REPRESENTATION OF HETEROGENEOUS OBJECTS IN ISO 10303 (STEP)

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

Until recently, solid modeling focused mainly on the modeling of objects to capture geometry and topology (Hoffman, 1989). Information derived from data regarding the solid model is used extensively for down-line applications such as mechanical design analysis, computer-aided process planning, and manufacturing. Attributes such as material information, color etc. are attached to the model information externally. However, this is not an integral part of the solid model data and so all the down-line applications are developed under the assumption of homogeneous material distribution throughout the interior of the solid.

Heterogeneous objects are composed of different constituent materials and can exhibit continuously varying composition and/or micro-structure, thus producing gradation in their properties (Kumar and Dutta, 1998). Over the last decade, layered manufacturing (LM) has evolved as a technology that has shown promise for the manufacture of multi-material i.e., heterogeneous parts. While other processes concentrate on the removal of material to create an object, this fabrication technique involves *addition* of material to create a new object. With this method of fabrication, LM inherently depicts an ability to deposit several materials in varying composition within a layer and between layers.

For the purpose of design, analysis and manufacture of heterogeneous objects, the CAD model of an object is required to maintain information about geometry, topology and material throughout the interior of the object. It thus becomes necessary to represent information about material distribution as an integral part of the solid model information (Kumar and Dutta, 1998).

This paper presents a concept of representing any object or a group of objects as an assembly instead of a single object for its fabrication in a Layered Manufacturing environment. It also focuses on the development of a proposed information model (as one input for consideration by ISO 10303 (ISO/WD 10303-1, 1994)) to represent heterogeneous objects for the application of LM by using information modeling and ISO 10303 (STEP). The objectives of this development are to:

1. provide a uniform base to develop heterogeneous solid modeling systems.
2. equip the solid modeler with ability to integrate efficiently with other applications and process planning in the layered manufacturing environment.

Section 2 presents a brief review of approaches for heterogeneous solid representation. This paper considers only the r_m-object (Kumar and Dutta, 1998) approach in all subsequent sections. Section 3 presents the concept of using an assembly representation for fabrication of more than one object at the same time. The motivation for the use of STEP is explained in Section 4. Section 5 proposes a Data Planning Model (DPM) within the domain of ISO 10303 for the r_m-object representation. Validation of the DPM using some case studies is performed in Section 6. Some observations and some issues to be handled in more details form the concluding section of the paper.

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2 Heterogeneous solid modeling

Heterogeneous solid modeling aims to incorporate material distribution information along with geometry into the CAD model. This section summarizes results reported in the literature.

2.1 $\mathbf{r_m}$ object model (Kumar and Dutta, 1998)

This modeling scheme forms the basis of the proposed representation to develop a standard for heterogeneous modeling (for details refer to (Kumar and Dutta, 1998; Kumar, 1999)). It is based on the exact representation of geometry and material distribution function.

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 S is a combination of n primary materials and is specified by the volume fractions of these primary materials. The material composition of any point p is represented as a material point v in $\mathbf{R}^3$, with each dimension representing exactly one primary material. As these volume fractions must sum to unity, the space of material points (*material space*) is defined as:

$$\mathbf{V} = \{v \in \mathbf{R}^n \mid \|v\|_1 \equiv \sum_{i=1}^{n} v_i = 1 \text{ and } v_i \geq 0\} \qquad (1)$$

where v_i represents the volume fraction of the i^{th} primary material.

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.

Material r-set($\mathbf{r_m}$ set) An $\mathrm{r_m}$ set is defined as a subset $D \equiv (P,B)$ of $\mathbf{T}$ where $P \subset \mathbf{E}^3$ is an r-set and $B \subseteq \mathbf{V}$ assigns material to the r-set P.

1. 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 $F(P)$.
2. An $\mathrm{r_m}$ set is undefined for all the points lying in the exterior of P.
3. If $F = 1$ & $n = 1$, then it is a single material $\mathrm{r_m}$ set.
4. To avoid the need for modeling discontinuities, it is assumed that the material function F is C^∞ continuous in P.

Material object ($\mathbf{r_m}$-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 following conditions hold true:

1. The $\mathrm{r_m}$-sets are geometrically interior-disjoint.
2. The $\mathrm{r_m}$-sets are minimal.

$$\begin{aligned} S &= \{D_j\} = \{(P_j, B_j)\}, j \in Z_+ \\ P_i \cap^* P_k &= \phi, i \neq k, \forall i,k \in Z_+ \\ B_j &= F_j(P_j) \end{aligned}$$

Certain geometrical points termed as irregular points lie on the boundary of more than one r-set in the $\mathrm{r_m}$-object. This can be handled using the following two strategies:

1. The material on these irregular points can be defined using the combine operator $\oplus$ (Kumar and Dutta, 1998).
2. The material is assigned to volumes and not to the boundaries which are lower dimensional entities. Hence, the material functions can be restricted only to the interior of each r-set.

Modeling operations similar to the regularized boolean operations have also been defined in (Kumar and Dutta, 1998) in order to create and manipulate heterogeneous solid models. However, the applicability and use of booleans to synthesize heterogeneous objects requires further study.

2.2 Decomposition methods

2.2.1 The tetrahedral model (Jackson et al., 1998)

In this representation 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. More details on representing objects using this strategy can be obtained in (Jackson et al., 1998).

This approach attempts to maintain the flexibility in geometric design that a standard solid modeler would allow for. It allows models to be decomposed into sub-regions of graded compositions to efficiently represent multi-material parts. One of the major advantages of decomposing the model into tetrahedra is that the model can directly be used for finite element analysis.

However, the following are the major drawbacks associated with this representation as compared to the representation in Section 2.1:

1. Any modification in the material distribution function, $m(x)$ will necessitate regeneration of the mesh because the mesh generation depends on $m(x)$.

2. The exact material distribution function is used to obtain the compositions at the vertices of every tetrahedron. However, the composition at other points in the tetrahedron is calculated by interpolation. The advantage of increase in the computational speed may be offset by the approximation in representation.
3. The approximation in the shape due to meshing may lead to inaccurate dimensions and errors in the required surface finish. Note that this approach approximates the object geometry and material distribution function as well.

2.2.2 Voxel-based model (Zhongke et al., 1999)

This 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.

It is observed that the voxelization is independent of the material distribution function. This representation provides to the designer a unique ability to selectively assign materials to individual voxels. This is also better suited for fabrication using layered manufacturing as each individual slice can be represented as a collection of voxels.

The following constitute some of the limitations associated with this representation as compared to the representation in Section 2.1:

1. This model also faces limitations like the one in Section 2.2.1 because of the approach of decomposition.
2. Geometry-dependent function distributions are not easily applicable because of approximation of the geometry in the voxel object.
3. This method of representation is not compatible for any kind of data transfer amongst CAD systems. Research is being carried out to construct a solid model from voxel models (Marsan and Dutta, 1996).
4. This technique does not seem to be suited for finite element analysis where tetrahedral structures are preferred to cubical ones.

2.3 The R-Function approach (Rvachev et al., 2000)

An R-function (which should not be confused with an r-set) is a real-valued function whose sign is completely determined by the signs of its arguments. Such functions provide analogies to the Boolean logical functions. Simple examples are provided by $\min(x_1,x_2)$ and $\max(x_1,x_2)$, which are analogous to Boolean 'and' and 'or', respectively, if we take $+$ and $-$ values of the arguments to correspond to the logical values of TRUE and FALSE. Many other R-functions are known (Rvachev et al., 2000), and some prove more suitable than those given above for practical applications.

The analogy with Boolean functions allows any closed shape model in 2D or 3D, expressed in terms of Boolean combinations of half-spaces, to be defined in terms of a single implicit function, by composition of appropriate R-functions. It can be arranged for this function to be positive inside the shape, and its value will be zero on the boundary. More generally, an extension of the R-function approach allows the generation of functions on such a domain that interpolate continuous distributions of function values or derivatives on its boundary. The method may therefore be used to model distributions, e.g., of material properties, in the interior of the shape.

Although R-functions show promise for future applications, their study is currently in its infancy. It is observed that the use of R-functions appears to be compatible with the ISO 10303 (STEP) standard described in Section 4, because Part 50 (ISO/CD 10303-50, 1999) of the standard will provide the appropriate means for representing all the necessary mathematical constructs.

2.4 Summary

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 paper 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 surveyed above have their advantages and disadvantages, we chose the $\mathrm{r_m}$-object model 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 described in Section 2.1.

3 Assembly representation

Layered manufacturing is typically used to fabricate a single object/part/component at one time. However, more than one component (the modeling envelope of the machine is large enough to accommodate more than one component at the same time) can also be built simultaneously on one LM machine.

Consider a collection (H) of components $\{S_i\}$ as shown in Figure 1. It consists of more than one material object(S_i)
$H = \{S_i \mid i \in Z_+\}$
$S_i = \{(P_j, B_j) \mid j \in Z_+\}$
P_j and B_j represent geometry(r-set) and the material composition of an $\mathrm{r_m}$-set represented by (P_j, B_j).

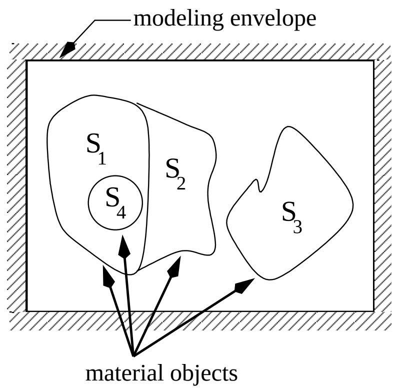


Figure 1. Representation of an an assembly of objects

Two possible ways of representation of the set H are studied in relevance to fabrication using layered manufacturing.

Representation as a single object The set H can be represented as a single object. Every individual component (S_i) forms a geometric component of the object. However, this representation leads to a loss of individual component information. The addition, deletion or re-orientation of S_i is not possible as each S_i is an integral geometric entity of the object H.

Representation as an assembly The set H is represented as an assembly of different objects $\{S_i\}$. Each component S_i maintains its identity. It will not degenerate to represent only a geometric entity in the object representation. This will also permit manipulation of the individual objects S_i in the collection H.

Considering the advantages of representing components for fabrication using layered manufacturing, it is proposed that representation of components should be considered at the level of an assembly.

In this context, *an assembly is defined as a group of assemblies/sub-assemblies or components that can be fabricated in the same setup of the LM machine*. Every assembly in turn comprises more assemblies or components. Components which can have relative physical motion between them can be supposed to form an assembly. Thus, a component will represent an atomic entity in the entire product/assembly. Each component will, therefore, be represented as a heterogeneous solid (material object).

This representation will also help in fabrication of functional assemblies like gear-boxes, bearings etc. This method of fabrication can also help in reduction of some components required to hold the assembly together.

4 Motivation for the use of ISO 10303

Existing standards to represent objects in LM and data formats to exchange model information in the domain of Layered Manufacturing have been studied in (Dutta et al., 1998; Marsan et al., 1998). A need exists to represent and transfer exact geometry information together with information such as materials and their distribution, and tolerances. The need to represent and manufacture heterogeneous objects coupled with the possibility that some stages of process planning may migrate into the CAD domain leads to the necessity of development of an application protocol for Layered Manufacturing. Literature documents the suitability of ISO 10303 to satisfy the technical requirements for this purpose (Dutta et al., 1998; Marsan et al., 1998; Jurrens, 1999).

ISO 10303 (STEP)

ISO 10303 or STEP (STandard for the Exchange of Product model data) is an international standard that describes the product data completely during the life cycle of a product from the design to its manufacture. STEP is an ISO activity that will be documented as ISO 10303. STEP is not a *de facto* standard developed from a specification. It is an international effort towards standardization of the exchange of product model data. It is an international standard for the computer-interpretable representation and exchange of product data. ISO 10303 has been proven to be a successful architecture for the representation of solid models.

ISO 10303 does not have an Application Protocol for layered manufacturing. However, a Rapid Prototyping (RP) interest group has been formed within the standards organization developing STEP (ISO TC184/SC4) to consider the requirements for RP data and the possible applicability of the existing STEP standard.

After a detailed study of ISO 10303 and heterogeneous solid modeling, the following data planning model is proposed as a first step to form a basis for the representation of heterogeneous solid models in ISO 10303.

5 Data Planning Model (DPM)

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 that were required for representing heterogeneous solid models are not available in ISO 10303. Therefore, appropriate entities were created using original data representations conforming to the STEP data structure.

Figure 2 shows the data planning model for the proposed structure to represent heterogeneous objects. The DPM shows only a high level representation of the proposed format using the EXPRESS-G modeling language. It does not provide detailed in-

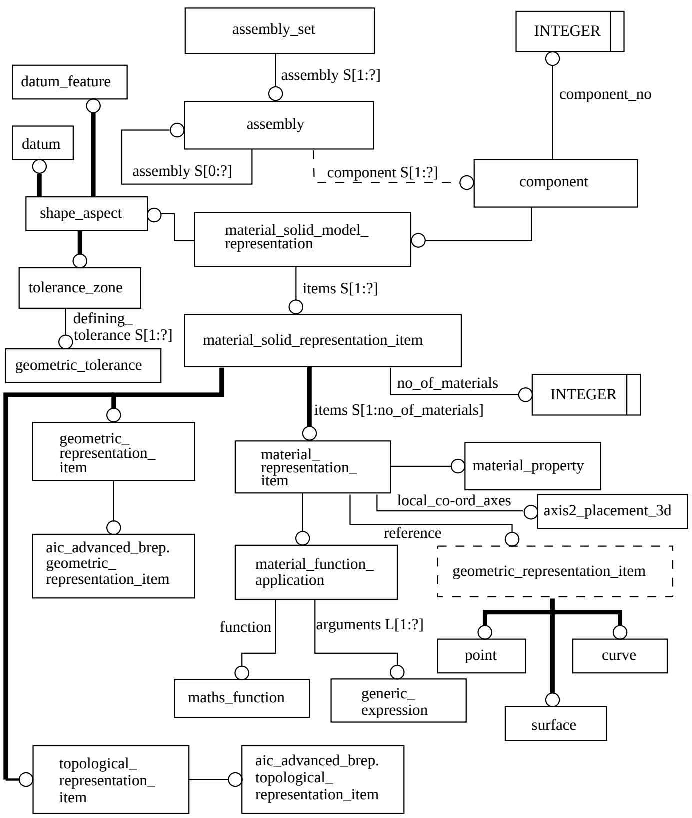


Figure 2. Data planning model to represent heterogeneous solids in STEP

ternal working of the structure. However, it does provide an overall structure and the necessary capabilities of the representation before presenting a more detailed low level representation of the specific data. The DPM includes portions of the (Application Interpreted Construct) AIC 514 (ISO/DIS 10303-514, 1997) structure along with the specific capability requirements. It should be noted that every entity represented by a solid rectangle will be defined in further details through attribute specifications.

Suitability of ISO 10303

ISO 10303 provides several advantages because of the possibility of using parts from the documentation. These are the parts that satisfy some of the requirements that are needed for the proposed data structure. It also suggests the introduction of new entities in the data structure.

A summary of the capability requirements satisfied by the STEP data structure is presented in Table 1.

It is observed from Table 1 that parts such as AIC 514, Application Protocol (AP) 203 represent the geometry and topology of an object. The proposed representation utilizes the existence of these parts and the entities therein to represent geometry and topology of a component.

Table 1. Capability requirements satisfied by STEP

Capability requirement	Corresponding resource in STEP
Geometry & Topology	Part 42, AP 203, AIC 514
Material information	Part 45
Tolerances	Part 47, AIC 519
Mathematical constructs	Part 50
Assembly	Part 44

However, some of the requirements are specific to the application domain of heterogeneous solids. These have to 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 representation that could be used in the proposed structure of heterogeneous solid modeling (Kumar, 1999). This leads to the introduction of new entities conforming to the STEP data structure.

Entity descriptions

The structure of the proposed DPM according to the EXPRESS-G modeling format proposed in ISO 10303 (ISO/WD 10303-11 ed-2, 1998) is shown in Figure 2.

Entity assembly_set is an organized collection of elements that together represent a set of assemblies. Each assembly may contain one or more assemblies in the role of sub-assemblies. An assembly comprises zero, one or many assemblies. The atomic entity of an assembly is a component which is depicted by material_solid_model_representation. Every component is associated with a component_no that represents an identity given to it.

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

Entity material_solid_representation_item represents an element 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. In other words, multiple instances of a material_solid_representation_item within the same materials_solid_model_representation represent the existence of more than one r_m-set in the material object.

The material_representation_item along with geometric_representation_item and topological_representation_item is derived from the previously defined entity, material_solid_model_representation_item to represent material, geometric and topological properties of the solid model respectively. This corresponds to the definition that an r_m-object is defined as a finite collection of r_m-sets $\{(P_i, B_j)\}$. Currently, aic_advanced_brep_representation is used to represent the solid model geometry.

The 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.

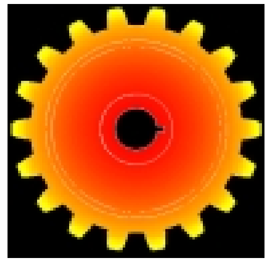
Every material_solid_representation_item comprises a set of no_of_materials number of instances of the material_representation_item. This consists of the entity material_property as one of its attributes. This entity constitutes the individual properties of the material in concern. Part 45 (ISO 10303-45, 1994) of ISO 10303 serves as the basis for this entity.

There can be multiple methods to represent the function for representing the material gradient. Therefore, a local co-ordinate system is defined to aid in the definition of the material function. Local co-ordinate axes are represented by local_co-ord_axes which is an entity of the type axis2_placement_3d. The geometry information may also be associated with the definition of the material distribution function. Therefore an entity (reference) of the type geometric_representation_item is introduced. This selects one of the entities viz. point, curve, surface as the reference entity for variables in the function.

Attribute material_function_application (entity of the type function_application) in material_representation_item represents the composite mathematical function that can be used to represent the material for an instance of the r_m-set. This comprises 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 (ISO/CD 10303-50, 1999).

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 $F = 1$.

Entity shape_aspect is also associated with every material_solid_model_representation. Entities datum, datum_feature and tolerance_zone are derived from shape_aspect. tolerance_zone further defines the associated geometric_tolerance. These entities represent the tolerances associated with an object. Detailed explanations of these entities can be found in Part 47 (ISO 10303-47, 1996) and AIC 519 (ISO/FDIS 10303-519, 1999).



(a) HSM(Gear)

$$\boxed{\begin{aligned} S &= \{(P,B)\} \\ P &= \text{geometry of the gear} \\ B &= \{(x^2+y^2), 1-(x^2+y^2)\} \end{aligned}}$$

(b) r_m-object model

Figure 3. Model of a gear made of two materials

6 Case studies

This section presents some examples to depict the schematic validation of the proposed data planning model to support heterogeneous solid modeling (Kumar and Dutta, 1998) in ISO 10303.

6.1 Case study 1

Consider the object shown in Figure 3(a). This is depicted as an assembly_set that comprises an assembly consisting of only one component as a member of the assembly. The component represents a heterogeneous gear. It is a bi-material object with continuous material variation. The material near the tooth of the gear is such that it accounts for the required hardness for the contact with its associated spur gear. The material near the core of the gear has to be tough to absorb shocks, etc. However, it is a single geometry and so the entire object thus comprises a single r_m-set. The object model is represented in Figure 3(b). The representation of this object as per the data planning model in a schematic STEP physical file format is shown in Figure 4. Figure 4 shows schematically that the proposed data planning model can represent a heterogeneous object completely using ISO 10303. Func11 = (x^2+y^2) represents material distribution for material 1. This is modeled in the STEP representation (Figure 4) as #1023 using entity function_application of Part 50 of ISO 10303.

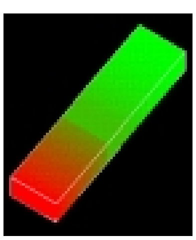
ISO 10303 has a well-developed application protocol (ISO 10303-203, 1997) to represent the geometry of an object. Therefore, Figure 4 does not provide all details of representation of the geometry. The entity manifold_solid_brep represents geometry (denoted as P in Figure 3(b)). The example component considered in Section 6.2 details the representation of a typical r-set in ISO 10303. A similar representation can be applied to the geometry of the gear under consideration in this section.

6.2 Case study 2

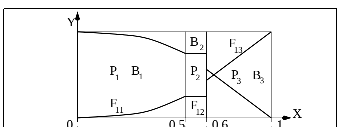
Consider the object shown in Figure 5(a) adapted from (Kumar and Dutta, 1998). This is depicted as an assembly_set that

```
#1000=ASSEMBLY('GEAR', #1001);
#1001=COMPONENT('', #1002, 1);
#1002=MATERIAL_SOLID_MODEL_REPRESENTATION('', #1003);
#1003=MATERIAL_SOLID_REPRESENTATION_ITEM('RMSET1',2,#1004,#1005,#1006);
#1004=MANIFOLD_SOLID_BREP('RSETGEAR',... );
#1005=MATERIAL_REPRESENTATION_ITEM('MAT1',#1010,#1011,#1023);
#1006=MATERIAL_REPRESENTATION_ITEM('MAT2',#1010,#1024,#1027);
#1007=CARTESIAN_POINT('',(0.,0.,0,));
#1008=DIRECTION('',(0.,0.,1.));
#1009=DIRECTION('',(1.,0.,0.));
#1010=AXIS2_PLACEMENT_3D('LOCAL_CO-RD_AXES',#1007,#1008,#1009);
#1011=MATERIAL_PROPERTY(... );
#1012=MATHS_REAL_VARIABLE(#1014, 'XCOORD');
#1013=MATHS_REAL_VARIABLE(#1015, 'YCOORD');
#1014=MATHS_REAL_VARIABLE(#1016, 'ZCOORD');
#1015=FINITE_REAL_INTERVAL(0.0, CLOSED, 60., CLOSED);
#1016=FINITE_REAL_INTERVAL(0.0, CLOSED, 60., CLOSED);
#1017=FINITE_REAL_INTERVAL(0.0, CLOSED, 10., CLOSED);
#1018=ELEMENTARY_FUNCTION('', .EF_EXPONENTIATE_R);
#1019=FUNCTION_APPLICATION('EXPONEN1', #1018, (#1012, 2.0));
#1020=FUNCTION_APPLICATION('EXPONEN2', #1018, (#1013, 2.0));
#1021=ELEMENTARY_FUNCTION('', .EF_ADD_R);
#1022=FUNCTION_APPLICATION('ADDITION', #1021, (#1019, #1020));
#1023=FUNCTION_APPLICATION('FUNC11', #1022, (#1012, #1013, #1014));
#1024=MATERIAL_PROPERTY(... );
#1025=ELEMENTARY_FUNCTION('SUB', .EF_SUBTRACT_R);
#1026=FUNCTION_APPLICATION('SUBFUNC', #1025, (1.0, #1022));
#1027=FUNCTION_APPLICATION('FUNC12', #1026, (#1012, #1013, #1014));
```

Figure 4. Schematic representation of the heterogeneous gear in Figure 3 using ISO 10303



(a) HSM(Rectangular geometry)



$$
\begin{aligned}
S &= \{(P_1, B_1), (P_2, B_2), (P_3, B_3)\} \\
P_1 &= \{(x, y), 0 \leq x < 50, 0 \leq y < 20\} \\
P_2 &= \{(x, y), 50 \leq x < 60, 0 \leq y < 20\} \\
P_3 &= \{(x, y), 60 \leq x < 100, 0 \leq y < 20\} \\
B_1 &= \{(0.01 \times x)^2, 1 - (0.01 \times x)^2\} \\
B_2 &= \{0.25, 0.75\} \\
B_3 &= \{1.5 \times 0.01 \times x - 0.5, 0.5 - 1.5 \times 0.01 \times x\}
\end{aligned}
$$

(b) r_m object model

Figure 5. Model of two material object with three r_m-sets

```
#1000=ASSEMBLY('MULTI-RM', #1001);
#1001=COMPONENT('', #1002, 1);
#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);
#1007=CARTESIAN_POINT('',(0.,0.,0,));
#1008=DIRECTION('',(0.,0.,1.));
#1009=DIRECTION('',(1.,0.,0.));
#1010=AXIS2_PLACEMENT_3D('LOCAL_CO-RD_AXES',#1007,#1008,#1009);
⋮                ⋮                ⋮
#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', ...);
#3005=CARTESIAN_POINT('',(0.,0.,0,));
#3006=DIRECTION('',(0.,0.,1.));
#3007=DIRECTION('',(1.,0.,0.));
#3008=AXIS2_PLACEMENT_3D('LOCAL_CO-RD_AXES',#3005, #3006,#3007);
⋮                ⋮                ⋮
#5001=MATERIAL_SOLID_REPRESENTATION_ITEM('RMSET3',2,#5002,#5003,#5004);
#5002=MANIFOLD_SOLID_BREP('RSET3', ...);
#5003=MATERIAL_REPRESENTATION_ITEM('MAT1', ...);
⋮                ⋮                ⋮
```

Figure 6. Representation of multiple r_m-sets (Figure 5) in ISO 10303

comprises an assembly consisting of only one component as a member of the assembly. This component is a heterogeneous object with rectangular geometry used to explain the representation of a material object comprising more than one r_m-set. The object model is represented in Figure 5(b). The definition of an r_m-set is such that the material distribution function is C^∞ (Kumar and Dutta, 1998). Thus, the r_m object with a piecewise continuous material distribution function is decomposed into three r_m-sets as shown in Figure 5(b). The representation of this object as per the data planning model in a schematic STEP physical file format is shown in Figure 6.

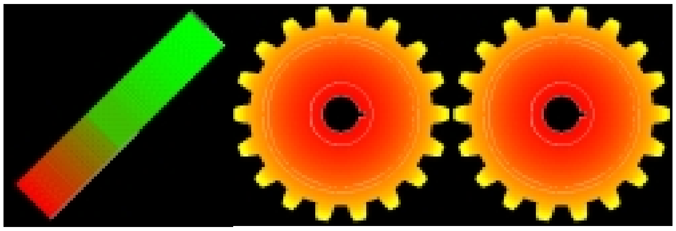


Figure 7. Assembly of objects in the same setup

Figure 6 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 in the above representation as #1020 using entity function_application of Part 50 (ISO/CD 10303-50, 1999).

However, Figure 6 does 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. The details of the representation of this geometry is shown in Appendix A. It presents a typical representation and other geometries can be represented in a similar way.

6.3 Case study 3

Consider the fabrication of an assembly of objects as shown in Figure 7. The constituent objects are discussed in Section 6.1 and Section 6.2.

This assembly consists of three components. Each component is a heterogeneous object and is represented as a material_solid_representation in the schematic EXPRESS representation of this assembly shown in Figure 8. The details of the individual representations of the components are presented in Figure 4 and Figure 6. The two gears in this assembly may be functionally related to each other. However, the third component (box) is not functionally related to the remaining two. Thus, the three components constitute an assembly based on the assumption that they can be fabricated in the same setup on an RP machine (*the workspace of the LM machine is assumed to be large enough to accommodate the three components*).

A similar structure can be used to represent completely functional assemblies like gear boxes, valve assemblies etc.

All these case studies present a successful validation of the data planning model proposed in Section 5. However, some issues need to be tackled before ISO 10303 can be used to completely represent every assembly consisting of heterogeneous objects. The following sections present some observations based on the proposed DPM and some issues that need to be dealt with for a complete representation of heterogeneous objects in ISO 10303.

```
#1000=ASSEMBLY('MULTIOBJ', #1001, #6001, #7001);
#1001=COMPONENT('', #1002, 1);
#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);
⋮                    ⋮                    ⋮
#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', ...);
#5004=MATERIAL_REPRESENTATION_ITEM('MAT2', ...);
⋮                    ⋮                    ⋮
#6001=COMPONENT('', #6002, 2);
#6002=MATERIAL_SOLID_MODEL_REPRESENTATION('', #6003);
#6003=MATERIAL_SOLID_REPRESENTATION_ITEM('',2,#6004,#6005,#6006);
#6004=MANIFOLD_SOLID_BREP('RSETGEAR',... );
⋮                    ⋮                    ⋮
#7001=COMPONENT('', #7002, 3);
#7002=MATERIAL_SOLID_MODEL_REPRESENTATION('', #7003);
#7003=MATERIAL_SOLID_REPRESENTATION_ITEM('',2,#7004,#7005,#7006);
#7004=MANIFOLD_SOLID_BREP('RSETGEAR2',... );
#7005=MATERIAL_REPRESENTATION_ITEM('MAT10',#7010,#7011,#7023);
```

Figure 8. Schematic representation of an assembly comprising more than one heterogeneous objects using ISO 10303

7 Conclusion

The DPM (Data Planning Model) proposed in Section 5 provides an overview of the methodology and the structure to represent heterogeneous objects in the domain of ISO 10303.

It takes into account the representation of an object as an assembly in the domain of Layered Manufacturing. This represents the creation of objects (similar or dissimilar) and complete assembly(ies) in one setup of the LM machine.

The DPM represents a complete integration of material information with the corresponding geometry to represent heterogeneous objects as proposed in (Kumar and Dutta, 1998). 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.

This format of representation of heterogeneous objects can represent a major step towards the successful physical realization of heterogeneous objects through layered manufacturing.

8 Further issues

To enable complete STEP-based data transfer in Layered Manufacturing, more 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 a standard information model for interoperability of LM data (analogous to CL Data in CNC machining) in commercial layered manufacturing systems.
3. Validation of this representation scheme for more complex shapes and assemblies and the demonstration of the down-line fabricability using Layered Manufacturing.

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Patil and Dutta acknowledge the financial support (Grant #70NANB9H0053) from National Institute of Standards and Technology, Gaithersburg, Maryland.

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REFERENCES

Dutta, D., Kumar, V., Pratt, M. J., and Sriram, R. (1998). Towards STEP-based Data Transfer in Layered Manufacturing. In *Proceedings of the tenth international IFIP WG5.2/5.3 PROLAMAT Conference*, Trento, Italy.

Hoffman, C. (1989). *Solid and Geometric Modeling: An Introduction*. Morgan Kaufmann Publishers, San Mateo, CA.

ISO 10303-203 (1997). *Product data representation and exchange: Application Protocol: Configuration Controlled Design*.

ISO 10303-45 (1994). *Product data representation and exchange: Integrated generic resources: Materials*.

ISO 10303-47 (1996). *Product data representation and exchange: Integrated generic resources: Shape Variation Tolerances*.

ISO/CD 10303-50 (1999). *Product data representation and exchange: Integrated generic resources: Mathematical Constructs*.

ISO/DIS 10303-514 (1997). *Product data representation and exchange: Application Interpreted Construct: Advanced Boundary Representation*.

ISO/FDIS 10303-519 (1999). *Product data representation and exchange: Application Interpreted construct: Geometric Tolerances*.

ISO/WD 10303-1 (1994). *Product data representation and exchange: Overview and fundamental principles*.

ISO/WD 10303-11 ed-2 (1998). *Product data representation and exchange: Description methods: The EXPRESS Language Reference Manual*.

Jackson, T., Patrikalakis, N., Sachs, E., and Cima, M. (1998). Modeling and designing components with Locally Controlled Composition. In *Proceedings of the Solid Freeform Fabrication Symposium*.

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

Kumar, V. (1999). *Solid Modeling and Algorithms for Heterogeneous Objects*. PhD thesis, University of Michigan, Ann Arbor.

Kumar, V. and Dutta, D. (1998). An Approach to Modeling and Representation of Heterogeneous Objects. *ASME journal of mechanical design*, 120:659–667.

Marsan, A. and Dutta, D. (1996). Construction of a Surface Model and Layered Data from 3D Homogenization Output. *Journal of Mechanical Design*, 118(3):412–418.

Marsan, A., Kumar, V., Dutta, D., and Pratt, M. J. (1998). 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.

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

Zhongke, W., Soon, S. H., and Feng, L. (1999). NURBS-Based Volume Modeling. In *International Workshop on Volume Graphics*, pages 321–330.

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 5(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,$);
#14=PLANE('',#17);
:                                    :
#25=AXIS2_PLACEMENT_3D('',#23,#24,$);
#26=LINE('',#28,#29);
#27=DIRECTION('',(-1.,0.,0.));
#28=CARTESIAN_POINT('',(0.,12.5,5.));
#29=VECTOR('',#27,1.);
#30=PLANE('',#33);
#31=CARTESIAN_POINT('',(-25.,0.,0.));
#32=DIRECTION('',(1.,0.,0.));
#33=AXIS2_PLACEMENT_3D('',#31,#32,$);
#34=LINE('',#36,#37);
#35=DIRECTION('',(0.,-1.,0.));
#36=CARTESIAN_POINT('',(-25.,0.,5.));
#37=VECTOR('',#35,1.);
#38=PLANE('',#41);
#39=CARTESIAN_POINT('',(0.,-12.5,0.));
#40=DIRECTION('',(0.,1.,0.));
#41=AXIS2_PLACEMENT_3D('',#39,#40,$);
#42=LINE('',#44,#45);
#43=DIRECTION('',(1.,0.,0.));
#44=CARTESIAN_POINT('',(0.,-12.5,5.));
#45=VECTOR('',#43,1.);
#46=PLANE('',#49);
#47=CARTESIAN_POINT('',(0.,0.,-5.));
#48=DIRECTION('',(0.,0.,1.));
#49=AXIS2_PLACEMENT_3D('',#47,#48,$);
#50=LINE('',#52,#53);
#51=DIRECTION('',(0.,-1.,0.));
#52=CARTESIAN_POINT('',(25.,0.,-5.));
#53=VECTOR('',#51,1.);
#54=LINE('',#56,#57);
#55=DIRECTION('',(-1.,0.,0.));
#56=CARTESIAN_POINT('',(0.,-12.5,-5.));
#57=VECTOR('',#55,1.);
#58=LINE('',#60,#61);
#59=DIRECTION('',(0.,1.,0.));
#60=CARTESIAN_POINT('',(-25.,0.,-5.));
#61=VECTOR('',#59,1.);
#62=LINE('',#64,#65);
#63=DIRECTION('',(1.,0.,0.));
#64=CARTESIAN_POINT('',(0.,12.5,-5.));
#65=VECTOR('',#63,1.);
#66=LINE('',#68,#69);
#67=DIRECTION('',(0.,0.,-1.));
#68=CARTESIAN_POINT('',(-25.,-12.5,0.));
#69=VECTOR('',#67,1.);
#70=LINE('',#72,#73);
#71=DIRECTION('',(0.,0.,-1.));
#72=CARTESIAN_POINT('',(25.,-12.5,0.));
#73=VECTOR('',#71,1.);
#74=LINE('',#76,#77);
#75=DIRECTION('',(0.,0.,-1.));
#76=CARTESIAN_POINT('',(-25.,12.5,0.));
#77=VECTOR('',#75,1.);
#78=LINE('',#80,#81);
#79=DIRECTION('',(0.,0.,-1.));
#80=CARTESIAN_POINT('',(25.,12.5,0.));
#81=VECTOR('',#79,1.);
#82=AXIS2_PLACEMENT_3D('',#83,#85,#84);
#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.);
#106=VERTEX_POINT('',#107);
#107=CARTESIAN_POINT('',(-25.,-12.5,5.));
#108=ORIENTED_EDGE('',*,*,#109,.T.);
#109=EDGE_CURVE('',#106,#94,#110,.T.);
#110=INTERSECTION_CURVE('',#42,(#10,#38),.CURVE_3D.);
#111=ADVANCED_FACE('',(#112),#46,.F.);
#112=FACE_BOUND('',#113,.T.);
#113=EDGE_LOOP('',(#114,#121,#126,#131));
#114=ORIENTED_EDGE('',*,*,#115,.T.);
#115=EDGE_CURVE('',#117,#119,#116,.T.);
#116=INTERSECTION_CURVE('',#50,(#46,#14),.CURVE_3D.);
#117=VERTEX_POINT('',#118);
#118=CARTESIAN_POINT('',(25.,12.5,-5.));
#119=VERTEX_POINT('',#120);
#120=CARTESIAN_POINT('',(25.,-12.5,-5.));
#121=ORIENTED_EDGE('',*,*,#122,.T.);
#122=EDGE_CURVE('',#119,#124,#123,.T.);
#123=INTERSECTION_CURVE('',#54,(#46,#38),.CURVE_3D.);
#124=VERTEX_POINT('',#125);
#125=CARTESIAN_POINT('',(-25.,-12.5,-5.));
#126=ORIENTED_EDGE('',*,*,#127,.T.);
#127=EDGE_CURVE('',#124,#129,#128,.T.);
#128=INTERSECTION_CURVE('',#58,(#46,#30),.CURVE_3D.);
#129=VERTEX_POINT('',#130);
#130=CARTESIAN_POINT('',(-25.,12.5,-5.));
#131=ORIENTED_EDGE('',*,*,#132,.T.);
#132=EDGE_CURVE('',#129,#117,#133,.T.);
#133=INTERSECTION_CURVE('',#62,(#46,#22),.CURVE_3D.);
#134=ADVANCED_FACE('',(#135),#38,.F.);
#135=FACE_BOUND('',#136,.T.);
#136=EDGE_LOOP('',(#137,#140,#141,#144));
#137=ORIENTED_EDGE('',*,*,#138,.T.);
#138=EDGE_CURVE('',#106,#124,#139,.T.);
#139=INTERSECTION_CURVE('',#66,(#38,#30),.CURVE_3D.);
#140=ORIENTED_EDGE('',*,*,#122,.F.);
#141=ORIENTED_EDGE('',*,*,#142,.F.);
#142=EDGE_CURVE('',#94,#119,#143,.T.);
#143=INTERSECTION_CURVE('',#70,(#38,#14),.CURVE_3D.);
#144=ORIENTED_EDGE('',*,*,#109,.F.);
#145=ADVANCED_FACE('',(#146),#30,.F.);
#146=FACE_BOUND('',#147,.T.);
#147=EDGE_LOOP('',(#148,#151,#152,#153));
#148=ORIENTED_EDGE('',*,*,#149,.T.);
#149=EDGE_CURVE('',#101,#129,#150,.T.);
#150=INTERSECTION_CURVE('',#74,(#30,#22),.CURVE_3D.);
#151=ORIENTED_EDGE('',*,*,#127,.F.);
#152=ORIENTED_EDGE('',*,*,#138,.F.);
#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));
```