A proposed ISO 10303 (STEP)-based approach for representing heterogeneous objects for layered manufacturing

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Abstract

Solid modeling of objects forms an important task in design and manufacturing. Recent developments in the field of layered manufacturing (LM) have shown potential for the physical realization of heterogeneous (multi-material) objects. Thus, there is a need to represent material information as an integral part of the CAD model data.

Slicing of the CAD model is an inherent part of process planning for LM. There is a need for a neutral 2D slice format to transfer data from the CAD system (slicing is done on the 3D CAD model) to the commercial LM machine. This can also be used as a file format to demonstrate inter-operability among LM machines having comparable layer thickness specifications. To fabricate heterogeneous objects, the slice format should be capable of representing both material and geometry information.

Information models for the representation of product data are being developed as an international standard (ISO 10303) informally called STEP. However, the current application protocols focus on the representation of homogeneous objects only. This paper suggests an information model to represent heterogeneous objects using the information modeling methodology developed for ISO 10303. The information model

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is then extended to represent the 2D slice information using concepts from ISO 10303. The proposed formats are validated by physical realization of objects on different LM machines. This information model will help in providing a uniform base in the development of heterogeneous solid modeling systems. It will also equip the solid modeler with the ability to integrate with other applications and process planning in the domain of layered manufacturing.

1 Introduction

Layered manufacturing / rapid prototyping, also known as solid freeform fabrication (SFF), is an additive manufacturing process in which objects are constructed by deposition of material in layers, usually in terms of a sequence of parallel planar laminae. Many layered manufacturing (LM) processes have been developed in recent years, using different materials and bonding methods. Although LM was originally used for rapid prototyping to help the designer verify part form and fit (geometry), it is now progressing towards the production of functional parts. It has also shown significant potential for the manufacture of unique and small batch production parts.

Until recently, the domain of solid modeling focused mainly on modeling of solids to capture geometry and topology of external and internal features. Information about material gradation has not been an integral part of the Computer Aided Design (CAD) model data. Thus, all down-line process planning assumes the presence of homogeneous material distribution throughout the interior of the solid.

The exigencies of optimal design specify the need for functionally graded or non-homogeneous material compositions. These heterogeneous objects are composed of different constituent materials and can exhibit continuously varying composition and/or micro-structure, thus producing a gradation in their properties [1]. Due to its additive nature, LM is well suited to the fabrication of heterogeneous objects. It can deposit several materials in varying compositions within a layer and with variations between adjacent layers.

Heterogeneous objects have found use in several engineering applications. Therefore, there is a need to be able to design and manufacture heterogeneous objects [1]. However, currently there does not exist the capability to create a three-dimensional (3D) CAD model that can represent a product's solid interior, in terms of continuously varying material compositions. It is expected that the development of a representation suitable for this area can also be applied to represent color, porosity, and other properties that have gradient characteristics. Some of the reasons that make such a representation essential in the design domain are as follows:

- All LM technologies are computer based and use the CAD model for the purpose of process planning and fabrication of the part.
- Orientation of an object to be fabricated will depend on material composition and variation in a particular direction and across a cross-section as well.
- Slicing calculations will require material information because the minimum and maximum allowed layer thicknesses vary with different materials.
- Applications for analysis (thermal, structural, etc.) will require such information to be incorporated in the CAD model itself.

Slicing is an inherent part of the process of LM. However, slicing may best be done in the CAD system on the 3D solid model itself [2]. The need for a neutral format for the purpose of slice information is presented in [2]. Such a format should encapsulate exact, rather than faceted geometric information. There is no de facto standard to represent such slice information. With the advent of LM techniques to manufacture heterogeneous objects, the neutral format should also be able to represent both the material and the geometry information in the 2D slice domain.

Thus, the absence of representations to integrate material and geometry information at the design stage will hinder new developments in LM technology as key process planning steps depend on such a representation. A standard information model for this representation is required to realize the following objectives:

- Provide a uniform base to develop heterogeneous solid modeling systems.

- Transfer of data in a standard format among various CAD/CAE systems such that it can be used efficiently for the engineering analysis and process planning in the LM environment.

ISO 10303 (informally known as STEP) is an international standard for the electronic exchange of product data between computer aided design and other computer-based systems used in the product life-cycle. This paper focuses on an aspect of the representation of heterogeneous objects, and utilizes a modeling methodology suitable for possible use in the application of STEP to layered manufacturing.

This paper is built upon the work reported in [3]. This work focused on the development of an IS0 10303 representation scheme for heterogeneous solids. However, an information model to represent heterogeneous slices is necessary because slicing forms a fundamental step in the process planning for LM [2]. A slice level representation is also a means to validate the 3D representation by fabrication of physical parts. This paper also presents a data planning model to represent slice level information. It further reports development of software to convert the slice representation file to machine-specific slice formats so that example parts can be physically fabricated on commercial machines.

Section 2 presents a brief review of various approaches for heterogeneous solid representation and considers one of them for elaboration in subsequent sections. Section 3 focuses on the motivation to use STEP for such a representation. Details of the proposed information models are discussed at two levels (solid level and slice level) in Section 4. Validation of the proposed data planning models (DPM) is presented in Sections 5 and 6. The paper concludes with some observations and issues for future research.

2 Heterogeneous solid modeling schemes

Heterogeneous solid modeling aims to incorporate information about material distribution along with geometric information into a CAD model. This necessitates the definition of a function that can represent the material macrostructure. This section summarizes various research efforts in modeling heterogeneous objects.

Irregular *tetrahedral decompositions* of the finite element type provide possibilities for modeling of material distributions. A solid model created on a state-of-the-art CAD system is meshed into finite elements (tetrahedra). The topology is maintained using the cell-tuple structure as a graph of cells. Every cell is then associated with information about the composition and the geometry. Material space is defined as M, spanning the d_m materials available to the LM machine. The material composition of the model is represented as a vector valued function $m(x)$ defined over the interior of the model. The designer specifies the overall variation in terms of distance from a particular feature. This expression is used to obtain the volume fractions at the vertices of each tetrahedron. The composition in the interior of the cell is then obtained in terms of a set of control points and control compositions blended with barycentric Bernstein polynomials. Representing objects using this strategy is the subject of [4].

Voxel based representation is a special case of cell decomposition. The cell is cubical in shape and is located in a fixed grid. A voxel (x,y,z) in a 3D discrete space is defined by a unit cube centered at (x,y,z). Voxelization is the process of converting a geometrically represented 3D object into a voxel model defined by a set of voxels. The voxelization is such that the voxel size is uniform and every voxel is small enough to be considered as a homogeneous lump. A scalar value associated with every voxel indicates the material that is associated with that voxel. Voxelization is independent of the material distribution function. This representation allows the designer to selectively assign materials to individual voxels. More details on this representation can be found in [5].

The *R-function method* interpolates boundary conditions directly from the geometric model using normalized functions. Normalized functions are smooth functions that approximate distance functions in the neighborhood of the boundary and can be constructed automatically from most geometric representations (e.g. boundary representation) using the theory of R-functions. More detail on this theory can be obtained from [6]. This theory appears to have the potential to represent the variation of material composition in the interior of a solid.

Along with the above, several other schemes are being proposed for the representation of heterogeneous objects [7, 8].

The $\mathbf{r_m}$ *object model* is a set based approach to represent multi-material objects. It is based on exact representation of geometry and associating a material distribution function with this geometry. The product space $\mathbf{T} = \mathbf{E}^3 \times \mathbf{R}^n$ forms the mathematical space to model heterogeneous objects. Material points are restricted to lie in the material space $\mathbf{V} \subset \mathbf{R}^n$. Each point p in the object $\mathbf{S}$ is a combination of n primary materials and is specified by the volume fractions of these primary materials. These volume fractions must sum to unity. Thus, each point $p \in S$ can be modeled as a point $(x \in \mathbf{E}^3,\ v \in \mathbf{V})$ in $\mathbf{T}$, where x and v represent the geometric and material points respectively. This approach is based on the notion of an $\mathrm{r_m}$ set which is defined as a subset $D \equiv (P, B)$ of $\mathbf{T}$ where $P \subset \mathbf{E}^3$ is an r-set [9] and $B \subseteq \mathbf{V}$ assigns material to the r-set P. The set B is specified by a material function F which is required to be C^∞. Thus, an $\mathrm{r_m}$ set can also be defined as the pair (P, F) where the subset B is defined implicitly through its material function as $F(P)$. To represent a physical object, an $\mathrm{r_m}$-object is then defined as a finite collection of $\mathrm{r_m}$-sets $\{(P_j, B_j)\}$ such that the $\mathrm{r_m}$-sets are minimal and are geometrically interior-disjoint. More details on this approach can be obtained in [1].

Heterogeneous Solid Modeling is an important new topic that is receiving increased attention. Our brief survey was not intended to be exhaustive and the interested reader is urged to delve into the references for more details and further literature on this and related topics.

The focus of this paper is not the representation of heterogeneous objects per se. Instead we consider one representation scheme for heterogeneous objects and investigate extensions necessary within ISO 10303 (STEP) for supporting it. While all representation methods studied above have their advantages and disadvantages, we chose the $\mathrm{r_m}$-object model approach since we are most familiar with it. In the remainder of this paper, all discussion about heterogeneous solid representations and STEP extensions is in the context of this scheme.

3 Motivation for the use of ISO 10303

Information about exact geometry, materials and their distribution, and tolerances needs to be represented and exchanged in computer-compatible format. A detailed study of existing standards for representing objects in LM and data formats for exchanging model information in the domain of Layered Manufacturing has been presented in [2, 10].

The need to represent and manufacture heterogeneous solids coupled with the possibility that some stages of process planning may migrate into the CAD domain leads to the necessity of development of a standard data representation for layered manufacturing. There is ample justification for the suitability of ISO 10303 for this purpose [2, 10, 11].

ISO 10303 (STEP)

ISO 10303 (informally known as STEP - STandard for the Exchange of Product model data) is an evolving international standard for the computer-interpretable representation and exchange of product data for engineering purposes. The nature of this description makes it suitable for neutral file exchange, and also as a basis for implementing and sharing product databases [12].

ISO 10303 is intended ultimately to cover a wide range of product types and product life-cycle stages. It is being issued as a series of parts, including Generic Resources, Description Methods, Implementation Methods and Application Protocols (APs). APs are complex data models used to describe specific product-data applications and are meant to be implementable. These parts describe not only what data is to be used in describing a product, but also how the data is to be used in the model. Thus actual information exchanges are based on the application protocols.

Currently, there is no STEP AP in the area of LM. However, following several meetings of an informal interest group, a formal project has been recently launched in ISO TC184/SC4 (the sub-committee responsible for ISO 10303 development) to fill this gap in the spectrum of manufacturing related activities covered by ISO 10303.

Table 1: Capability requirements satisfied by ISO 10303

Capability requirement	Corresponding resource in ISO 10303
Geometry & Topology	Part 42, AIC 511, AIC 514
Material information	Part 45
Tolerances	Part 47, AIC 519
Mathematical constructs	Part 50

Suitability of ISO 10303

The possibility of using resources from the STEP documentation provides several advantages in developing the proposed LM data representation models. The APs use the underlying information resources in well defined combinations and configurations to represent a particular data model within a given application context. These resources include the EXPRESS information modeling language (Part 11 of ISO 10303), a series of Integrated Generic Resources (Parts 41 - 49 of ISO 10303), and a series of Application Interpreted Constructs (AICs) (Parts 500+).

Some of the requirements that are needed for the development of a standard data representation for layered manufacturing are directly satisfied in the current documentation of ISO 10303. A summary of the capability requirements satisfied by the STEP data structure is presented in Table 1.

Part 42 [13] and the AICs based on it allow the exact representation and modeling of the geometry and topology of an object. Other parts provide the capabilities to represent material type and tolerance specifications. The representation proposed in this paper utilizes these existing capabilities. In the domain of 2D slices, ISO 10303 has the capabilities for exact representation of the geometry of a 2D contour [13].

However, some requirements are specific to the application domain of heterogeneous objects. These must be represented uniquely because of the absence of these specifications in ISO 10303. One of these is the specification of continuously varying material composition to create a material gradient. In order to accommodate this property, it is necessary to create a STEP-compliant representation that can be used in the proposed structure of heterogeneous solid modeling [14]. This leads to the introduction of new entities conforming to the STEP data structure. A specialization of this information model to the 2D domain will serve for the representation of graded material distributions in the interior of 2D slices.

After a study of ISO 10303 and heterogeneous solid modeling, a data planning model (DPM) is proposed as a first step towards the representation of heterogeneous solids in the domain of ISO 10303. The remainder of the paper discusses this DPM.

4 Data Planning Model (DPM)

A data planning model illustrates the primary concepts of the application domain and the general relationships among the major concepts. It does not fully describe the details of the relationships. It provides an overview of the scope of the application domain.

The structure of ISO 10303 was reviewed and specific documents (parts) in ISO 10303 were studied in detail. These parts were analyzed to determine if they satisfied the requirements. It was found that some entities required for representing heterogeneous solid models are not available in ISO 10303. Therefore, appropriate entities were created using original data representations written in the STEP computer-interpretable information modeling language EXPRESS [15].

Data planning models are proposed at two levels of the data transfer for layered manufacturing. The DPM presented in Section 4.1 is a proposed structure to represent heterogeneous solid objects in the domain of data transfer as 3D CAD models. Section 4.2 presents a proposed structure to represent information in a 2D slice domain of layered manufacturing. Both these models account for the material gradation and are aimed to be the basis of neutral file formats for data transfer among various commercial LM machines.

The proposed data planning models depict only a high level presentation of the proposed formats using the EXPRESS-G modeling language. The EXPRESS-G modeling language is a formal graphical notation for the display of data specifications defined in the EXPRESS language [15]. The DPMs do not provide detailed internal working of the structure. However, they provide an overall structure and the necessary capabilities of the representation before developing a more detailed low level representation of the specific

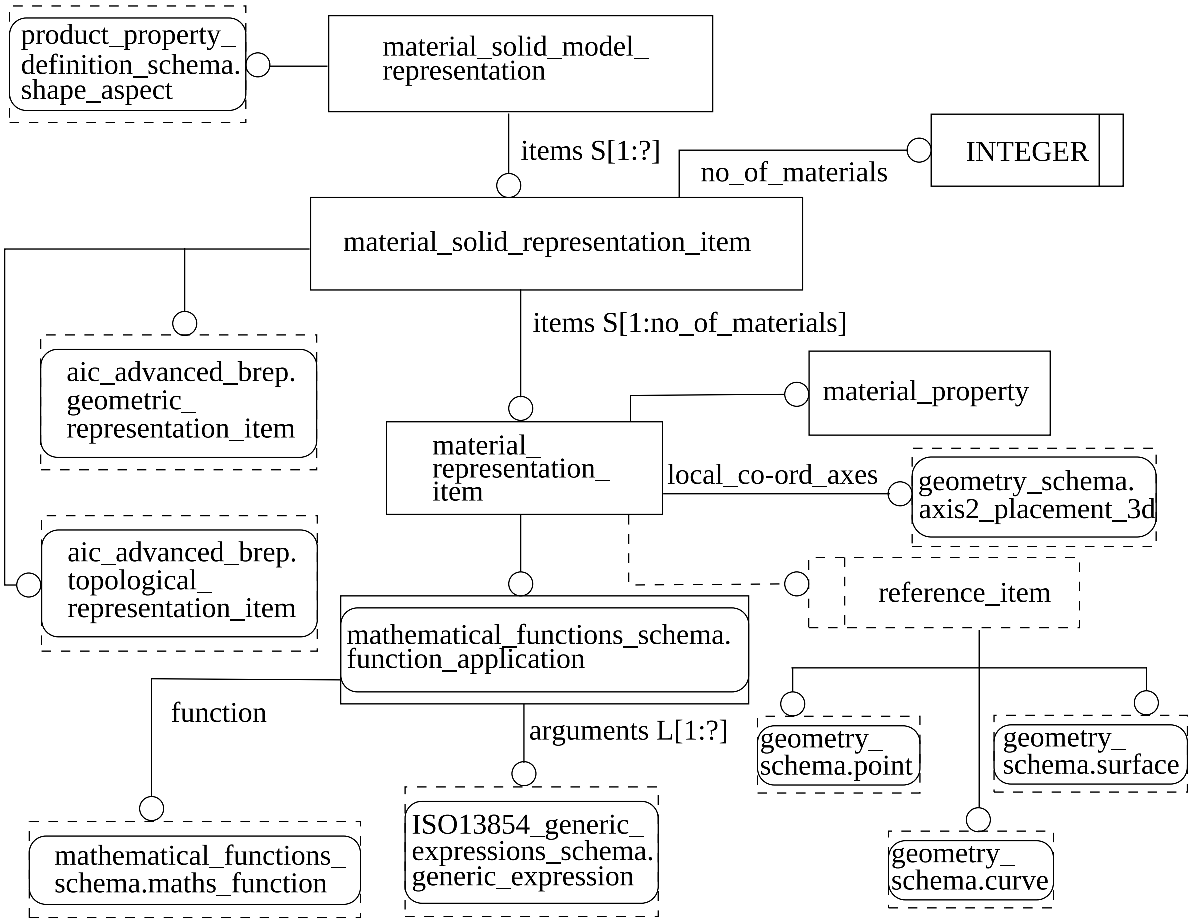


Figure 1: Data planning model to represent heterogeneous solids in STEP

data. It should be noted that every entity will be defined in further detail through attribute specifications.

4.1 Representation of heterogeneous solids

Figure 1 shows the DPM for the proposed structure to represent heterogeneous objects. Exact geometry is represented with the help of existing resources in STEP, while new entities are proposed to represent continuous variation of material composition.

Entity descriptions

The entities shown in the DPM in Figure 1 are described in this section.

A material_solid_model_representation is an organized collection of data elements, collected together to represent any solid model with material properties associated with it. It thus represents an r_m-object.

The entity material_solid_representation_item forms an attribute of the entity material_solid_model_representation. Thus, material_solid_model_representation comprises instances of material_solid_representation_item to represent an individual material set (r_m-set) of the object model. The existence of more than one r_m-set in the material object is represented by multiple instances of a material_solid_representation_item within the same materials_solid_model_representation.

The geometry and the topology of the 3D solid are represented by attributes geometric_representation_item and topological_representation_item respectively. These are defined in Part 514 [16] of the ISO 10303 documentation. The material properties and the composition is represented by an entity called material_representation_item. This corresponds to the definition that an r_m-object is defined as a finite collection of r_m-sets $\{(P_i, B_j)\}$.

Entity material_solid_representation_item has an attribute with an integer data type (no_of_materials) to represent the number of the materials used in the representation for a r_m-set. Every material_solid_representation_item comprises a set of no_of_materials number of instances of the material_representation_item. This consists of the entity material_property as one of its attributes. This entity constitutes the individual properties of the material in concern. Part 45 [17] of ISO 10303 serves as the basis for this entity.

There can be multiple methods to represent the material gradient function. Therefore, a local co-ordinate system is defined to aid in the definition of the material function. Local co-ordinate axes are represented by axis2_placement_3d. Geometry information may also be associated with the definition of the material distribution function. Therefore an optional select type entity, reference_item is introduced. This selects one of the entities viz. point, curve, surface as the reference entity for variables in the function. These entities are already defined in Part 42 [13] of the ISO 10303 documentation.

The composite mathematical function that represents the material composition for an instance of the r_m-set is represented by the attribute function_application (used from the mathematical_constructs_schema [18]). It utilizes a maths_function and a corresponding list of arguments. This (function_application) represents the operation of applying a mathematical function to an appropriate set of arguments. The entity maths_function represents the function to be applied. The arguments in this case would be the tuple (x, y, z) that represents the Cartesian co-ordinates of the geometric point in that r-set. The function thus, may be represented as $F(x, y, z)$. A more detailed explanation of this entity (function_application) can be found in [18].

The representation is such that any assembly/part to be physically realized can be in the domain of heterogeneous objects. A component with a homogeneous material distribution will be characterized by exactly one material (no_of_materials = 1) and the corresponding material distribution function will be $F = 1$.

A shape_aspect is associated with every material_solid_model_representation. This attributed is referenced from product_property_definition_schema. Entities such as datum, datum_feature and tolerance_zone are defined in this scheme. These entities represent the tolerances associated with an object. Detailed explanations of these entities can be found in Part 47 [19] and AIC 519 [20].

4.2 Representation of heterogeneous slices

The ability of LM machines to fabricate heterogeneous objects suggests a need for incorporating varying material composition into the slice information. Section 4.1 discussed the representation of heterogeneous solids using concepts from ISO 10303. A similar approach can be utilized to represent a gradient in the material composition in the 2D slice domain. Figure 2 shows the data planning model for the proposed structure to represent slice information for heterogeneous objects. This model is also presented using the EXPRESS-G notation. The ability of ISO 10303 to represent exact geometries is utilized to represent the contours in a slice. Thus, poly-line approximation does not form the basis of this representation.

Entity descriptions

The entities given in the DPM of Figure 2 are described in this section.

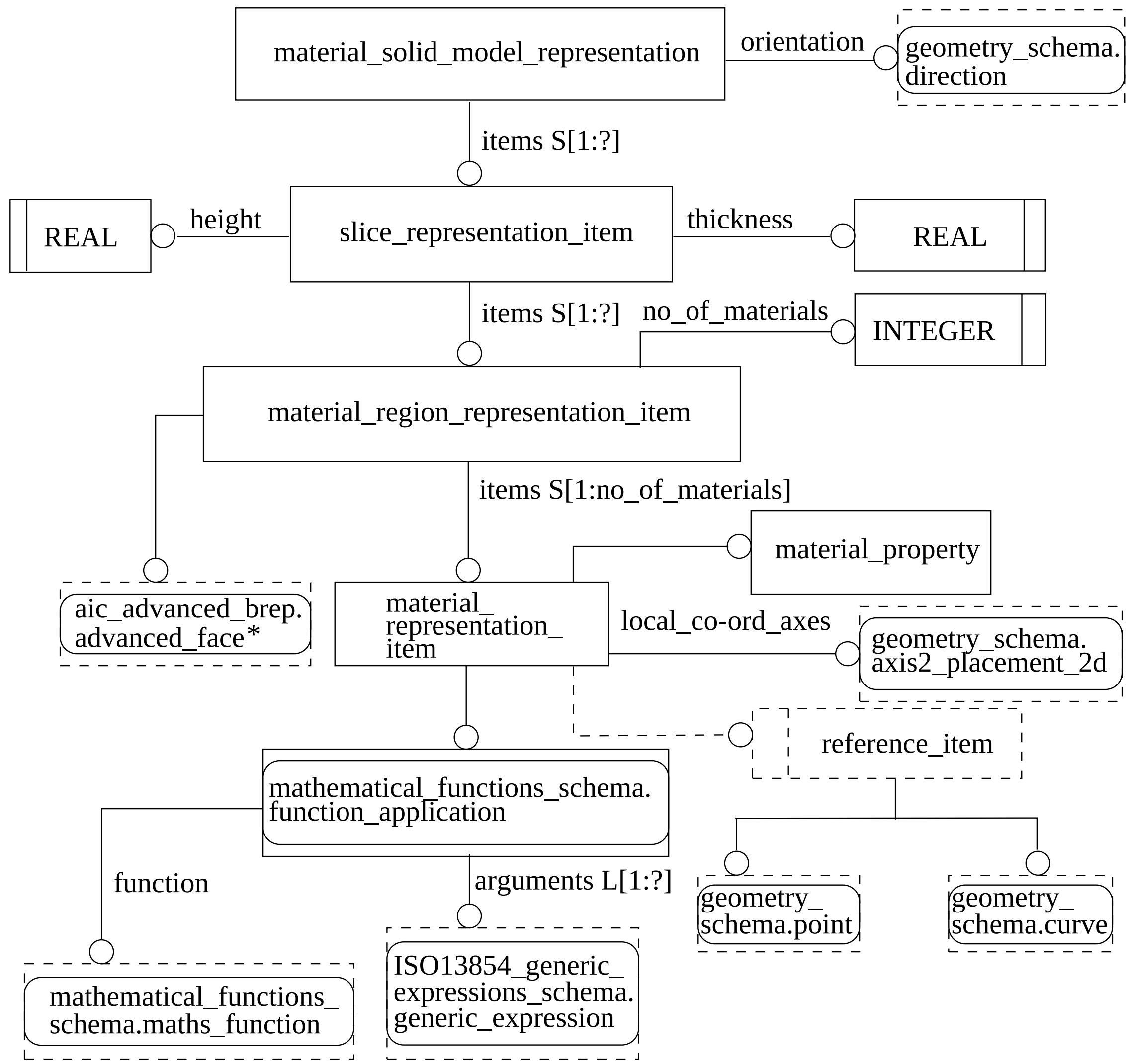


Figure 2: Data planning model to represent slice information

A material_solid_model_representation represents a heterogeneous solid. It is processed through the orientation module and an appropriate orientation is determined. This orientation is represented by the entity direction. The entity direction is defined in geometry_schema of Part 42 [13] of the ISO 10303 documentation. Thus orientation represents the direction of stacking the slices. The slices are generated normal to this direction.

As a result of slicing, a material_solid_model_representation comprises a finite set of slice_representation_item. Each slice_representation_item represents an individual slice. Slice thickness and height of the slice from the base are attributes associated with every slice. They are represented as real numbers.

Every slice is an organized collection of data elements represented by the entity material_region_representation_item, which represents a 2D region on the slice. The union of such regions which have disjoint geometric interiors represents a single slice.

The geometry of the region can be represented as an advanced_face defined in Part 511 [21]. It is a special type of face_surface that has additional constraints to ensure that the geometry is directly and completely defined. It is required to be fully bounded by at least one face_bound which is a topological entity representing a loop. In this case, the slice is a planar entity. Therefore, the face geometry shall be restricted to a plane. More information on these entities can be obtained in [13, 21].

The material_region_representation_item has an attribute with an integer data type (no_of_materials) to represent the number of the materials used in the representation of the region. Every material_region_representation_item consists of a set of no_of_materials number of instances of the material_representation_item. This consists of the entity material_property as one of its attributes. This entity constitutes the individual properties of the material in concern. Part 45[17] of ISO-10303 serves as the basis for this entity.

There can be multiple methods to represent the function for representing a material gradient. In order to address this ambiguity, a local co-ordinate system is defined to aid in the definition of the material function. Local co-ordinate axes are represented by axis2_placement_2d, which is an entity already defined in Part 42 [13] of ISO 10303. Geometry information may also be associated with the definition. Therefore, an optional select type entity reference_item that selects a point or a curve as the geometric reference entity for the variables in the function. Both of these entities are referenced from the geometry_schema of Part 42 [13] of ISO 10303.

The composite mathematical function to represent the gradient in material composition in the region is represented by the attribute function_application (used from mathematical_constructs_schema [18]). This utilizes a maths_function and a corresponding list of arguments. It (function_application) represents the operation of applying a mathematical function to an appropriate set of arguments. The entity maths_function represents the function to be applied. The arguments in this case would be the tuple (x, y) that represents the Cartesian co-ordinates of a geometric point in that region. The function thus, may be represented as $F(x,y)$. A more detailed explanation of the entity function_application can be found in [18].

This information model is based on the set-based method of heterogeneous solid modeling [1]. The theory is applied to a 2D domain. A slice can be considered to be equivalent to an r_m-object. It consists of geometrically, interior-disjoint regions. Each region is equivalent to an r_m-set. The advanced_face represents the geometry of the region. A material distribution function is used to represent the material gradient in this region.

5 Validation

The data planning models proposed in Section 4 need to be validated to check for the correctness of the representation.

In the domain of ISO 10303 validation means testing whether the syntax of an EXPRESS schema is correct and whether all appropriate external references (to entities defined in other schema) are made. It should be noted that this is not the concept of validation considered in this section. However, this validation process is a required component for development of a new STEP AP.

A two-level validation scheme, based on the available resources, was developed to physically fabricate parts represented in the proposed STEP format.

5.1 Validation of the solid model representation

Several sample case studies were considered for validation. Data files conforming to the proposed format and STEP rules for mapping EXPRESS to physical file format were first generated manually. These were manually checked to see if the proposed format contained all the required information about the geometry integrated with the material information. However, for physical fabrication of parts, the solid model has to be sliced. The manual check is thus complemented by the development of a slice level representation which is used to fabricate physical parts at the University of Michigan, Ann Arbor.

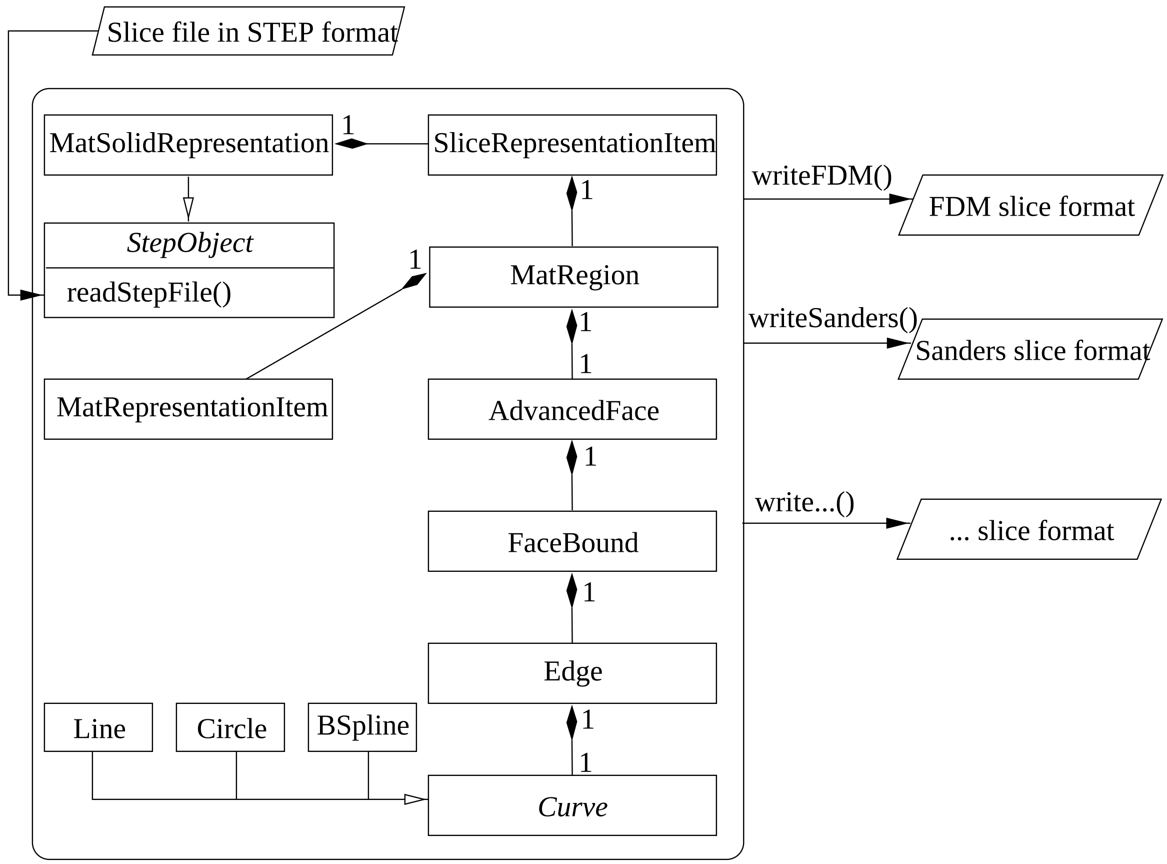


Figure 3: Conversion of slice data in STEP format to other slice file formats

5.2 Validation of slice level representation

An orientation of the 3D model is determined for the purpose of fabrication. It is then subjected to slicing to generate slices in the direction normal to the orientation. Data files conforming to the proposed format (Figure 2) and STEP rules for mapping EXPRESS to physical file format are generated manually. The file format for the physical fabrication of the part is specific to the machine on which the part is to be produced. So, the proposed format should be convertible to the commercial formats for slice information. This will test the ability of the proposed format to encapsulate slice information as supported by slice formats of commercial LM machines. For this purpose, software (Figure 3) was designed and implemented to convert the proposed STEP file format to the slice format of commercial LM machines.[1] A successful conversion is validated by visualizing the generated slice files using the proprietary software of the LM machines. Fabrication of the final physical part on the commercial LM machines provides a physical validation to the encapsulation of information of the slice geometry.

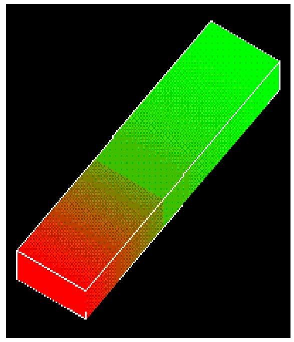
The conversion software (Figure 3) reads in all information represented in the proposed neutral slice file and stores it in a class structure compatible with the proposed structure in ISO 10303 (Figure 2). The hierarchical nature of the data structure in STEP facilitates its implementation in the object oriented paradigm using C++ as a programming tool.

The class diagram in Figure 3 is shown in accordance with the OMG Unified Modeling Language Specification [22]. Class *StepObject* is the parent abstract class. The virtual method *readStepFile* is used to read the physical STEP file (containing slice information). *MatSolidRepresentation* represents a sliced heterogeneous solid. Thus, *SliceRepresentationItem* (2D r_m-object) forms the elements for the composition of a *MatSolidRepresentation*. Every slice is composed of a finite number of *MatRegions* (2D r_m-set). One *AdvancedFace* and a finite number of *MatRepresentationItems* form one *MatRegion*. Each *MatRepresentationItem* is defined by a mathematical function to represent the material distribution. Every *AdvancedFace* is defined by a finite number of boundaries (*FaceBound*). A closed *FaceBound* is made of one or more *Edges*. An *Edge* is composed of a *Curve*. Class *Curve* is an abstract class that can be represented as a *Line,* a *Circle* or a *BSpline*.

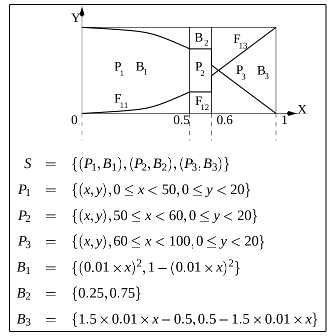
This information stored in the memory of the computer has to be converted into a machine specific physical file format. This purpose is solved by writing routines such as *WriteFDM* to convert the information into the FDM slice format. The same data structure can be utilized to output information through a module to print the information in a particular slice file format. The software is thus a post-processor that processes STEP based slice information to the machine specific slice information.

The slice information for the fabrication of a part on one particular LM machine may be valid for the fabrication of the part using a different LM technology. A single STEP file

[1] The Stratasys' FDM 3D modeler and Sanders Prototype's Modelmaker are used as representative machines



(a) HSM(Rectangular geometry)



(b) r_m object model

Figure 4: Model of bi-material object with three r_m-sets

(for one heterogeneous object) can be used to fabricate a part on various machines (having comparable layer thickness specifications) by conversion to respective machine specific slice formats. Thus, this conversion also validates the concept of inter-operability of LM data (at slice level) similar to Cutter Location data in NC machining.

6 Case study

A physical validation of the data planning models proposed in Section 4 is presented in this section by considering an example component to represent heterogeneous objects.

The object shown in Figure 4(a), adapted from [1] is a heterogeneous object with rectangular geometry. It is a representative object to explain the representation of a material object comprising more than one r_m-set. The object model is represented in Figure 4(b). The definition of an r_m-set is such that the material distribution function is C^∞ [1]. Thus, the r_m object with a piecewise continuous material distribution function is decomposed into three r_m-sets as shown in Figure 4(b). Figure 5 shows the representation of this object as per the DPM in a schematic STEP physical file format.

Figure 5 schematically shows that the proposed data planning model can represent completely an r_m-object comprising more than one r_m-set. The mathematical function given by $(0.01 \times x)^2$ represents the material distribution for material 1. This is modeled

```
#1002=MATERIAL_SOLID_MODEL_REPRESENTATION('', #1003, #3001, #5001);
#1003=MATERIAL_SOLID_REPRESENTATION_ITEM('RMSET1',2,#1004,#1005,#1006);
#1004=MANIFOLD_SOLID_BREP('RSET1',...);
#1005=MATERIAL_REPRESENTATION_ITEM('MAT1',#1010,#1011,#1020);
#1006=MATERIAL_REPRESENTATION_ITEM('MAT2',#1010,#1021,#1024);
⋮                    ⋮                    ⋮
#1018=ELEMENTARY_FUNCTION('', .EF_EXPONENTIATE_R);
#1019=FUNCTION_APPLICATION('EPONEN1', #1018, (#1012, 2.0));
#1020=FUNCTION_APPLICATION('FUNC11', #1019, (#1012, #1013, #1014));
#1021=MATERIAL_PROPERTY(...);
#1022=ELEMENTARY_FUNCTION('SUB', .EF_SUBTRACT_R);
#1023=FUNCTION_APPLICATION('SUBFUNC', #1022, (1.0, #1019));
#1024=FUNCTION_APPLICATION('FUNC12', #1023, (#1012, #1013, #1014));
⋮                    ⋮                    ⋮
#3001=MATERIAL_SOLID_REPRESENTATION_ITEM('RMSET2',2,#3002,#3003,#3004);
#3002=MANIFOLD_SOLID_BREP('RSET2', ... );
#3003=MATERIAL_REPRESENTATION_ITEM('MAT1',#3008, #3009, ... );
#3004=MATERIAL_REPRESENTATION_ITEM('MAT2', ... );
⋮                    ⋮                    ⋮
#5001=MATERIAL_SOLID_REPRESENTATION_ITEM('RMSET3',2,#5002,#5003,#5004);
#5002=MANIFOLD_SOLID_BREP('RSET3', ... );
#5003=MATERIAL_REPRESENTATION_ITEM('MAT1', ... );
⋮                    ⋮                    ⋮
```

Figure 5: Representation of multiple r_m-sets (Figure 4) in ISO 10303

```
#1001 = MATERIAL_SOLID_MODEL_REPRESENTATION('', #1008) ;
#1002 = SLICE_REPRESENTATION_ITEM('', 0.1, 0, #1003, #1100, #1200) ;
#1003 = MATERIAL_REGION_REPRESENTATION_ITEM('',2,#180,#1005,#1006) ;
⋮                    ⋮                    ⋮
#1100 = MATERIAL_REGION_REPRESENTATION_ITEM('',2,#181,#1005,#1006) ;
#1200 = MATERIAL_REGION_REPRESENTATION_ITEM('',2,#182,#1005,#1006) ;
#1201 = SLICE_REPRESENTATION_ITEM('', 0.1, 0.1, #1003, #1100, #1200) ;
⋮                    ⋮                    ⋮
#180=ADVANCED_FACE('',(#177),#228,.T.);
#181=ADVANCED_FACE('',(#178),#229,.T.);
#182=ADVANCED_FACE('',(#179),#230,.T.);
⋮                    ⋮                    ⋮
```

Figure 6: Representation of slices comprising multiple r_m-sets (Figure 4) in ISO 10303

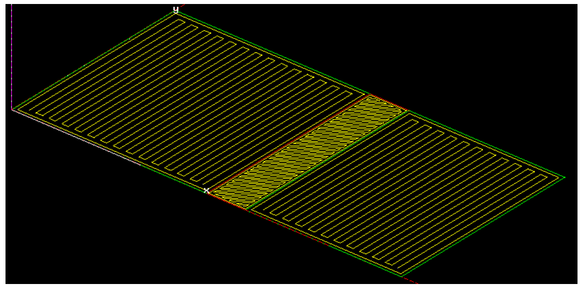


Figure 7: Sliced box (Figure 4) as seen on the software for FDM

in the above representation as #1020 using entity function_application of Part 50 [18].

The solid model is subject to slicing and slice data is generated. The proposed STEP file that represents slices of the box is shown in Figure 6. The cross-section of the box is uniform. Thus, all the slices that represent the object are identical. The STEP format schematically represents the slice level information for heterogeneous slices of the box. The presence of the three instances of the entity advanced_face indicates the presence of three r_m-sets.

The software mentioned in Section 5 is used to convert this STEP-based file to the slice format for the FDM 3D modeler and the Sanders prototyping machine. During this conversion, information about the geometry of the part is utilized while information about the material gradation is lost because the machines are not capable of handling this information. The slice file is then viewed using the proprietary software of these machines. Figure 7 depicts a single slice as viewed by the software for the FDM 3D modeler. It is seen that although material information in the slice is lost, the information of the existence of three r_m-sets in the object is stored and transferred to the machine specific file format. This effect is demonstrated in Figure 7 by the existence of three geometries and the variation in the raster deposition in the three different geometries. A physical prototype was also fabricated on the prototyping machine. The fabrication validates the practical application of the proposed information model.

However, Figures 5 and 6 do not provide details of representation of the geometry. This is done because ISO 10303 has a well-developed application protocol (Part 203) to represent the geometry of an object. Thus, geometry is depicted in the form of a manifold b-rep solid representation for the solid and advanced face for the slice. The details of the representation of this solid geometry is shown in Appendix A. It presents a typical representation and other geometries can be represented in a similar manner.

7 Conclusion

The DPM (Data Planning Model) proposed in Section 4.1 provides an overview of the methodology and the structure to represent heterogeneous solids using the concepts of ISO 10303. The DPM represents a complete integration of material information with the corresponding geometry to represent heterogeneous objects as proposed in [1].

The DPM proposed in Section 4.2 provides a slice level representation scheme. It helps in validation of the DPM for representing heterogeneous solids by physical realization of the objects. It can also be used to demonstrate an initial concept of utilizing slice level information as a neutral file format for the transfer of data among different LM machines.

Use of ISO 10303 (STEP) as the basis will allow for faster standardization and adoption because the core STEP functionality has reached consensus and has been also implemented in software systems.

To enable complete STEP-based data transfer in Layered Manufacturing, additional aspects of heterogeneous solid modeling and the down-line transfer of data for process planning need to be considered. Some of these are as follows:

1. Representation of object properties such as color and surface finish.
2. Development of an information model to represent data requirements for the entire process planning for layered manufacturing

The format of representation of heterogeneous objects in a standardized format will be an important step towards the successful physical realization of heterogeneous objects through layered manufacturing.

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References

[1] Vinod Kumar and Debasish Dutta. An Approach to Modeling and Representation of Heterogeneous Objects. *ASME journal of mechanical design*, 120:659–667, December 1998.

[2] Debasish Dutta, Vinod Kumar, Mike J. Pratt, and R.D. Sriram. Towards STEP-based Data Transfer in Layered Manufacturing. In *Proceedings of the tenth international IFIP WG5.2/5.3 PROLAMAT Conference*, Trento, Italy, September 1998.

[3] Lalit Patil, Debasish Dutta, A. D. Bhatt, K. Jurrens, K. Lyons, M. J. Pratt, and R. D. Sriram. Representation of heterogeneous objects in ISO 10303 (STEP). In *Proceedings of the ASME Manufacturing Engineering Division 2000*, volume 11, pages 355–364, Orlando, FL, 2000.

[4] T. R. Jackson, N. M. Patrikalakis, E. M. Sachs, and M.J. Cima. Modeling and designing components with Locally Controlled Composition. In *Proceedings of the Solid Freeform Fabrication Symposium*, Austin, TX, 1998.

[5] Wu Zhongke, Seah Hock Soon, and Lin Feng. NURBS-Based Volume Modeling. In *International Workshop on Volume Graphics*, pages 321–330, Swansea, UK, 1999.

[6] V. L. Rvachev, T. I Sheiko, V. Shapiro, and I. Tsukanov. Transfinite Interpolation over Implicitly Defined Sets. Technical Report SAL 2000 – 1, Spatial Automation Laboratory, University of Wisconsin - Madison, 2000.

[7] Seok-Min Park, Richard Crawford, and Joseph Beaman. Functionally Graded Material Representation by Volumetric Multi-Texturing for Solid Freeform Fabrication. In *Proceedings of the 11th Annual Solid Freeform Fabrication Symposium*, Austin, TX, August 2000.

[8] A.V Kumar and A. Wood. Representation and design of heterogeneous components. In *Proceedings of the 1999 Solid Freeform Fabrication Symposium*, pages 179–186, Austin, TX, August 1999.

[9] A. A. G. Requicha. Representation of rigid solids - theory, methods and systems. *ACM Computing Surveys*, 12:437–464, 1980.

[10] Anne Marsan, Vinod Kumar, Debasish Dutta, and Mike J. Pratt. An Assessment of Data Requirements and Data Transfer Formats for Layered Manufacturing. Technical Report NISTIR 6216, National Institute of Standards and Technology(NIST), Gaithersburg, Maryland, September 1998.

[11] Kevin Jurrens. Standards for the rapid prototyping industry. *Rapid Prototyping Journal*, 5(4):169–178, 1999.

[12] *The STEP Project*. URL: http://www.nist.gov/sc4/www/stepdocs.htm, valid as of January 2001.

[13] *Industrial automation systems and integration - Product data representation and exchange - Part 42: Integrated generic resources: Geometric and topological representation*, ISO 10303-42:2000.

[14] Vinod Kumar. *Solid Modeling and Algorithms for Heterogeneous Objects*. PhD thesis, University of Michigan, Ann Arbor, 1999.

[15] *Industrial automation systems and integration - Product data representation and exchange - Part 11: Description methods: The EXPRESS language reference manual*, ISO/WD 10303-11:1998 ed-2.

[16] *Industrial automation systems and integration - Product data representation and exchange - Part 514: Application interpreted construct: Advanced boundary representation*, ISO 10303-514:1999.

[17] *Industrial automation systems and integration - Product data representation and exchange - Part 45: Integrated generic resources: Materials*, ISO 10303-45:1998.

[18] *Industrial automation systems and integration - Product data representation and exchange - Part 50: Integrated generic resources: Mathematical constructs*, ISO/CD 10303-50:1999.

[19] *Industrial automation systems and integration - Product data representation and exchange - Part 47: Integrated generic resources: Shape variation tolerances*, ISO 10303-47:1998.

[20] *Industrial automation systems and integration - Product data representation and exchange - Part 519: Application interpreted construct: Geometric tolerances*, ISO 10303-519:2000.

[21] *Industrial automation systems and integration - Product data representation and exchange - Part 511: Application interpreted construct: Topologically bounded surface*, ISO/FDIS 10303-511:1997.

[22] *OMG Unified Modeling Language specification, version 1.3*. available at URL: http://www.rational.com/uml/resources/documentation/index.jsp, June 1999.

Appendix A

Representation of a typical geometry in STEP

The following represents a part of the ISO 10303 (STEP) representation of the geometry denoted as P_1 in Figure 4(b). This file is obtained by submitting the relevant ACIS file over the world wide web server to the STEP translation service offered by STEP Tools Inc. at *http://www.steptools.com/translate/translate.cgi*

```
#10=PLANE('',#13);
#11=CARTESIAN_POINT('',(0.,0.,5.));
#12=DIRECTION('',(0.,0.,1.));
#13=AXIS2_PLACEMENT_3D('',#11,#12,$);
#14=PLANE('',#17);
⋮                    ⋮
#83=CARTESIAN_POINT('',(25.,0.,0.));
#84=DIRECTION('',(1.,0.,0.));
#85=DIRECTION('',(0.,0.,1.));
#86=MANIFOLD_SOLID_BREP('',#87);
#87=CLOSED_SHELL('',(#88,#111,#134,#145,#154,#163));
#88=ADVANCED_FACE('',(#89),#10,.T.);
#89=FACE_BOUND('',#90,.T.);
⋮                    ⋮
#101=VERTEX_POINT('',#102);
#102=CARTESIAN_POINT('',(-25.,12.5,5.));
#103=ORIENTED_EDGE('',*,*,#104,.T.);
#104=EDGE_CURVE('',#101,#106,#105,.T.);
#105=INTERSECTION_CURVE('',#34,(#10,#30),.CURVE_3D.);
⋮                    ⋮
#153=ORIENTED_EDGE('',*,*,#104,.F.);
#154=ADVANCED_FACE('',(#155),#22,.F.);
#155=FACE_BOUND('',#156,.T.);
#156=EDGE_LOOP('',(#157,#160,#161,#162));
#157=ORIENTED_EDGE('',*,*,#158,.T.);
#158=EDGE_CURVE('',#96,#117,#159,.T.);
#159=INTERSECTION_CURVE('',#78,(#22,#14),.CURVE_3D.);
#160=ORIENTED_EDGE('',*,*,#132,.F.);
#161=ORIENTED_EDGE('',*,*,#149,.F.);
#162=ORIENTED_EDGE('',*,*,#99,.F.);
#163=ADVANCED_FACE('',(#164),#14,.F.);
#164=FACE_BOUND('',#165,.T.);
#165=EDGE_LOOP('',(#166,#167,#168,#169));
```