value for a **mesh_function_basis** need not have a position. Whether or not a control value has a position is determined by the **mesh_function_basis**. If a control value does not have a position then the corresponding value of the **value_positions** function is of no signficance.

Formal propositions:

value_positions_as_table: the **value_positions** shall be a table.

Informal propositions:

consistent_topology_dimension: the **cell_topological_dimension** shall be the same as the **topological_dimension** of any **topological_region** to which the **mesh_function_basis** is assigned.

consistent_value_position_table_domain: the domain of the table of control value positions shall be consistent with the **value_array_order**. It shall be the tuple space that is the Cartesian product of integer intervals $[1, n_1] \times [1, n_2] \times \cdots [1, n_m]$, where:

— m is the **value_array_dimension**; and

— n_i is **value_array_order**[i] + 1.

consistent_value_position_table_range: the dimension of the tuple space that is the range of the table of control positions shall be equal to the **cell_topological_dimension**.

valid_weighting_at_value_position: if a control value is assigned to a position, then the value of the **mesh_function_basis** at that position shall be:

— 1 for the control value assigned to the position;

— 0 for all other control values.

6.4 mesh_function_schema subtype constraint definitions

6.4.1 sc1_application_defined_function

There is a ONEOF relationship between the **mesh_function** and **mesh_function_basis** subtypes of **application_defined_function**.

EXPRESS specification:

```
*)
SUBTYPE_CONSTRAINT sc1_application_defined_function FOR
                   application_defined_function;
  ONEOF(mesh_function,
        mesh_function_basis);
END_SUBTYPE_CONSTRAINT;
(*
```


6.4.2 sc1_unary_generic_expression

There is a ONEOF relationship between the **mesh_function** and **mesh_function_basis** subtypes of **unary_generic_expression**.

EXPRESS specification:

```
*)
SUBTYPE_CONSTRAINT sc1_unary_generic_expression FOR
                   unary_generic_expression;
  ONEOF(mesh_function,
        mesh_function_basis);
END_SUBTYPE_CONSTRAINT;
(*
```

EXPRESS specification:

```
*)
END_SCHEMA;  -- end of mesh_function_schema
(*
```


Annex A
(normative)
Short names of entities

Table A.1 provides the short names of entities specified in this part of ISO 10303. Requirements on the use of short names are found in the implementation methods included in ISO 10303.

NOTE The short names are available from the Internet — see annex C.

Table A.1 – Short names of entities

Entity data types names	Short names
array_based_unstructured_mesh	ABUM
array_based_unstructured_mesh_and_vertices	ABUMAV
cell_of_structured_mesh	COSM
composition_of_structured_mesh	COS0
explicit_unstructured_mesh	EXUNMS
explicitly_defined_cell_patch	EDCP
explicitly_defined_vertex_patch	EDVP
indices_list	INDLST
indices_range	INDRNG
matched_mesh_connection	MTMSCN
mesh	MESH
mesh_connectivity	MSHCNN
mesh_derived_maths_space	MDMS
mesh_function	MSHFNC
mesh_function_basis	MSFNBS
mesh_overset_hole	MSOVHL
mismatched_donor_mesh	MSDNMS
mismatched_mesh_connection	MSMSCN
mismatched_mesh_region	MSMSRG
multiple_mesh_block	MLMSBL
product_of_mesh	PROFMS
rind	RIND
structured_donor_mesh	STDNMS
structured_mesh	STRMSH
structured_mesh_with_rind	SMWR
topological_region	TPLRGN
topological_region_with_boundary	TRWB
unstructured_donor_mesh	UNDNMS
unstructured_mesh	UNSMSH
vertex_defined_cell	VRDFCL
vertex_range_defined_patch	VRDP

Annex B
(normative)
Information object registration

B.1 Document identification

To provide for unambiguous identification of an information object in an open system, the object identifier

{ iso standard 10303 part(52) version(-1) }

is assigned to this part of ISO 10303. The meaning of this value is defined in ISO/IEC 8824-1, and is described in ISO 10303-1.

B.2 Schema identification

To provide for unambiguous identification of the schema-name in an open information system, the object identifier

{ iso standard 10303 part(52) version(1) schema(1) mesh-topology-schema(1) }

is assigned to the **mesh_topology_schema** schema (see 4). The meaning of this value is defined in ISO/IEC 8824-1, and is described in ISO 10303-1.

To provide for unambiguous identification of the schema-name in an open information system, the object identifier

{ iso standard 10303 part(52) version(1) schema(1) mesh-connectivity-schema(1) }

is assigned to the **mesh_connectivity_schema** schema (see 5). The meaning of this value is defined in ISO/IEC 8824-1, and is described in ISO 10303-1.

To provide for unambiguous identification of the schema-name in an open information system, the object identifier

{ iso standard 10303 part(52) version(1) schema(1) mesh-function-schema(1) }

is assigned to the **mesh_function_schema** schema (see 6). The meaning of this value is defined in ISO/IEC 8824-1, and is described in ISO 10303-1.

Annex C
(informative)
EXPRESS listing

This annex references a listing of the EXPRESS entity data type names and corresponding short names as specified in this part of ISO 10303. It also references a listing of each EXPRESS schema specified in this part of ISO 10303, without comments or other explanatory text. These listings are available in computer-interpretable form and can be found at the following URLs:

Short names: `<http://www.mel.nist.gov/div826/subject/apde/snr/>`
EXPRESS: `<http://www.mel.nist.gov/step/parts/part52/cd/>`

If there is difficulty accessing these sites contact ISO Central Secretariat or contact the ISO TC 184/SC4 Secretariat directly at: `sc4sec@cme.nist.gov`.

NOTE The information provided in computer-interpretable form at the above URLs is informative. The information that is contained in the body of this part of ISO 10303 is normative.

Annex D
(informative)
EXPRESS-G diagrams

The diagrams in this annex correspond to the EXPRESS schemas specified in this part of ISO 10303. The diagrams use the EXPRESS-G graphical notation for the EXPRESS language. EXPRESS-G is defined in annex D of ISO 10303-11.

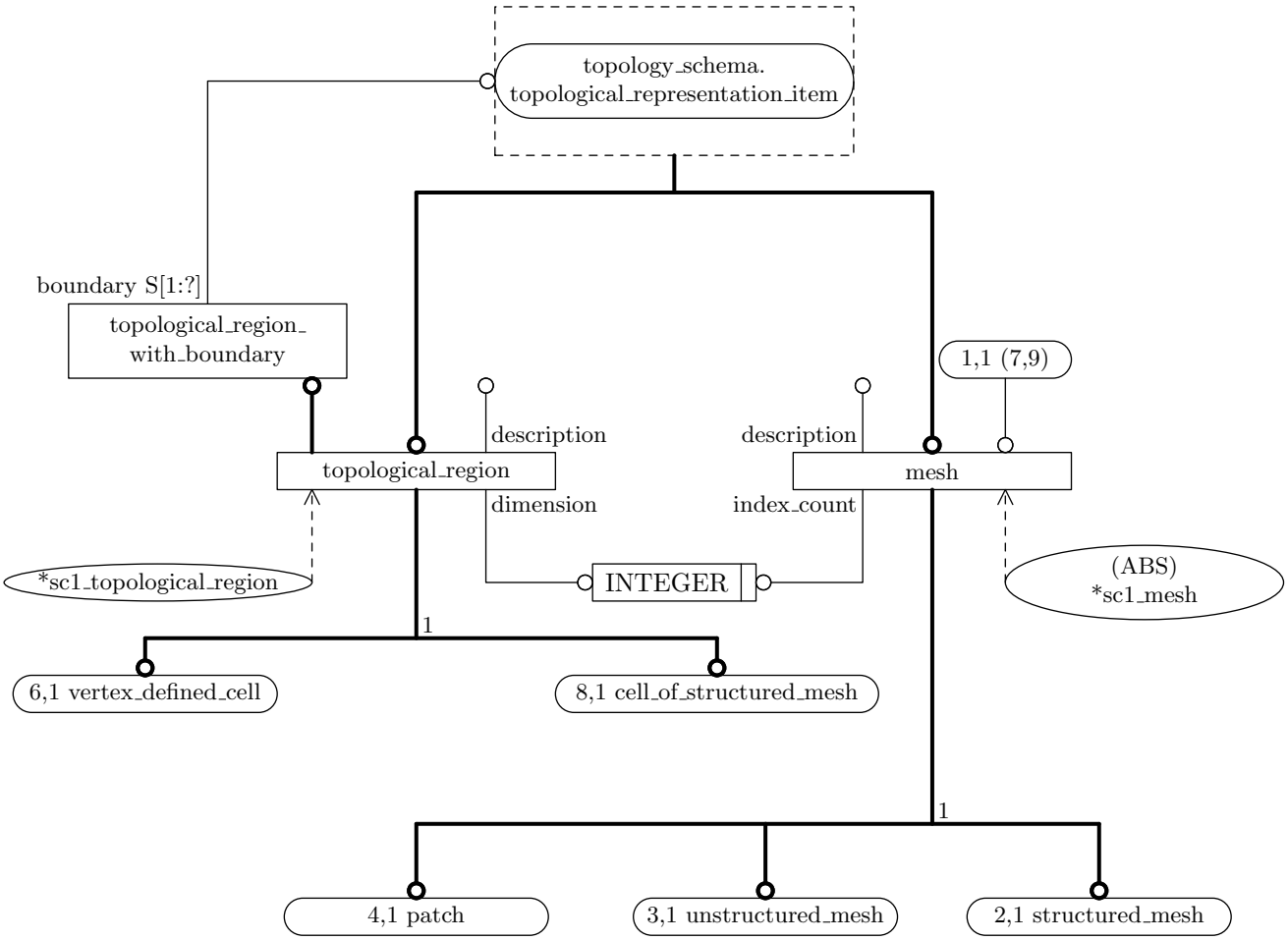


Figure D.1 – Entity level diagram of mesh_topology_schema schema (page 1 of 10)

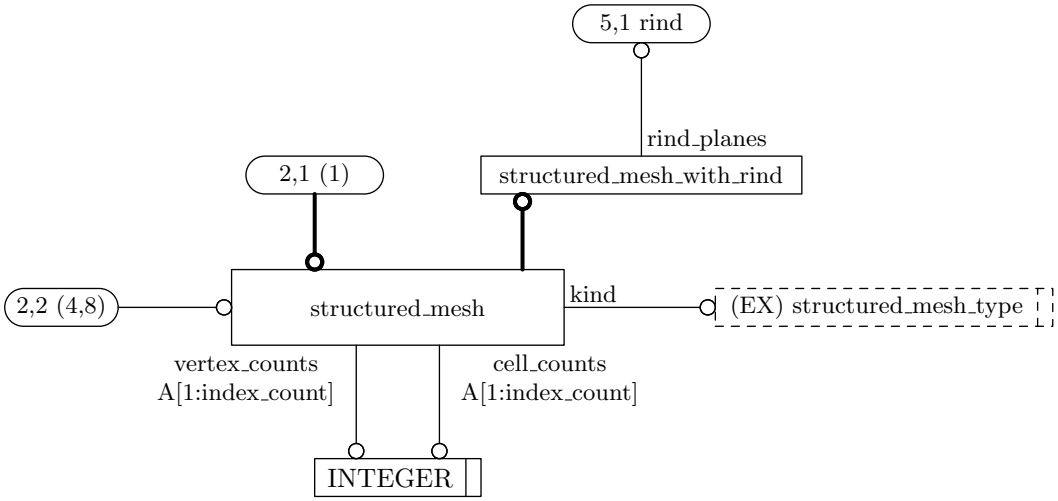


Figure D.2 – Entity level diagram of mesh_topology_schema schema (page 2 of 10)

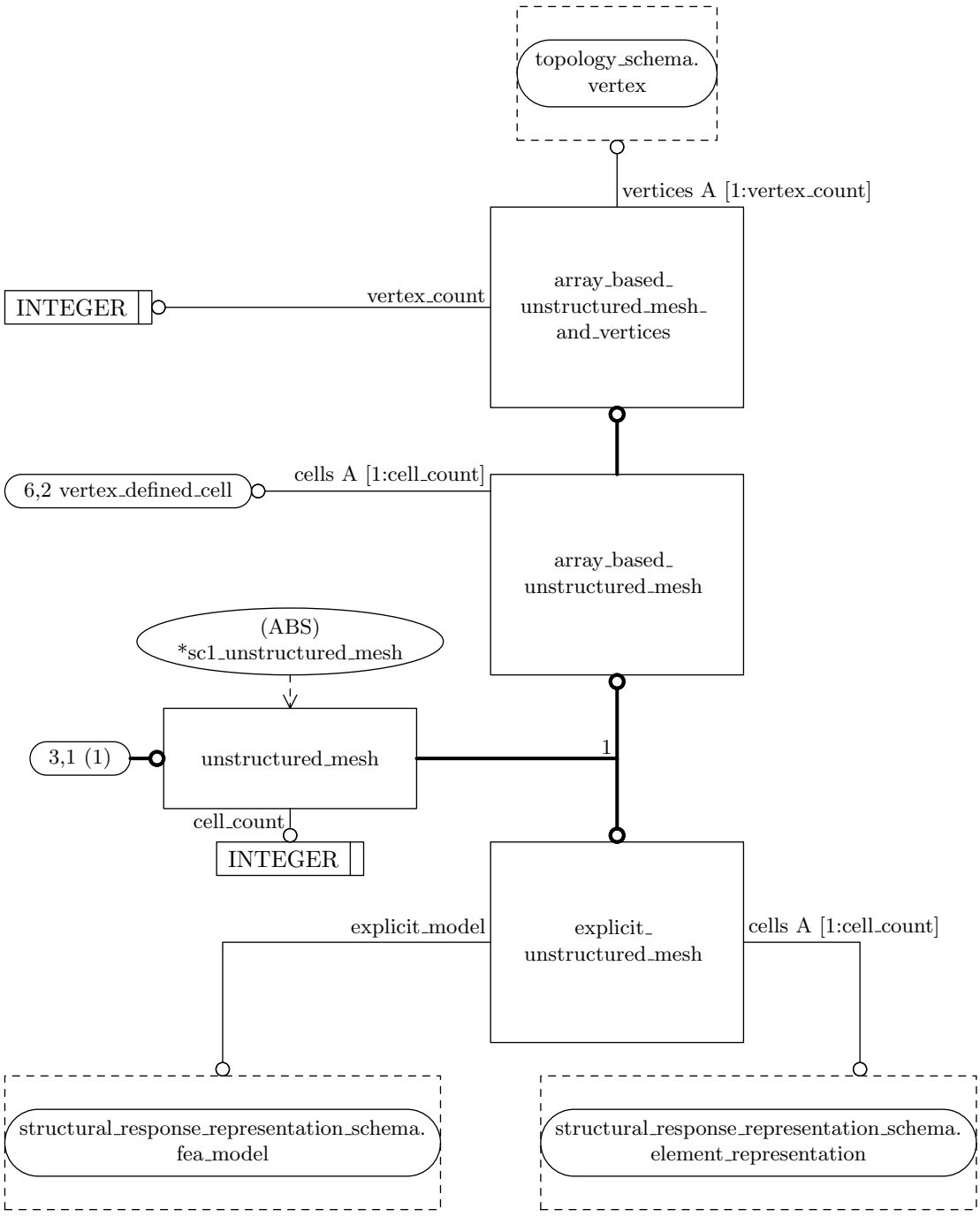


Figure D.3 – Entity level diagram of mesh_topology_schema schema (page 3 of 10)

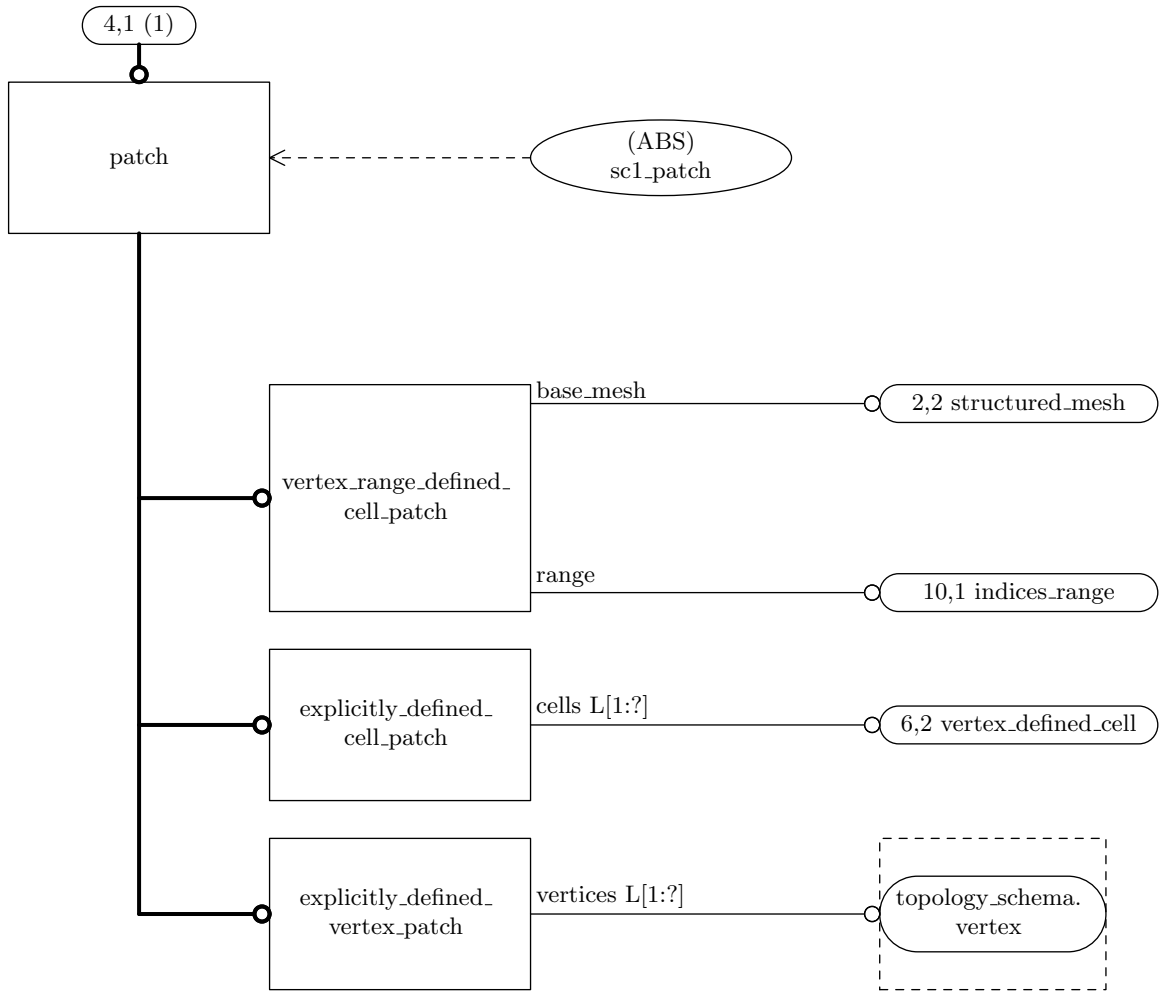


Figure D.4 – Entity level diagram of mesh_topology_schema schema (page 4 of 10)

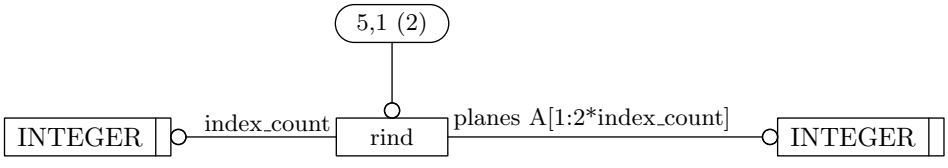


Figure D.5 – Entity level diagram of mesh_topology_schema schema (page 5 of 10)

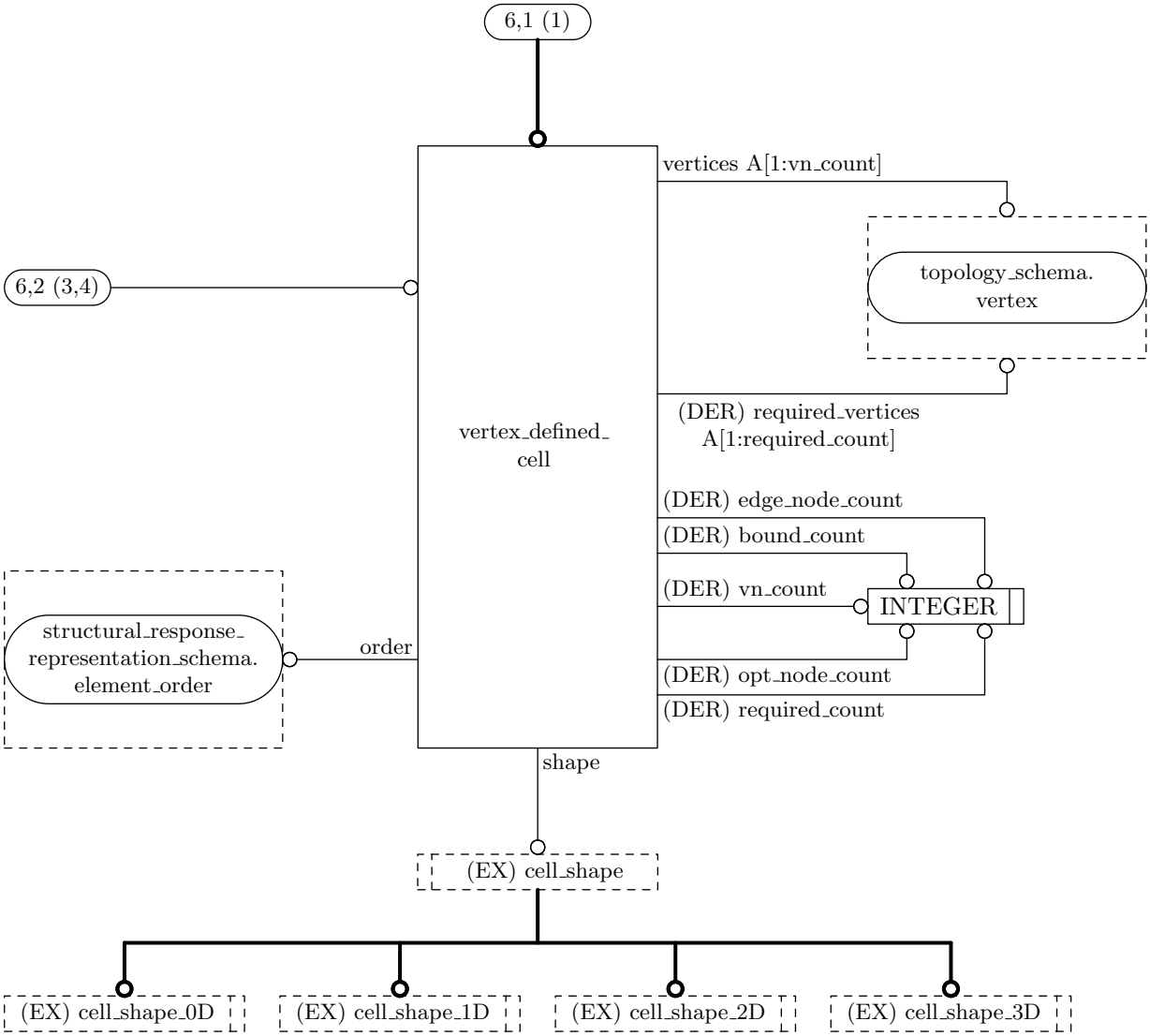


Figure D.6 – Entity level diagram of mesh_topology_schema schema (page 6 of 10)

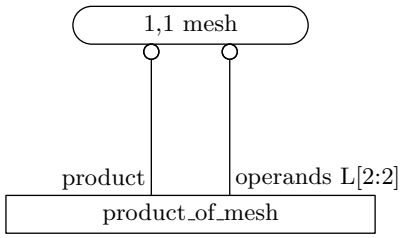


Figure D.7 – Entity level diagram of mesh_topology_schema schema (page 7 of 10)

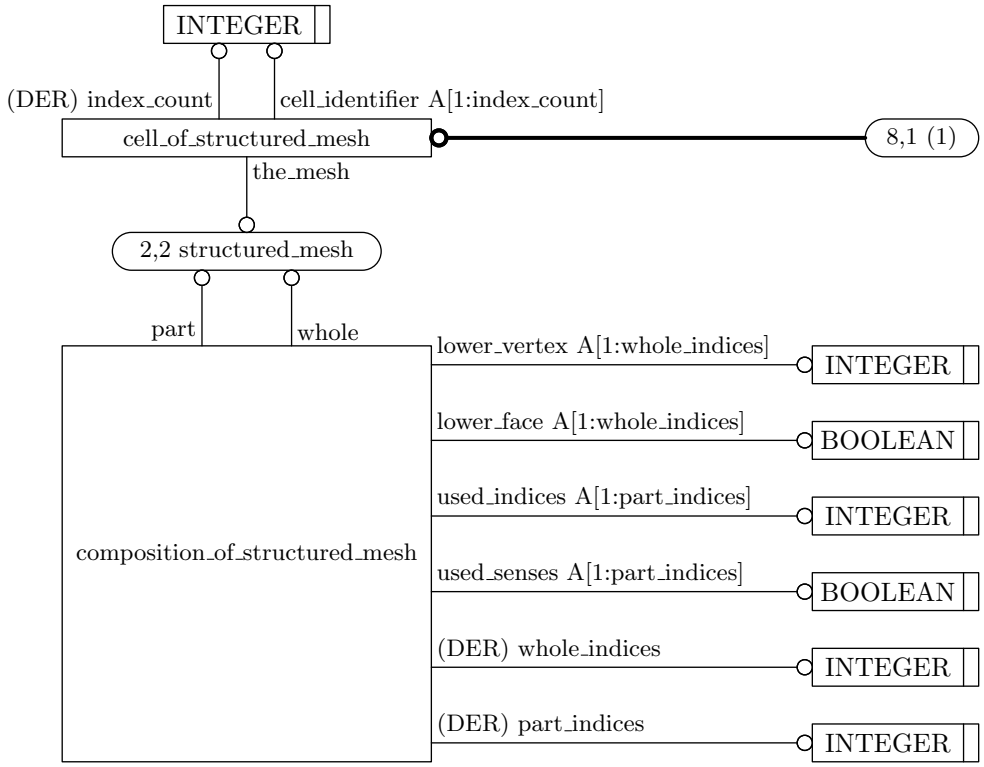


Figure D.8 – Entity level diagram of mesh_topology_schema schema (page 8 of 10)

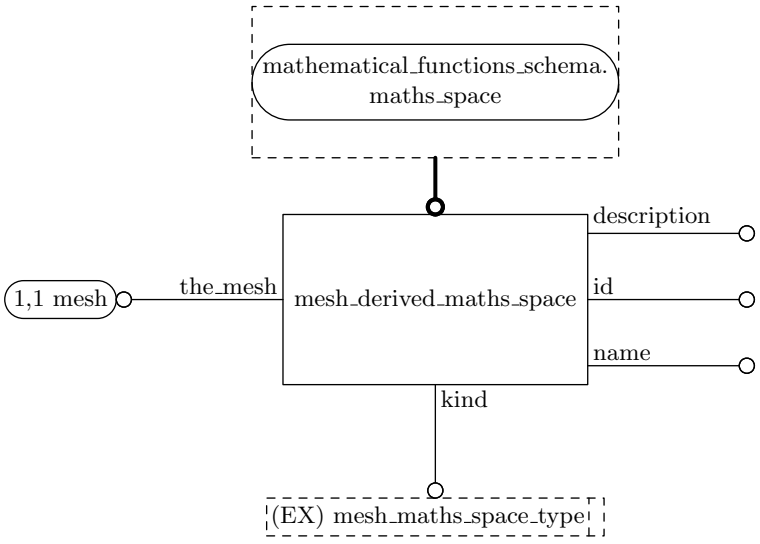


Figure D.9 – Entity level diagram of mesh_topology_schema schema (page 9 of 10)

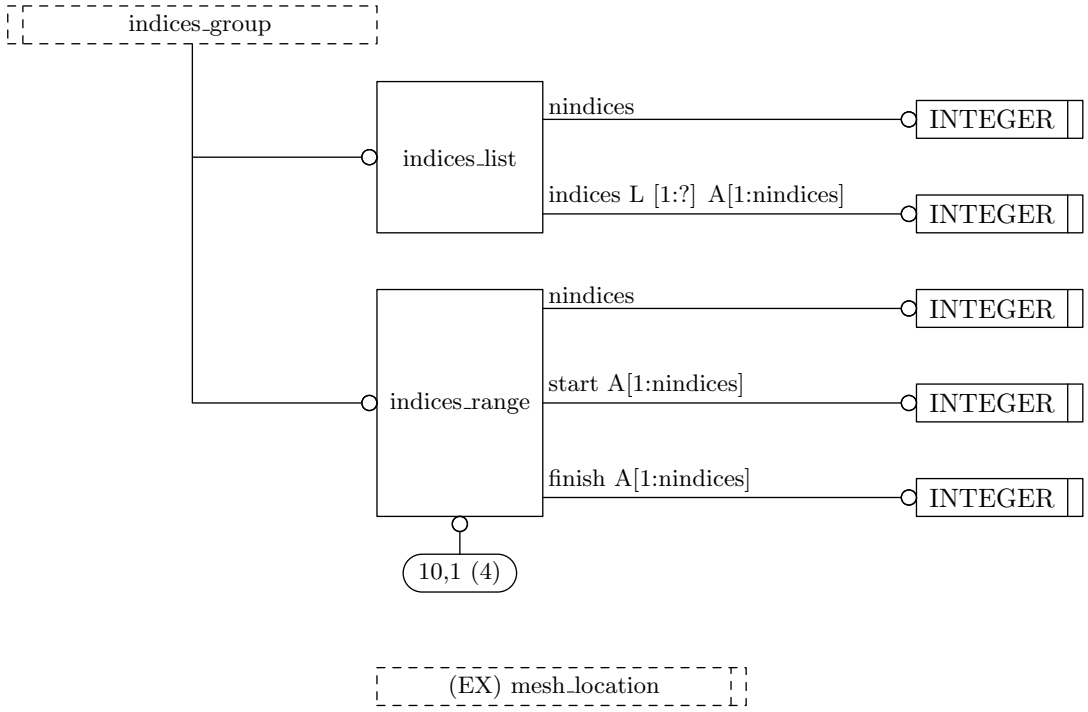


Figure D.10 – Entity level diagram of mesh_topology_schema schema (page 10 of 10)

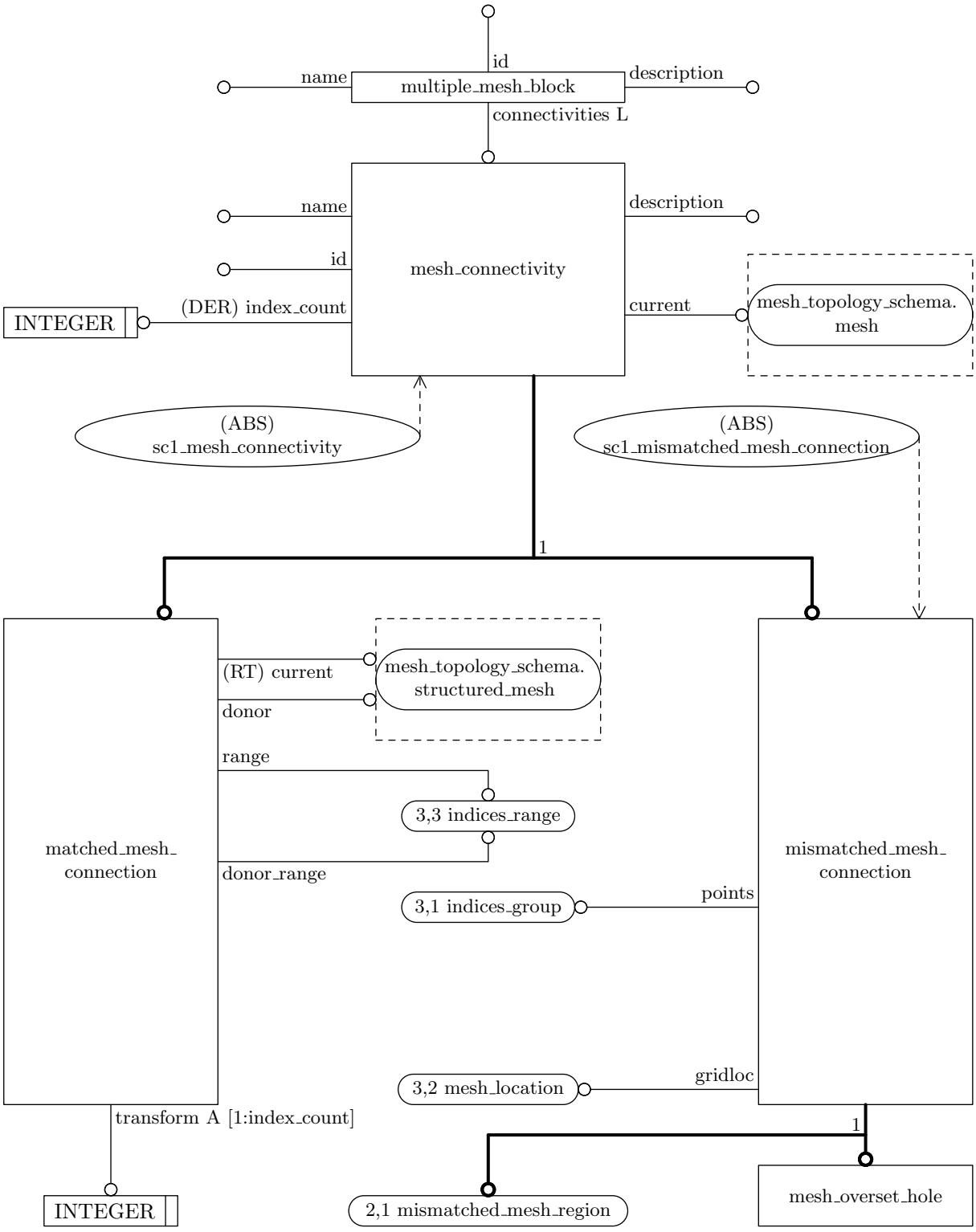


Figure D.11 – Entity level diagram of mesh_connectivity_schema schema (page 1 of 3)

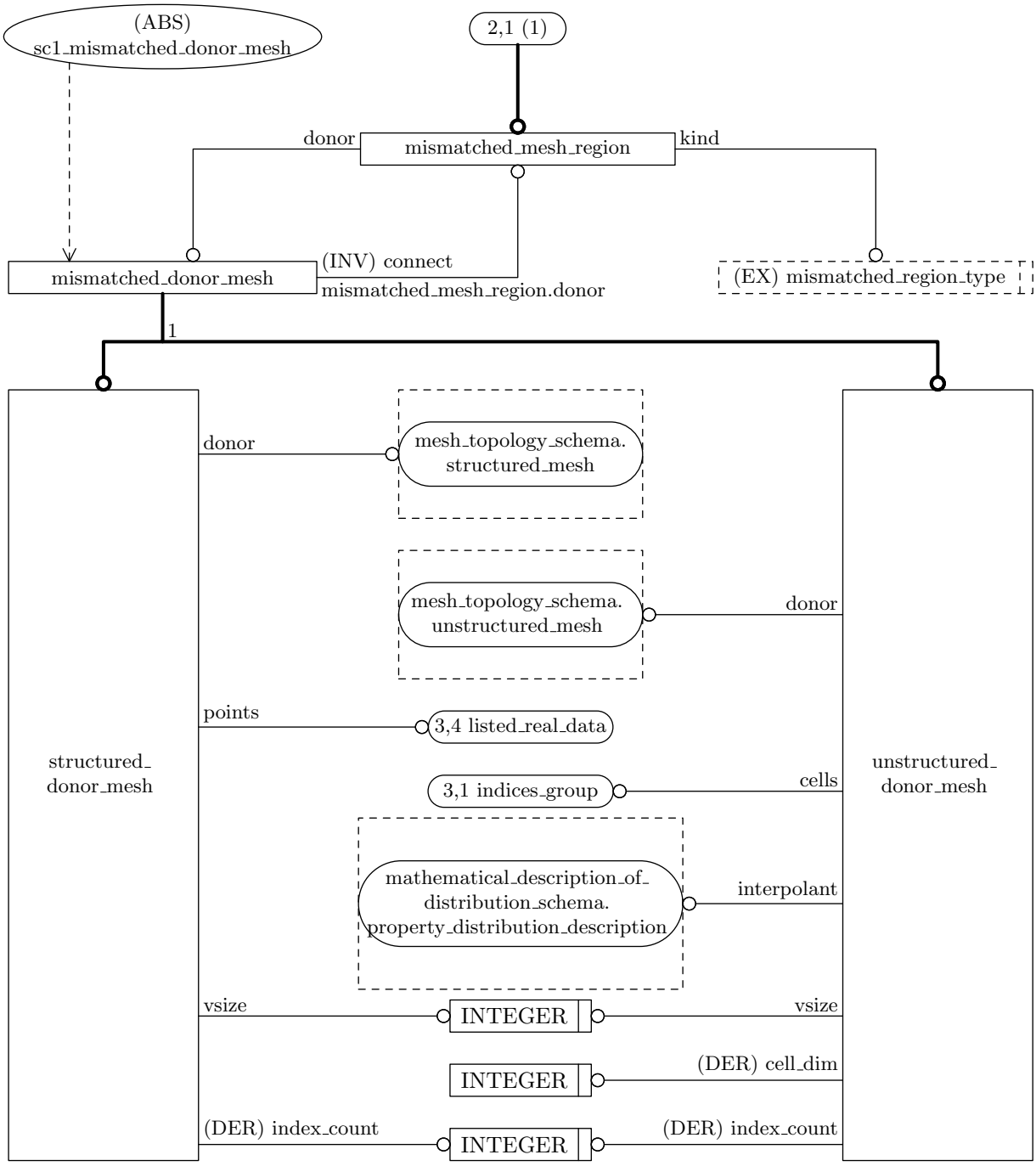


Figure D.12 – Entity level diagram of mesh_connectivity_schema schema (page 2 of 3)

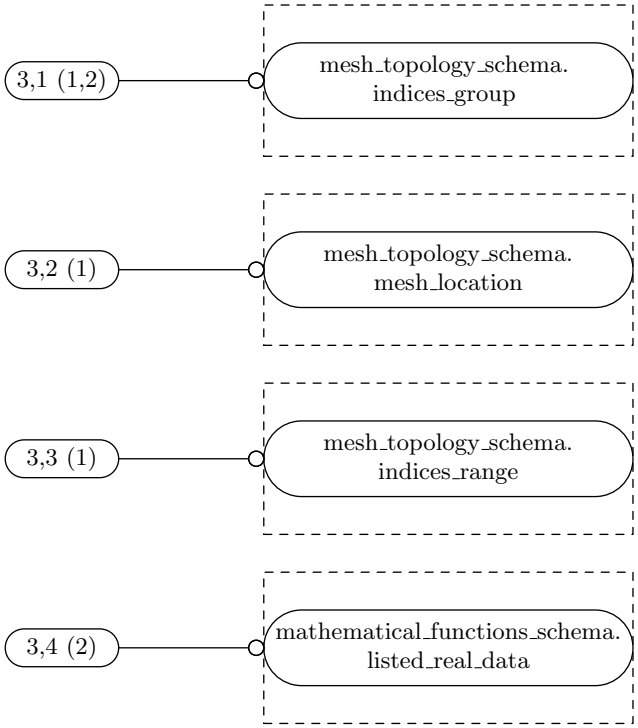


Figure D.13 – Entity level diagram of mesh_connectivity_schema schema (page 3 of 3)

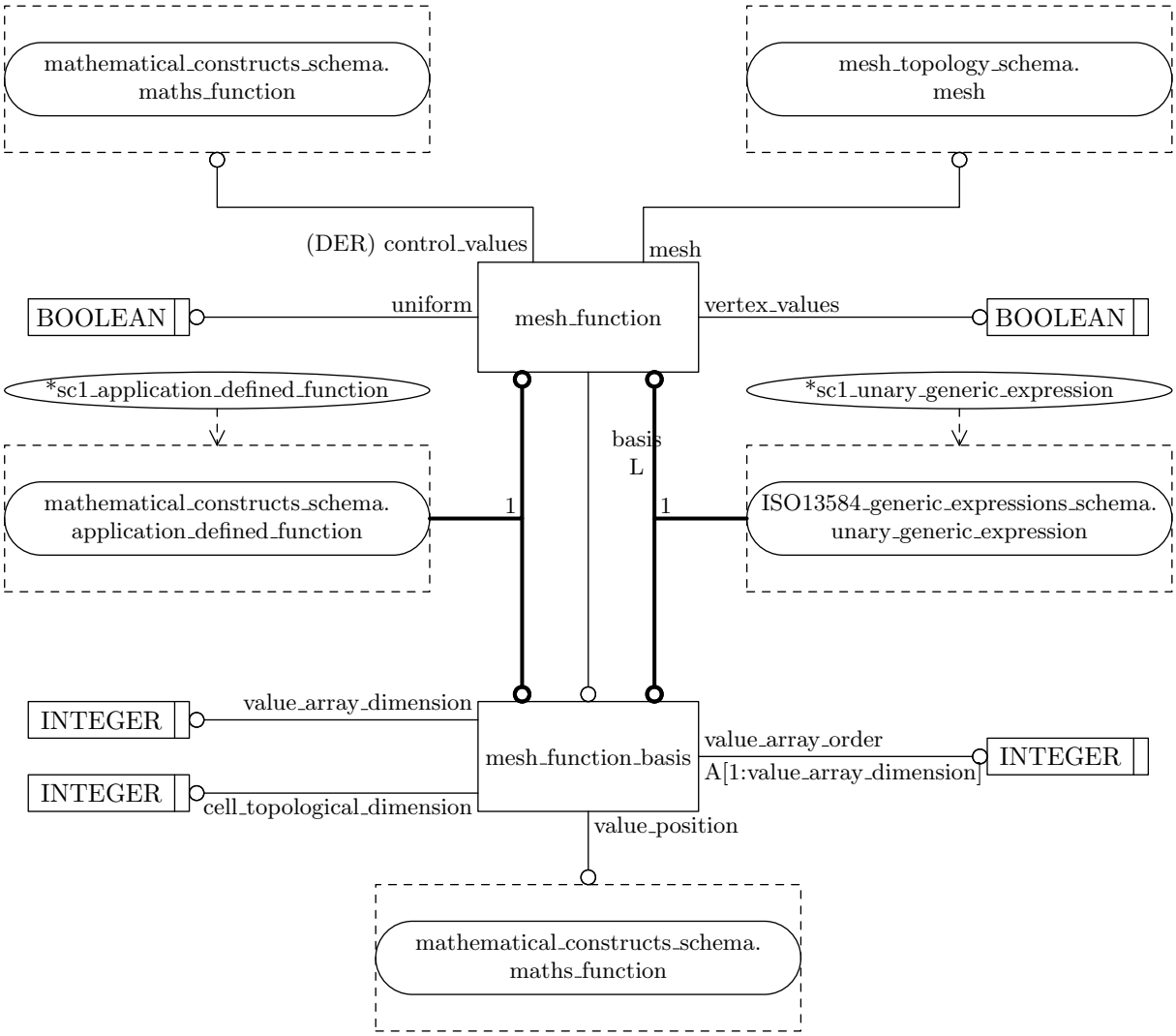


Figure D.14 – Entity level diagram of mesh_function_schema schema (page 1 of 1)

Annex E
(informative)
Additional information

Table E.1 lists the elements of the **mesh_topology_schema** that are used by other schemas.

Table E.1 – Elements of mesh_topology_schema used by other schemas

Element	Used in schema	By element
indices_group	**mesh_connectivity_-schema**	**mismatched_mesh_connection** **unstructured_donor_-mesh**
indices_range	**mesh_connectivity_-schema**	**matched_mesh_connection**
mesh	**mesh_connectivity_-schema** **mesh_function_schema**	**mesh_connectivity** **mesh_function**
mesh_location	**mesh_connectivity_-schema**	**mismatched_mesh_connection**
structured_mesh	**mesh_connectivity_-schema**	**matched_mesh_connection** **structured_donor_mesh**
unstructured_mesh	**mesh_connectivity_-schema**	**unstructured_donor_-mesh**

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