TERRIFIC
Enhancing Interoperability

SEVENTH FRAMEWORK PROGRAMME

Deliverable D5.3:

Relation of isogeometric technology and standards

Task T5.3:

Isogeometric representation and standards

Circulation: PU[1]

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Version: 1

Date: September 16, 2012

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Document History

Vers.	Issue Date	Stage	Content and changes
1	September 16, 2012		Ready for submission

Executive Summary

This document contains deliverable D5.3 of the TERRIFIC FoF STREP Project. D5.3 is a Technical Report that describes the relation of isogeometric technology and standards.

An analysis of existing standards was performed in the areas of shape representation, model quality and long term data retention that may require updates to benefit from isogeometric technology. Focus was on product data standards from ISO TC 184/SC 4 and especially ISO 10303. The aerospace-specific agreements of the ASD EN 9300 series have also been considered.

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1 Introduction

This report is the first one of two concerning the impact of isogeometry on standards. It has been compiled in cooperation between SINTEF and JOTNE. The second one, D5.5 – "*Recommended list of actions to standard updates*", will be delivered at the end of the project.

The task here is to address the standards-related challenges of a future shift to trivariate isogeometric representations in design, analysis, manufacturing and Enterprise Simulation Management (ESM). Such a shift will influence business processes and data flows, and consequently also have impact on future revisions of standards related to representation, data exchange and long term storage of product related information. In this regard, the TERRIFIC project coordinates and contributes to standard developments directly, namely by attending standardization meetings, and by proposing upgrades to existing standards that will put forward results from the project. The following standards were identified as candidates for TERRIFIC during the proposal stage: ISO 10303-203, ISO 10303-209, ISO 10303-214, ISO 10303-239, ISO 10303-242, EN 9300-110 and EN-9300-210; furthermore ASD DEX 1, ASD DEX 3, ASD DEX 11 and ISO 14721 for Engineering Simulation Management (ESM). Not all of these are considered relevant anymore; EN 9300-210 and the ASD DEXs have been removed from the list as they neither concern geometry nor geometry-related data quality.

This report elaborates in section 2 why isogeometry is a topic for standardization and in which domain, before it presents in section 3 relevant domain standards. The project has already concluded on a way forward, and this approach is described in section 4. Several standardization meetings were attended already. The current states of discussions and negotiations are summarized in section 5.

2 Isogeometry – a topic for standardization

Why shall aspects of isogeometry be a topic for standardization? And what are these aspects? What shall be edited into standard documents?

2.1 Background for standardizing isogeometry

Isogeometry is a method for describing shape, in other words, it is a way of representing geometry. As other types of geometric representations, such as constructive solid geometry and boundary representations, it grew out of academia for then being embraced by industry. For its qualities in the design of 3-dimensional objects isogeometry was first used in computer-aided design (CAD) in the mechanical industry. CAD is applied early in the life-cycle of product manufacturing. CAD-models are moved downstream to serve as the basis for engineering and manufacturing, and even after product delivery for maintenance and support. The geometric representation of the design model needs to be handed over from its originating CAD-system to other specialized applications, such as finite element analysis tools and machining tools. The representation that geometry is transferred in must enable access and manipulation by the target system. Here the need for data exchange solutions arises. Data exchange is - on a larger scale - most efficiently performed using standards. Traditional geometric representations have therefore been mirrored into a neutral format, that is, a standard. IGES was the first widely used standard for geometry and topology; STEP is its successor. Isogeometry is a new geometric representation. It will be used in the same industrial life-cycle processes, and will thus also need a standard representation.

The other reason for standardization besides data exchange is long-term archival. Archival is a repetitive event in the product life-cycle process. At several stages industry is required to store released versions of the product descriptions, for example, after design and after engineering analyses. These packages shall be retrievable after – in terms of information technology - long periods of time, that is, several decades up to 100 years. Among the main reasons for this requirement is product liability. The need for archival is not as urgent as the need for data exchange. Unless authorities hold up a product for the lack of, for example, the design model in an acceptable data archival format, a product can be released without long-term archival having been addressed. Therefore, the development and implementation of archival formats for engineering data is lagging behind data exchange and data integration formats. However, the extensive and increasing use of 3-dimensional models in product manufacturing in combination with authorities that force product liability solutions, has boosted the development of standards for product data archival. Isogeometry, as an emerging main type of shape representation, needs to be included in this world-wide standardization effort.

Finally, product data quality, the verification and validation of engineering data, pushes a standardized representation of isogeometry. Releases of product data throughout the product life-cycle depend on assessing and safeguarding data quality. Product data representations need to be processed by verification and validation tools. The fewer representations of the same category of geometry, that is, the more standard geometric representations, the fewer verification and validation tools are needed. With a standard representation for isogeometry one would need only one toolset for data quality assessment of isogeometric representations.

In conclusion, the task at hand is to find a comprehensive data representation of isogeometric models and to add this to one or several appropriate standards. These standards shall be sufficient for exchange, validation and archival of product data in industrial settings.

2.2 What shall be standardized

A 3-dimensional isogeometric model is a collection of adjacent volumes that are defined by splines, in contrary to a boundary represented solid. A single volume is also called a block. The splines that describe a volume will usually be of the type non-uniform rational B-splines (NURBS). However, to enable meshing for finite element analysis (FEA), local refinement is needed. T-splines and LR-splines (locally refined splines) can provide this capability.

Isogeometric representation has the following implications:

- Analytic surfaces need to be converted to NURBS;
- Trimming must be replaced by
  - Block structuring and
  - T-splines or LR-splines;
- A volume is represented by its outer shell and needs:
  - A trivariate representation
  - A boundary element method where Green’s function applies
  - A shell formulation.

The basic geometric and topological elements of isogeometric volumes need to be standardized. The correct use of these in applications, such as CAD, FEA and archival shall be ensured.

3 Introduction to relevant standards

Both SINTEF and JOTNE have long-standing experience in the standardization of product data. Already in the proposal stage of TERRIFIC a long list of standards was identified as relevant for isogeometry in the context of its industrial use in the project. The list was then refined to the following candidates: ISO 10303, EN 9300, ISO 8000 and ISO 14721. The following sub-sections briefly introduce these series of standards and comment on those that are most relevant for TERRIFIC.

3.1 STEP – ISO 10303

3.1.1 Why STEP?

The growing need for interoperability of different CAD-systems resulted in 1994 in the initial release of the ISO 10303 standard under the title: "Industrial automation systems and integration - Product data representation and exchange". Today the Standard for the Exchange of Product Model Data (STEP) – as ISO 10303 is often informally referred to - is well tested and widely used daily, especially in the CAD area. STEP offers efficient interoperability among CAD-systems from different vendors and within CAD-system families. The scope of current CAD-systems is mainly covered by the functionality in STEP.

There are the following reasons for the wide uptake of STEP by industry, especially in the domain of product shape:

- STEP can represent volume models with the required industrial accuracy and quality;
- STEP integrates product shape with other product properties and life-cycle information;
- STEP is not only an information model, but defines also several implementation methods, such as file formats and database access interfaces;
- STEP has a framework for testing of vendor translators, CAx-IF (implementers forum);
- STEP has no serious competitor.

There exist types of shape representation that had no priority in STEP; especially lightweight visualization and graphics formats have not been available in STEP. A tessellation format is now being added, but industry will probably continue to use, for example, JT from Siemens, Collada from the Khronos Group and X3D from ISO/IEC 19775 and 19776 in parallel to STEP for some time.

In spite of STEP not covering all types of engineering data formats, there is no alternative to the conclusion that STEP is the right home for standardizing a high-fidelity geometric representation of isogeometry. An initial pathway is called for from the current STEP-represented CAD-models to the trivariate isogeometric model. However, the solution needs to address the use of isogeometry not only in design, but also in engineering analysis and manufacturing. Therefore, several efforts need to be launched in STEP for a comprehensive coverage of the TERRIFIC use of isogeometry.

3.1.2 Structure of ISO 10303, STEP

STEP is not a single document, but a suite of standards; each document is called a part. For finding the right approach for the inclusion of isogeometry in STEP it is necessary to understand the structure of STEP. A part-numbering system has been imposed on ISO 10303 to structure its various aspects:

Part 1	: Overview and fundamental principles
Parts 10-19	: Description methods
Parts 20-29	: Implementation methods
Parts 30-39	: Conformance testing methodology and framework
Parts 40-99	: Integrated generic resources
Parts 100-199	: Integrated application resources
Parts 200-299	: Application protocols
Parts 300-399	: Abstract test suites
Parts 400-499	: Application Protocol Modules
Parts 500-999	: Application interpreted constructs
Parts 1000-2999	: Application modules
Parts 3000-...	: Business Object Models.

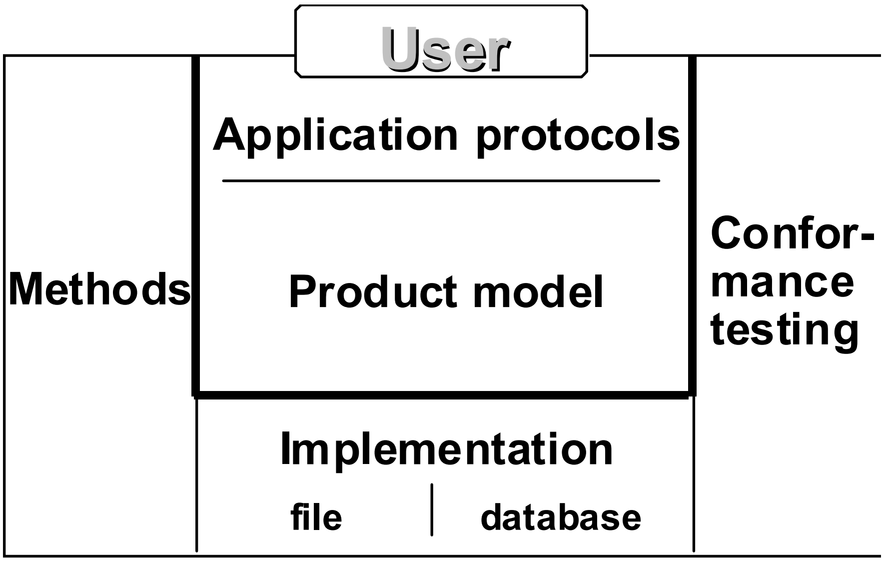

Figure 1: A simplified picture of the document structure in ISO 10303 (STEP)

For TERRIFIC, the kernel in Figure 1 is the most interesting part, that is, the product model inside the u-shaped bold line. This is the STEP data model with all its aspects, including geometry. This model consists of the 40, 100, 200, 400, 500, 1000 and 3000-series of ISO 10303.

The STEP product model is one integrated data model. For the sake of extensibility, documentation and maintenance it has been designed to be spread over many sub-models. There is a reference mechanism that links the sub-models together. Each model concept is defined only once.

The product model is documented in a bottom-up approach, with the most fundamental concepts at the bottom; see Figure 2. The subsequent layers add semantics or ease maintenance and documentation. The recently introduced 3000-series is an exception: these are implementation specific alternative models within an AP.

The model represented by the 40- and 100-series provides the information requirements of the supported industrial branches with respect to their applications and product life-cycles. Here we find terms like product, product version, product category as well as product properties, such as shape, material, and appearance. Methods for assembling and decomposition to allow functional and structural breakdowns are also available.

Isogeometric representations may require new such fundamental features. New features are only introduced in the integrated resources, that is, the 40- and the 100-series. New sub-models in those series extend the capabilities of the integrated product model into new characteristics of product models.

The sub-sections below describe each level of the product model and the relevance of each level for TERRIFIC. Already here it can be revealed that TERRIFIC will need to start all at the bottom, in the 40-series. To enable practical use for exchange and archival of data the new basic concepts will need to appear also in the higher level documents.

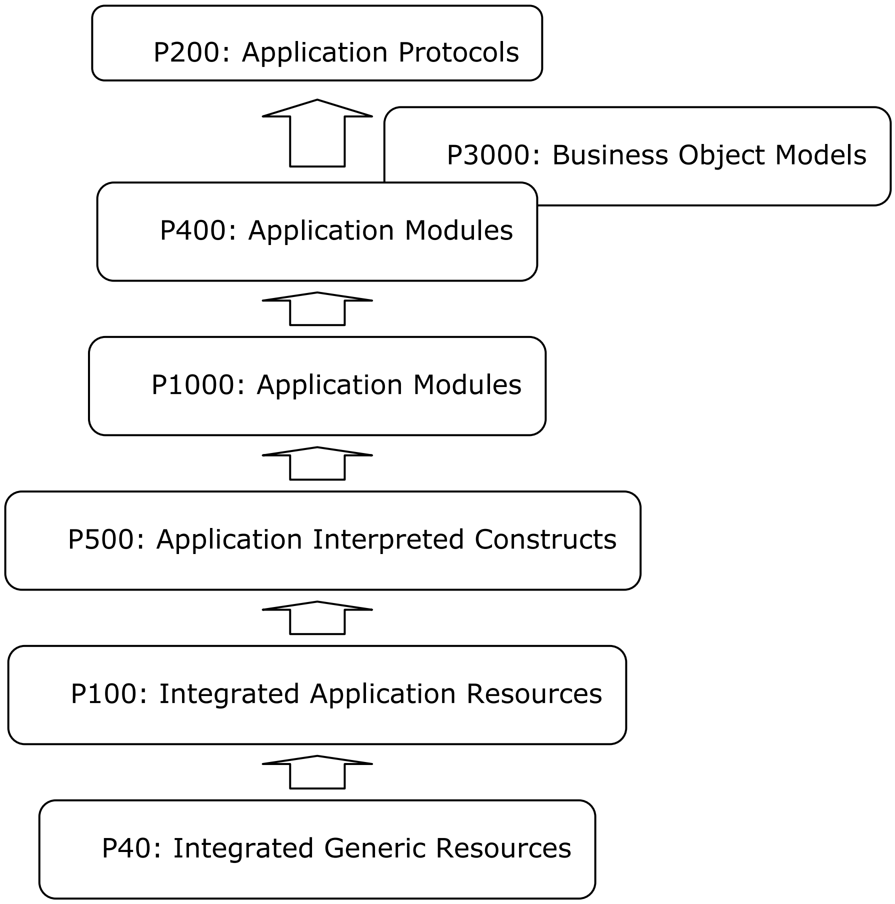

Figure 2: The stack of types of product model standards in STEP

3.1.3 Integrated Generic Resources

The most important group of sub-models is given by the "Integrated generic resources", the 40-series. They include the following standards, that is, parts of ISO 10303:

- Part 41: Fundamentals of product description and support;
- Part 42: Geometric and topological representation;
- Part 43: Representation structures;
- Part 44: Product structure configuration;
- Part 45: Materials;
- Part 46: Visual presentation;
- Part 47: Shape variation tolerances;
- Part 49: Process structure and properties;
- Part 50: Mathematical constructs;
- Part 51: Mathematical description;
- Part 52: Mesh based topology;
- Part 53: Numerical analysis;
- Part 54: Classification and set theory;
- Part 55: Procedural and hybrid representation:

- Part 56: State;
- Part 58: Risk;
- Part 59: Product Data Quality for Shape models;
- Part 61: Systems engineering representation.

When considering all those documents the following four are candidates for further investigations: Parts 42, 52, 53 and 59. Only these deal with geometry and topology, their application in CAD and FEA and their quality-related issues.

3.1.3.1 ISO 10303-42

Part 42 is no more and no less than the bible for a neutral representation of geometric models. Commercially available from ISO is currently edition 3, dated 2003, with a technical corrigendum from 2007. Edition 4 is in development.

The scope of part 42 is determined by the requirements for the explicit representation of an ideal product model; tolerances and implicit forms of representation in terms of features are out of scope [6].

Part 42 is divided into three sections, one for geometry, one for topology, and one for geometric shape models. The corresponding scope statements are the following [6]:

For geometry:

The following are within the scope of the geometry schema:

- definition of points, vectors, parametric curves and parametric surfaces;
- definition of finite volumes with internal parameterization;
- definition of transformation operators;
- points defined directly by their coordinate values or in terms of the parameters of an existing curve or surface;
- definition of conic curves and elementary surfaces;
- definition of curves defined on a parametric surface;
- definition of general parametric spline curves, surfaces and volumes;
- definition of point, curve and surface replicas;
- definition of offset curves and surfaces;
- definition of intersection curves.

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

- all other forms of procedurally defined curves and surfaces;
- curves and surfaces which do not have a parametric form of representation;
- any form of explicit representation of a ruled surface.

NOTE: For a ruled surface the geometry is critically dependent upon the parameterization of the boundary curves and the method of associating pairs of points on the two curves. A ruled surface with B-spline boundary curves can, however, be exactly represented by the B-spline surface entity.

For topology:

The following are within the scope of the topology schema:

- definition of the fundamental topological entities vertex, edge, and face, each with a specialised subtype to enable it to be associated with the geometry of a point, curve, or surface, respectively;
- collections of the basic entities to form topological structures of path, loop and shell and constraints to ensure the integrity of these structures;
- orientation of topological entities.

For geometric shape models:

The following are within the scope of the geometric model schema:

- data describing the precise geometric form of three-dimensional solid objects;
- constructive solid geometry (CSG) models;

- CSG models in two-dimensional space;
- definition of CSG primitives and half-spaces;
- creation of solid models by sweeping operations;
- manifold boundary representation (B-rep) models;
- constraints to ensure the integrity of B-rep models;
- surface models;
- wireframe models;
- geometric sets;
- creation of a replica of a solid model in a new location.

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

- non-manifold boundary representation models;
- spatial occupancy forms of solid models (such as octree models);
- assemblies and mechanisms.

An analysis of this scope of part 42 and of the underlying specification details by the WP5 team has identified the deficiencies with respect to isogeometry (see slides attached in annex 1). A 3D isogeometric model is not a boundary represented solid.

- Analytic surfaces may be represented by NURBS. However, trimming must be replaced by block structuring (see Figure 3, below) in combination with T-splines or LR-splines.
- The volume is represented by its outer shell and needs a trivariate representation. It also requires a boundary element method where Green's function applies and a shell formulation.

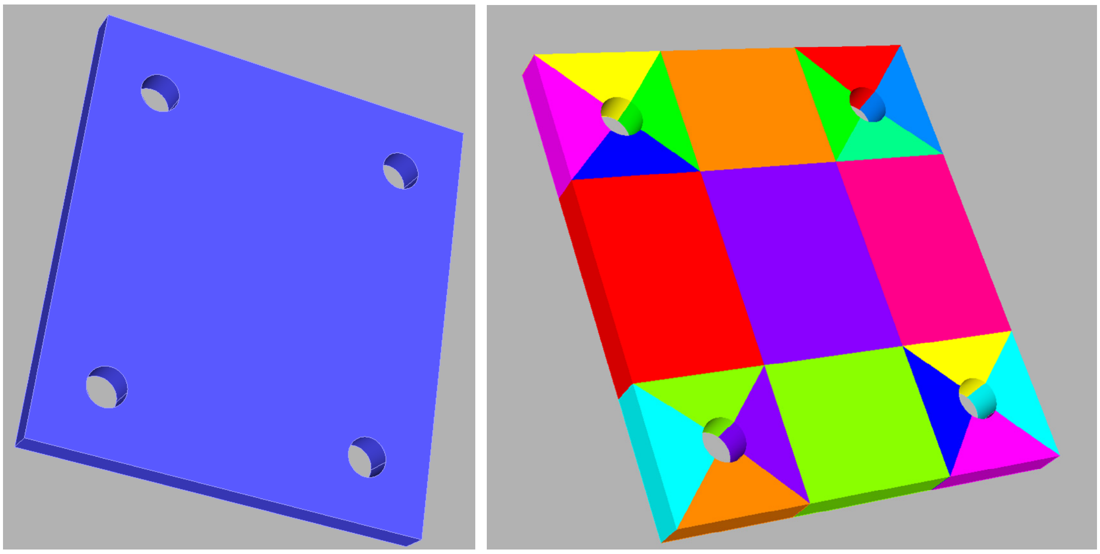

Figure 3: From a CAD solid (left) to a block structured volume (right)

The coloured picture shows that trivariate isogeometry not only requires a volume representation, but a representation of the connectivity among volumes. A B-spline volume representation exists in part 42, the corresponding volume connectivity model, however, is missing. A STEP volume is a manifold, a trivariate volume model is not.

Thus, block structuring can be resolved. Sophisticated trimming does, however, also require new B-spline representations; the regular structure of tensor-product NURBS does not allow local refinement. The tensor-product structure of B-spline surfaces and volumes is inconvenient in the context of diagonal features. A greater flexibility in the modelling of complex objects is asked for. TERRIFIC has considered T-splines as one of the options, but has now decided to base further developments on locally refined (LR) splines. LR-splines relate to geometry and solution fields, not to topology. Their representation format is right now being agreed in the project. This format needs to be added to part 42.

3.1.3.2 ISO 10303-52

Part 52, Mesh-based topology, is one of the resource parts for engineering analysis. It provides general and application-independent means of representing structured and unstructured meshes, and mathematical functions and numeric data defined over such meshes [7].

The document includes the following scope statements [7]:

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

- mesh-based topologies;
- cell connectivity and multi-block mesh interfaces;
- mathematical functions defined over meshes;
- the association of numeric data with the cells, faces, edges, and vertices of a mesh.

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

- applications of mesh topologies;
- applications of mesh interfaces;
- the semantics of data associated with a mesh.

This part extends part 104 into the field of computational fluid dynamics. It needs to be evaluated in combination with part 110, which applies it.

3.1.3.3 ISO 10303-53

Part 53, Numerical analysis, is another one of the resource parts for engineering analysis. It extends the environment for describing analyses and their results in the context of the analyzed product into time and 3-dimensional space, such as typically required for computational fluid dynamics.

The document includes the following scope statements [8]:

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

- application-independent analysis;
- idealisations of product definitions evinced by analyses.

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

- analysis applications.

Part 53 is less technical in nature than both parts 42 and 52; it covers product data management aspects of numerical analyses. Thus, an impact of isogeometry on this part is less likely.

3.1.3.4 ISO 10303-59

Part 59 covers a quite different domain, data quality. Part 59 does not cover data quality in general, but is specifically targeted to part 42 compliant data. It provides general specifications for the representation of quality criteria, quality measurement requirements, quality assessment specifications and quality inspection results of three dimensional shape data.

The document includes the following scope statements [14]:

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

- representation of high level data elements for managing quality related data;
- representation of general quality criteria for product data;
- representation of general quality criteria for product data associated to the corresponding measurement requirements;
- representation of general quality criteria for product data associated to the corresponding assessment specifications;
- representation of quality inspection results of given product data;
- representation of quality criteria for three-dimensional product shape data coupled with measurement requirements for the evaluation of quality criteria

and association with the pertinent assessment specifications. Quality criteria can be used for the representation of requirements, declaration of, or assurance of, product shape data quality. The target shape data models are equivalent to those defined in ISO 10303-42;

NOTE: Detailed requirements for product shape data quality are application context-dependent. This part of ISO 10303 provides a means to select appropriate criteria with required thresholds.

- representation of quality inspection results of given three dimensional product shape data.

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

- degree of satisfaction of design intents;
- quality inspection algorithms;
- relation of shape data quality with tolerance;

NOTE: This part of ISO 10303 deals with illegal or inappropriate product (shape) data represented by a finite number of digits where no unique correct solution exists. Therefore, what is specified in this part of ISO 10303 is essentially different from tolerance information.

- detailed information relating to quality of product data other than shape data;

NOTE: Though general specifications for the representation of criteria, measurement requirements, assessment specifications and inspection results of product data quality are given, detailed specifications are provided only for three-dimensional product shape data.

- data model to improve quality of product shape data;
- relationship of design quality and quality of product data;
- aesthetic quality of product shape data.

NOTE: Aesthetic quality of product shape is a decisive factor for some types of product, such as passenger cars. However, it is not included in this part of ISO 10303 since technology for the evaluation of the aesthetic quality is not yet well established, even though practical functions for its evaluation such as smooth highlight lines or smooth curvature distribution are deployed.

Two things are important to notice from this:

1) Part 59 provides a data representation for results of quality checks of part 42 compliant data.

2) Part 59 does not provide the algorithms for these quality checks. EN 9300 is a source for those.

As TERRIFIC is aiming at an extension of part 42 and as the quality awareness of long-term archiving is an issue for TERRIFIC, an extension to part 59 needs to be considered, too.

3.1.4 Integrated Application Resources

The other group of sub-models is made up of the “Integrated application resources”, the 100-series.

Whereas the generic resources are independent of applications and can reference each other, the application resources can reference the generic resources and can add other resource constructs for use by a group of similar applications. Application resources do not reference other application resources [3].

The following integrated application resources are available:

- Part 101: Draughting;
- Part 104: Finite element analysis;
- Part 105: Kinematics;
- Part 107: Finite element analysis definition relationships;
- Part 108: Parameterization and constraints for explicit geometric product models;
- Part 109: Kinematic and geometric constraints for assembly models;

- Part 110: Mesh based computational fluid dynamics;
- Part 111: Elements for the procedural modeling of solid shapes;
- Part 112: Modeling commands for the exchange of procedurally represented 2D CAD models.

The most important of the above resources is Part 104. Also Parts 107 and 110 will be considered by this task of WP5.

3.1.4.1 ISO 10303-104

Part 104 is concerned with information exchange needs of finite element analysis. Many types of analyses can be conducted to ensure the performance and integrity of a product. Different aspects of a product may be idealized and then analyzed as a continuum. Exact mathematical models for any but the simplest continuum shapes are intractable. Therefore, analytical methods that represent the continuum as discrete tractable shapes are used. There are many discrete analytical methodologies, some of which are finite element, finite difference, and boundary element. Part 104 addresses only finite element analysis [9].

This part of ISO 10303 specifies the resources for the exchange of the information associated with the discretized finite element model, and the analysis controls, boundary conditions, and analysis results information that are associated with it [9].

The document includes the following scope statements [9]:

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

- linear static analysis and linear dynamic modes and frequencies analysis of general 3D stress, plane stress, axisymmetric strain, and simple plane strain, based upon h-version finite element formulation using 2D and 3D continua and embedded elements which include thick shells, thin shells, beams, and bars;
- the definitional aspects of a finite element analysis model;
- the definitional aspects of a finite element;
- the definitional aspects of a node;
- nodes, h-version finite elements, and the associated element material and geometric property representations that combine to form a discretised mesh;
- material representations;
- coordinate space representations;
- analysis selection and related information;
- environment information;
- output control information;
- nodal and element output information;
- output information applying to a whole model;
- scalars;
- 2D and 3D first order tensors;
- 2D and 3D second order tensors;
- 2D and 3D symmetric fourth order tensors;
- administrative information.

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

- linear static analysis of generalized plane strain;
- p-version finite elements.

In identifying the central role of part 104, WP5 has started a deeper analysis of part 104. The following sketches how trivariate isogeometry could be applied to engineering analysis:

- The analysis solution field is related to a geometry entity (curve, surface, volume) represented in the spline format. One geometry entity may have several solution fields related to different computations on the same geometry and to time dependent problems. The solution field is represented in the same function space as the corresponding geometry entity or a refined version thereof. As the shape of the geometry entity does not change with refinement, no accuracy is lost. Derived quantities (computed from primary solutions) do not necessarily share the same function space (different degree), but the knot spacing (elements) will be the same. Two solution fields related to the same geometry entity may have different polynomial degree when mixed methods are applied (for instance pressure and velocity in fluid flow). The knot vectors may differ, but the parameterization of the geometry entity and the solution field(s) correspond.

This future way of working needs to be integrated into the current way STEP, and especially part 104, handles engineering analysis; the following offers initial ideas on the way forward:

- The finite element model is equal to the (possibly simplified) design shape which again is equal to the idealized analysis shape. A state is an aggregation of information about the analysis variables of a model that describes the model at an instant. A node plays a role that is similar to a coefficient, but a coefficient is less explicitly represented. The coefficients are governing the geometry, not interpolating it, as nodes are doing. There is no connection between the solution and the geometry representation for refined solution spaces, derived quantities or mixed methods.
- An element plays a role that is similar to a knot interval. This is the standard interpretation in isogeometric analysis. The knot interval is only implicitly defined by the knot vector. There is no connection between the solution and the geometry representation for refined solution spaces. Material properties are connected to elements in part 104.
- The geometry representation and the solution fields can always be connected through parametriziation.
- Both a node_group and an element_group can in some sense be associated with an isogeometric block (a NURBS curve, surface or volume), but the correspondence is not very clear. An analysis result corresponding to a group (field_variable_element_group_value) is in the isogeometric case not an aggregated result.
- The type of boundary conditions and the connection to boundaries or parts of boundaries are not new, but the representation may differ.
- A control for a finite element analysis describes the operations carried out upon the model. A finite element analysis application calculates the response of the model to these operations. Controls are also known as boundary conditions. Symmetry control is done by symmetry conditions (no_symmetry_control, cylindrical_symmetry_control). Constraints may match Dirichlet boundary conditions (point_constraint, curve_constraint, surface_constraint). Control_process may match Neumann boundary conditions. A control_process is the way in which the model is caused to depart from its initial state.

3.1.4.2 ISO 10303-107

Part 107 specifies associations between the idealised concepts that are used in a finite element analysis, and the design specifications for these concepts. The design specification information is managed by a Product Data Management system (PDM). The associations supported by this part of ISO 10303 support the navigation to a finite element from the design information within a PDM system [9].

The document includes the following scope statements [9]:

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

- an association between a set of finite element analysis steps and the design or specification for an action;
- an association between a finite element analysis state and a design or specification for a product state;
- an association between a finite element analysis result and a property which is possessed by a product state;

- an association between a surface or curve section property in a finite element model and a property which is possessed by a product;
- an association between a node or element in a finite element model and an aspect of the topology of the product.

The following are not within the scope of this part of ISO 10303:

- the identification or description of an action;
- the identification or description of a product, or state of a product;
- the identification or description of a property;
- the topology of a product;
- a finite element model of a product.

The scope statement definitely reveals a relationship to one of the core technical issues that TERRIFIC tries to resolve: the link between analysis and design. Part 107 suggests to provide this link on the level of PDM; TERRIFIC promises to solve it on the geometry level. The TERRIFIC solution is the more appealing one, but it will need to be supported by high level product data relations á la part 107.

3.1.4.3 ISO 10303-110

Part 110 provides a general application independent means of representing computational fluid dynamics numerical analyses on structured and unstructured meshes [10]. It heavily uses parts 52 and 53.

The document includes the following scope statements [11]:

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

- digital data on structured and unstructured meshes describing steady or unsteady fluid dynamics flow fields;
- data describing the fluid dynamics model including mesh description, mesh inter-connectivity, boundary conditions, and modeling parameters;
- data from solutions of equation sets commonly used in fluid dynamics analysis: Navier-Stokes equations, Euler equations, linear and nonlinear potential flow equations, small-disturbance equations, boundary layer equations, and stream function equations;
- data at any point in the analysis activity;
- single-phase flow of a liquid or a gas;
- laminar flow, transitional flow, turbulent flow (direct representation of turbulence, or represented by Reynolds-averaged data);
- incompressible or compressible flow;
- unsteady flow;
- perfect gas, or variable chemical composition (equilibrium flow, frozen flow, or finite-rate chemical reactions);
- data regarding the exchange of energy by molecular transport including convection, conduction, and advectation;
- rotating flow fields (e.g., turbomachinery);
- inertial and rotating frames of reference;
- Newtonian transport laws;
- reference to product geometry;
- administrative information necessary to track the approval and configuration control of the analysis of a product.

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

- representations of geometry;
- gross flow in networks (e.g., piping and ducting);
- the use that application programs may make of the data;
- the means by which application programs modify the data;
- the form in which the data is stored internal to an application.

The validity, accuracy and completeness of the data for a particular purpose are determined entirely by the applications’ software.

NOTE: The following are outside the scope of this edition of this part of ISO 10303 but are expected to be inside the scopes of later editions of this part:

- two- and three-phase flow;
- free surface flow;
- non-continuum flow (e.g., direct simulation of Monte Carlo data);
- data from non-analytical sources (e.g., experimental simulation such as wind tunnel or water tank testing, and product tests such as flight tests or sea trials);
- data regarding the exchange of energy by radiation;
- non-Newtonian transport laws;
- electro-magnetic interactions with a fluid;
- plasmas.

Part 110 has no direct link to part 42, however, shape representations are referenced, which is confirmed by the in-scope statement "reference to product geometry". The impact of isogeometry on the mesh representation of parts 110/52 needs to be evaluated.

3.1.5 Application Protocols

Certain industrial domains and industrial usages demand tailored aggregation and specialisation of the generic STEP resources. For example, the design of buildings does not require the same sophisticated geometry than the design of cars. Such specialisation is done by Application Protocols.

The integrated resources define a generic information model for product information. They are not sufficient to support the information requirements of an application without the addition of application specific constraints, relationships and attributes. ISO 10303 defines application protocols in which the integrated resources are interpreted to meet the product information requirements of specific applications. The interpretation is achieved by selecting appropriate resource constructs and refining their meaning, by specifying any appropriate constraints, relationships, and attributes [3].

Each Application Protocol (AP) is a standard in the 200-series. APs are the only parts of STEP that are intended for the end-user and for end-user applications, as indicated by the "User"-tag in Figure 1 above.

Several industries already have or have at least started to specify their specialised models. Aircraft and automotive industries have proceeded the longest; the international standard ISO 10303-203 originates from the aircraft industry, ISO 10303-214 from the automotive industry. These two are currently being merged into the emerging AP242. The electric/electronic, process, maritime, defence, and building and construction industries have their domain specific APs.

Dividing the world of engineering data into industry domains seemed a good idea. However, STEP addresses data exchange among engineering applications, and a CAD-system may be used in different industry domains. There should better not be differences in how the same types of data are handled among the Application Protocols. To guarantee this in a single source approach, is one of the reasons for the merger of AP203 and AP214 into AP242; AP239 may be added later.

The following Application Protocols exist:

- Part 201: Explicit draughting;
- Part 202: Associative draughting;
- Part 203: Configuration controlled 3D design of mechanical parts and assemblies;
- Part 204: Mechanical design using boundary representation;
- Part 207: Sheet metal die planning and design;
- Part 209: Composite and metallic structural analysis and related design;
- Part 210: Electronic assembly, interconnect, and packaging design;

- Part 212: Electrotechnical design and installation;
- Part 214: Core data for automotive mechanical design processes;
- Part 215: Ship arrangement;
- Part 216: Ship moulded forms;
- Part 218: Ship structures;
- Part 219: Dimensional inspection information exchange
- Part 221: Functional data and their schematic representation for process plants;
- Part 223: Exchange of design and manufacturing product information for cast parts;
- Part 224: Mechanical product definition for process planning using machining features;
- Part 225: Building elements using explicit shape representation;
- Part 227: Plant spatial configuration;
- Part 232: Technical data packaging core information and exchange;
- Part 233: Systems engineering (to be published shortly)
- Part 235: Engineering properties for product design and verification;
- Part 236: Furniture catalog and interior design;
- Part 238: Application interpreted model for computerized numerical controllers;
- Part 239: Product life cycle support;
- Part 240: Process plans for machined products;
- Part 242: Managed model based 3D engineering (under development).

For TERRIFIC only those APs are of interest that cover the TERRIFIC industry domains and that include shape representations. Also, TERRIFIC should not spend efforts on APs that are lacking industry support. First with isogeometric concepts being adopted by an AP will it be possible to write internationally accepted STEP converters to and from the TERRIFIC translators.

The following APs will be considered for inclusion of isogeometric concepts – as soon as those become available in the more fundamental STEP parts: APs 209, 238, 242.

3.1.5.1 AP209

AP209 is the only application protocol for engineering analysis. It was published as edition 1 in 2001 under the title of “Composite and metallic structural analysis and related design” [19] and as a modularized AP. Edition 2 is just waiting for its DIS ballot; it has the title “Multidisciplinary analysis and design”.

AP209 uses parts 53 and 104 and thus makes their features available for data exchange and data archival.

For TERRIFIC, AP209 is one of the main standardization targets as it embraces both design and analysis. This is therefore the right place to make the benefits of isogeometry available to the end user. TERRIFIC will probably need to initiate a third edition of AP209 as soon as the basic concepts are defined in the integrated resources and – maybe – AICs.

3.1.5.2 AP238

The only reason for considering AP238 is WP4, the machining application. AP238 includes the major shape representations of part 42 and associating those with "working steps": a library of specific operations that might be performed on a CNC machine tool [20].

A STEP-NC program based on AP238 can use the full range of geometric constructs from the

STEP standard to communicate device-independent tool paths to the CNC. It can provide CAM operational descriptions and STEP CAD geometry to the CNC so work pieces, stock, fixtures and cutting tool shapes can be visualized and analyzed in the context of the tool paths. STEP GD&T information can also be added to enable quality measurement on the control, and CAM-independent volume removal features may be added to facilitate regeneration and modification of the tool paths before or during machining for closed loop manufacturing [source: wikipedia].

Thus, when extrapolating the use of isogeometry beyond engineering analysis into manufacturing, TERRIFIC will meet AP238 and will need to contribute to its edition 2, which there are no known plans for yet.

3.1.5.3 AP242

AP242 is a design-centric application protocol, but includes composite shapes as they are used by engineering analysis. AP242 is awaiting its DIS ballot. It is a merger of two of the most popular standards of STEP and the industrial groupings behind those: AP203 and AP214. Also AP242 is a modularized AP.

The support of AP242 by the global car and aeronautics industries makes it an extraordinary important standard. Many application vendors will claim compliance to it. And other application protocols, such as AP209, will interface to AP242. The TERRIFIC extensions to the STEP integrated resources should also be integrated into AP242. Even though edition 1 is not published yet, plans for an edition 2 of AP242 are already being discussed. TERRIFIC has now the opportunity to impact the scope statement of this edition 2!

3.1.6 Application Interpreted Constructs (AIC)

One step of specialization of the integrated resources is done in the Application Interpreted Constructs (AIC). An AIC is a logical grouping of interpreted, that is, specialized constructs that support a specific function, such as faceted boundary representation model, for the usage across multiple application protocols.

The purpose of application interpreted constructs (AIC) is to provide a mechanism to identify and document the common requirements of different application protocols as represented within their information requirements. AICs provide a consistent and standardized interpretation of the integrated resources across different application contexts by identifying the semantics and shared data definitions to support a specific functionality [4].

When an AP uses an AIC, it is obvious for an implementer that this information domain, for example, faceted boundary representation, is solved in this AP in exactly the same manner as it is in any other AP that uses the same AIC.

The following Application Interpreted Constructs exist:

- Part 501: Edge-based wireframe;
- Part 502: Shell-based wireframe;
- Part 503: Geometrically bounded 2D wireframe;
- Part 504: Draughting annotation;
- Part 505: Drawing structure and administration;
- Part 506: Draughting elements;
- Part 507: Geometrically bounded surface;
- Part 508: Non-manifold surface;
- Part 509: Manifold surface;
- Part 510: Geometrically bounded wireframe;
- Part 511: Topologically bounded surface;

- Part 512: Faceted boundary representation;
- Part 513: Elementary boundary representation;
- Part 514: Advanced boundary representation;
- Part 515: Constructive solid geometry;
- Part 517: Mechanical design geometric presentation;
- Part 518: Mechanical design shaded presentation;
- Part 519: Geometric tolerances;
- Part 520: Associative draughting elements;
- Part 521: Manifold subsurface;
- Part 522: Machining features;
- Part 523: Curve swept solid.

The above list shows the focus of the AICs on shape representation. Thus, this class of STEP standards needs to be considered for isogeometry. It is not only important to establish an isogeometric representation in STEP, but also to ensure its harmonized use. It may not be relevant to update one of the existing AICs, but rather to create a new one dedicated to isogeometry alone.

3.1.7 Application Modules

Application modules (AM) are the key components of the modularization of the initial ISO 10303 architecture. The modular approach extends the application interpreted construct (AIC) concept of the initial ISO 10303 architecture through inclusion of the relevant portions of the AP’s information requirements. The basis of the approach is understanding and harmonizing the requirements, both new and those documented in existing APs, grouping the requirements into reusable modules, documenting the modules, and using the modules in the development of application protocols, thus enabling better sharing of information among APs [5].

An AM contains much of the technical content that in the initial ISO 10303 architecture was documented in an AP. The role of an AP document in the new architecture is to provide a business context for the industrial use and implementation of the application modules that are the data specification of the AP [5].

APs that do not use modules are called monolithic APs; the others are modularized APs. AP214 and AP238 are the most important monolithic APs.

There are three types of application modules: foundation modules (level 1), implementation modules (level 2), and AP modules. Foundation modules, which are in the 1000-series, provide lower level reusable structures that are not likely to be implemented alone, but are highly shareable and reusable. Implementation modules define a capability that can be implemented and against which conformance classes may be defined. Also implementation modules are documented in the 1000-series. Each AP references a single root module that is an AP module; these modules make up the 400-series of ISO 10303. An AP module is an implementation module, and the contents of an AP module are the same as other implementation modules, the only documentation difference is in their name and title. The AP module from one AP may be used by another AP [5].

Some details of the modular AP approach are shown in Figure 4, below. Pay attention to the interaction between AMs and integrated resources (IR).

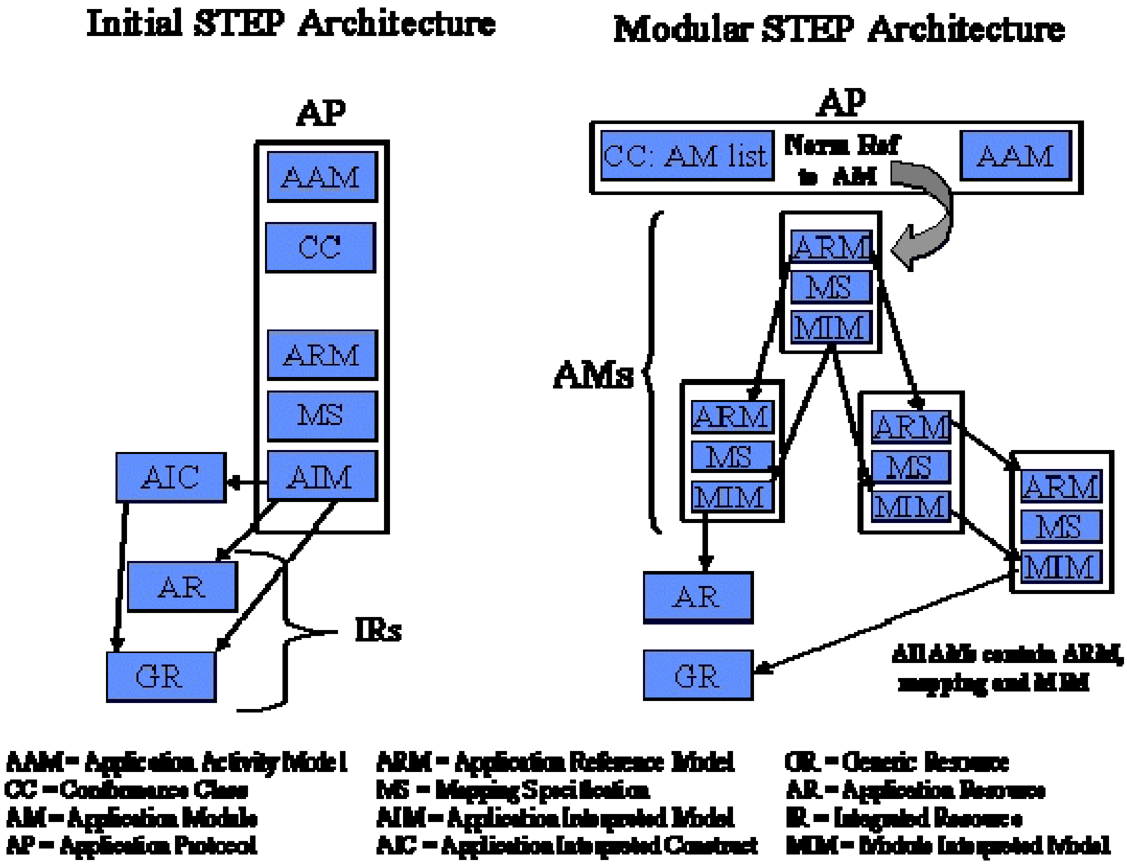

Figure 4: Architectures of monolithic and modularized APs [5]

The integrated resources have been transformed into several hundred application modules. It is not useful to list all those here. The key message for TERRIFIC is that isogeometry needs to be made available for modularized APs through one or several application modules. The two for TERRIFIC most important APs, namely AP209 and AP242, are modularized. Isogeometric representation will be included in part 42. One or several modules need to be added or extended to include an industrial requirement for isogeometry and to map this requirement to the new integrated resource of isogeometric representation in part 42. First then will new editions of AP209 and AP242 be able to pick up isogeometric capabilities so that application vendors can convert their isogeometric data into STEP.

3.2 LOTAR - EN 9300

LOTAR stands for Long Term Archiving and Retrieval (see http://long-term-archiving-and-retrieval.org/). LOTAR is an international collaboration of the Aerospace Industries Association (AIA) in the USA and the Aerospace and Defense Industries Association of Europe for Standardization (ASD-STAN) under the supervision of the International Aerospace Quality Group (IAQG). It is the mission of LOTAR to develop global standard-based archival and retrieval mechanisms for digital product and technical information. The results of LOTAR will be finally released as EN 9300 and NAS 9300 series. Part of the series is already released as prEN /NAS 9300. The driver for these developments is the transition from two-dimensional to three-dimensional design, engineering and manufacturing. It is not possible any more to store drawings as proof of a design; the complete product data are only available in three dimensions and digitally.

Also EN 9300 is a series of standards; Figure 5 gives a high-level overview.

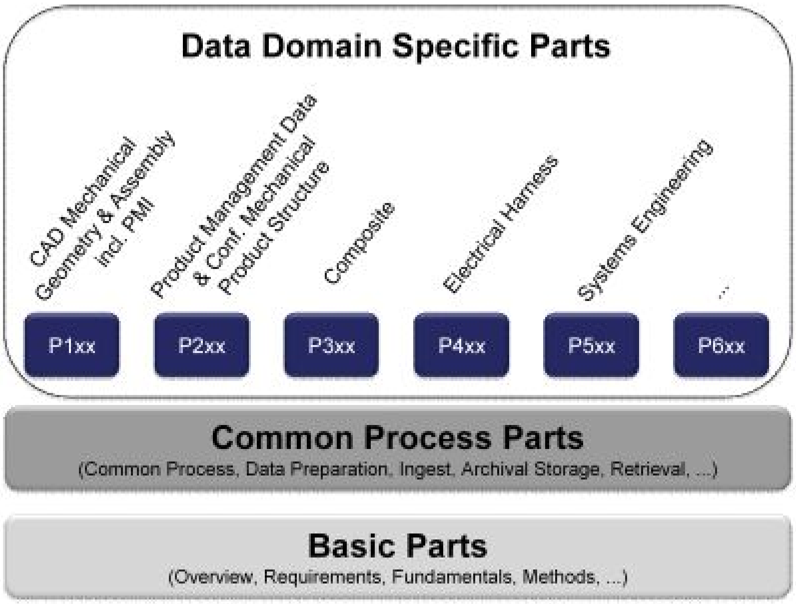

Figure 5: Structure of the LOTAR standards

The basic and common process parts specify the environment of a trustworthy archival and retrieval system. This framework references and is based upon ISO 14721, Reference Model for an Open Archival Information System (OAIS).

The main interest of TERRIFIC concerns the data domain specific parts. Of those, only the 100-series is well-developed. Currently the following three standards of the 100-series have been released:

- prEN/NAS 9300-100, Fundaments and concepts;
- prEN/NAS 9300-110, Explicit Geometry;
- prEN/NAS 9300-115, Explicit Assembly Structure.

The second one of these needs the attention of TERRIFIC.

3.2.1.1 prEN/NAS 9300-110

Part 110 defines the requirements on a digital archive to preserve for the long term the 3D explicit geometry of single CAD parts. The goal is to preserve the 3D information without loss with respect to the geometry produced by the original CAD system [15].

The document includes the following scope statements [15]:

The following is in the scope of this part of NAS9300:

- Business specification for long term archiving and retrieval of CAD 3D explicit geometry;
- Essential information of CAD 3D explicit geometry to be preserved;
- Data structures detailing the main fundamentals and concepts of CAD 3D explicit geometry;
- Verification rules to check CAD 3D explicit geometry for consistency and data quality;
- Validation rules to be stored with the CAD 3D explicit geometry in the archive to check essential characteristics after retrieval.

Note: This includes the geometrical external shape resulting from different CAD 3D disciplines (e.g., 3D Structural components, 3D Tubing, 3D electrical harness, 3D composite, etc.).

The following is outside the scope of this part of NAS9300:

- The formal definition of validation and verification rules to check 3D explicit

geometry for consistency and data quality using a machine-readable syntax;
- Implicit or parametric geometry;
- Geometric Dimensioning & Tolerancing (GD&T), Product & Manufacturing Information (PMI);
- Assembly structures.

In contrast to ISO 10303-59, this part specifies the validation algorithms that a data set shall be able to pass before it is permitted for long-term archival. References are made to algorithm specifications by SASIG, Strategic Automotive product data Standards Industry Group (www.sasig.com). The results of the tests may be stored in part 59 format.

Part 110 expects data sets to be compliant to ISO 10303-514 Advanced boundary representation. This limitation excludes trivariate isogeometry, which is non-manifold compared to the manifoldness of the AIC 514 representation.

In addition to overcoming this shortfall, TERRIFIC needs to identify algorithms that can verify the quality of an isogeometric representation for industrial purposes.

3.3 ISO 8000 – Data quality

ISO 8000 is a series of parts that specify data quality. Also these parts are, like STEP, managed by ISO TC 184/SC 4.

The ISO 8000 documents include the following introduction [27]:

> "The ability to create, collect, store, maintain, transfer, process and present data to support business processes in a timely and cost effective manner requires both an understanding of the characteristics of the data that determine its quality, and an ability to measure, manage and report on data quality.
>
> ISO 8000 defines characteristics that can be tested by any organization in the data supply chain to objectively determine conformance of the data to ISO 8000.
>
> ISO 8000 provides frameworks for improving data quality for specific kinds of data. The frameworks can be used independently or in conjunction with quality management systems.
>
> ISO 8000 covers industrial data quality characteristics throughout the product life cycle from conception to disposal. ISO 8000 addresses specific kinds of data including, but not limited to, master data, transaction data, and product data."

ISO 8000 is the result of a relatively new activity with few published standards. Of the ones that are available, the following needs attention by TERRIFIC [18]:

> ISO 8000-311: Guidance for the application of product data quality for shape (PDQ-S).

PDQ-S is a synonym for ISO 10303-59. To the degree part 59 needs to change for isogeometry, also ISO 8000-311 will need to change.

3.4 OAIS - ISO 14721

The Reference Model for an Open Archival Information System (OAIS) is specified in ISO 14721 edition 2. It includes the following [16]: it

- provides a framework for the understanding and increased awareness of archival concepts needed for Long Term digital information preservation and access;
- provides the concepts needed by non-archival organizations to be effective participants in the preservation process;
- provides a framework, including terminology and concepts, for describing and comparing architectures and operations of existing and future Archives;
- provides a framework for describing and comparing different Long Term Preservation strategies and techniques;
- provides a basis for comparing the data models of digital information preserved by

Archives and for discussing how data models and the underlying information may change over time;

- provides a framework that may be expanded by other efforts to cover Long Term Preservation of information that is NOT in digital form (e.g., physical media and physical samples);
- expands consensus on the elements and processes for Long Term digital information preservation and access, and promotes a larger market which vendors can support;
- guides the identification and production of OAIS-related standards.

Thus, ISO 14721 contains a terminology and a framework for archival applications. Originating from space organizations, OAIS has found wide acceptance by those who write detailed specifications for archival systems, such as LOTAR. The current reference model will support TERRIFIC‛s requirements for archival perfectly well. TERRIFIC rather needs to deal with the standards that refine the OAIS, such as EN 9300.

4 Plan of action

The focus of the standardization activities in TERRIFIC will be in STEP. Here the basis can be laid for a neutral representation of trivariate isogeometry that will enable data sharing and data archival. The supporting standards for data quality and archival will be monitored and investigated in parallel.

The following plan of action is suggested; some activities can be performed in parallel:

- Analyze the ISO 10303 series:
  - start with parts 42, 52, 104 and 107;
  - consider the importance of CFD for TERRIFIC and include parts 53 and 110 into the investigations.
- Identify required changes to these standards and start the corresponding processes to update them in ISO TC 184/SC 4.
- Include isogeometry in application protocols, first of all AP242 edition 2, and then AP209 edition 3, potentially using AICs.
- Consider together with WP4 the benefits of requesting an edition 2 of AP238.
- Define how the quality of isogeometric representations can be assured and consult part 59, EN 9300-110 and ISO 8000-311.
- Apply the results to TERRIFIC's industrial needs.
- Implement the resulting quality-related actions to ensure that isogeometry fulfills the long-term archival requirements of ISO 14721 and EN 9300.

The resources for implementing this plan lie mainly with JOTNE and SINTEF. Industry partners will be consulted in questions of end-user issues concerning application protocols and data quality.

An update to part 42 will be the first great milestone; this can possibly be achieved by the end of 2013. The inclusion of isogeometry into the scope of AP242 edition 2 is targeted for the first half of 2013.

5 Status to date

The WP5 team of TERRIFIC has started discussions with the part 42 team of STEP, the official name of which is ISO TC 184/SC 4/WG 3/T 1, Shape Representation, right after the kick-off of TERRIFIC. Such an early start was chosen for two reasons:

1) the key role of ISO10303-42 in standardizing isogeometry was obvious to the project consortium already at the proposal stage;

2) standardization is a long-lasting process.

WP5 team members attended two meetings of WG 3/T 1 as part of the ISO TC 184/SC 4 plenary meetings:

- SuZhou, China, 2011-10-16/21;
- Stockholm, Sweden, 2012-06-10/15.

The following are excerpts from the minutes of the shape representation team:

> SuZhou: "At the final session on Thursday morning Jochen Haenisch made a presentation of the work of the new TERRIFIC project. (See attached file TERRIFIC presentation.pdf. He said that the central feature of this project was the use of the same geometric model (isogeometric model) at all stages of the design, analysis and production process for mechanical parts. The geometry proposed was defined by tri-parametric rational B-splines. The definitions of b_spline_volume entities introduced into Part 42 edition 3 were then examined and found to have a very similar definition. One requirement from the project coming from the analysis stage of the life cycle, is for local refinement of the mesh and it is not yet clear precisely how compatible this is with the volume definitions." [12]

> Stockholm: "The Shape and Parametrics meetings continued on Tuesday with a presentation by Vibeke Skytt of the work of the Terrific project. (See attached SC4_voumes.ppt) This project uses an isogeometric approach with parameterised volumes both the geometry and the analysis. Complex shapes are decomposed into a number of adjacent volumes and B-spline basis functions are used for both the geometry and the analysis. She reported good results from this approach and was considering the use of T-splines or LR-splines for more complex analysis problems. She also considered the relationship of this work to existing STEP parts. Some extensions to part 42 are likely to be required and after consideration of the content of parts 104 and 209 we suggested that it was probably more appropriate to consider extending some of the 50 series parts, particularly part 52 mesh based topology." ... "At the final session on Thursday morning the requirements from the TERRIFIC project for additions to part 42 were discussed with Jochen Haenisch. He said that the existing b_spline_volume entities could be used but that additional entities would be required to associate face_surfaces with volumes and to represent an non-manifold model which is in effect an assembly of volumes. The initial suggestion is to add an entity volume_with_faces to the topology schema and to add to the geometric model schema an entity which is an assembly of volumes, this would be a subtype of geometric_representation_item but not of solid_model, the name volumetric_model was suggested for this entity. Noting the similarity of the attributes volume_with_faces to those of a closed_shell the possibility of making this a subtype of closed_shell should be investigated. A further requirement not fully resolved was the ability to associate parameter values with the faces of a volume, this might be achievable with an ordered list of faces. At the end of the meeting it was agreed that a further meeting will be required in Miami." [13]

The upcoming meeting of ISO TC 184/SC 4 in Miami is scheduled for 2012-11-11/16; the meeting between shape representation and TERRIFIC is scheduled for Thursday, November 15, 8.00 - 12.00 (local time).

6 Summary

TERRIFIC is introducing new geometric representations into industrial use. The new types of data will become part of the comprehensive set of product data. There are today identified needs for exchanging and archiving product data; these are met with international standards for data formats and data quality assessment.

New types of product data require updates to the corresponding standards. With this starting point, this document summarizes an analysis of the world of international standards that are relevant to the shape representation aspects of trivariate isogeometry and its quality and archival aspects. Which standards are relevant, and which of those will be affected by the arrival of isogeometry? TERRIFIC has identified the following candidates to require updates, in this order of priority:

- ISO 10303
- ASD/AIA EN 9300
- ISO 8000.

Isogeometry can impact processes for the design, the analysis and the manufacturing of products. Therefore, the STEP ISO 10303 application protocols 209, 238 and 242 should be updated. A new edition of AP242 is emerging from other stakeholders already and will be the first one to be addressed by TERRIFIC.

In parallel, isogeometric capabilities, such as non-manifold volumes and locally refined splines, need to be included in the STEP integrated resources, especially in ISO 10303-42. This process has started already; it may be completed within one year.

Algorithms need to be developed to assess the quality of isogeometric data sets. Only data of known quality can be archived. Standards like ASD EN 9300, ISO 10303-59 and ISO 8000 may need to be updated correspondingly.

References

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6. ISO 10303-42:2003, Industrial automation systems and integration - Product data representation and exchange - Part 42: Integrated generic resource: Geometric and topological representation
7. ISO 10303-52:2011, Industrial automation systems and integration - Product data representation and exchange - Part 52: Integrated generic resource: Mesh-based topology
8. ISO 10303-53:2011, Industrial automation systems and integration - Product data representation and exchange - Part 53: Integrated generic resource: Numerical analysis
9. ISO 10303-104:2000, Industrial automation systems and integration - Product data representation and exchange - Part 104: Integrated application resource: Finite element analysis

10. ISO 10303-107:2006, Industrial automation systems and integration - Product data representation and exchange - Part 107: Integrated application resource: Finite element analysis definition relationships

11. ISO 10303-110:2011, Industrial automation systems and integration - Product data representation and exchange - Part 110: Integrated application resource: Mesh-based computational fluid dynamics

12. WG12 N7632, ISO TC 184/SC4 Meeting Minutes, Suzhou, China, WG12 Shape Representation and parametrics (with WG3 T1), 2011-10-17/21, Ray Goult, SuzSrep.html

13. WG12 N8xxx, ISO TC 184/SC4 Meeting Minutes, Stockholm, Sweden, WG12 Shape Representation and parametrics (with WG3 T1), 2012-06-11/14, Ray Goult, StockShrep.html

14. ISO 10303-59:2008, Industrial automation systems and integration - Product data representation and exchange - Part 59: Integrated generic resource - Quality of product shape data

15. prEN/NAS 9300-110:2012, LOng Term Archiving and Retrieval of digital technical product documentation such as 3D, CAD and PDM data, Part 110: CAD mechanical 3D Explicit geometry information

16. ISO 14721:2012, Space data and information transfer systems - Open archival information system (OAIS) - Reference model

17. ISO 8000-1:2011, Data quality - Part 1: Overview

18. ISO/TS 8000-311:2012, Data quality - Part 311: Guidance for the application of product data quality for shape (PDQ-S)

19. ISO 10303-209:2001, Industrial automation systems and integration - Product data representation and exchange - Part 209: Application protocol: Composite and metallic structural analysis and related design

20. ISO 10303-238:2007, Industrial automation systems and integration - Product data representation and exchange - Part 238: Application protocol: Application interpreted model for computerized numerical controllers

Annex 1

Slides presented to the Shape Representation team at TC 184/SC4 meeting in Stockholm,

2012-06-10/16

Volumes in STEP

ISO 10303-42 and ISO 10303-104

Vibeke Skytt
TERRIFIC/SINTEF, Norway
June 2012

The reason for the request for an extension of Part 42 and Part 104 is the new domain of isogeometric design and analysis.

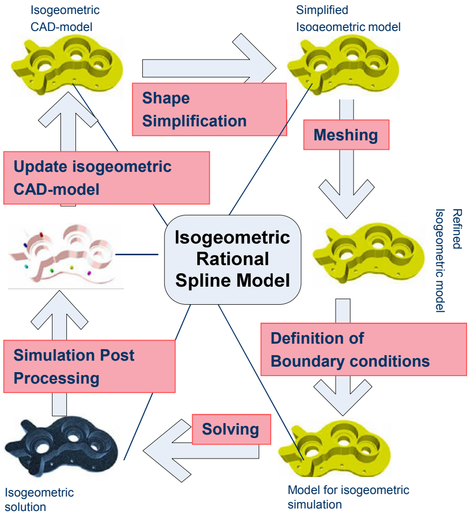
Outline

- What is isogeometry?
- Different approaches to volumetric isogeometric analysis
- Topology structures
- Examples of block structured, trivariate models including creation
- Extensions to STEP to represent volume models
- Analysis results
- Boundary conditions
- LR splines (T-splines)

Isogeometric analysis: Product Design Scenario

Isogeometric analysis introduced in 2005 by Prof. T.J.R. Hughes; University of Texas at Austin.

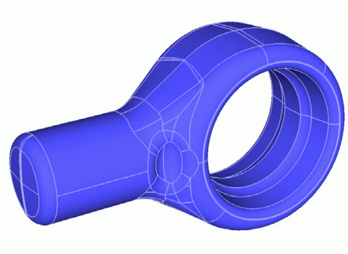
- Replace traditional h- and p-finite elements by NURBS
- Isogeometric CAD-model based on NURBS volumes
- Volumetric NURBS model at all stages in the analysis process
- Meshing replaced by refinement
- Exact geometry
- NURBS-elements better adapted to the continuity of the physical problems analyzed
- Claim: NURBS elements have many advantages compared to traditional Finite Elements
- Claim: Removes the bottleneck between CAD and analysis
- Examples published show superior performance of isogeometric analysis compared to traditional FEA



Why are splines important to isogeometric analysis?

- Representing geometry and solution field related to the numerical simulation in the same function space (isoparametric approach)
- B-Splines are polynomials, same as Finite Elements
- B-Splines are very stable numerically
- B-splines represent regular piecewise polynomial structure in a more compact way than Finite Elements, enables automatic continuity
- NonUniform rational B-splines can represent degree 2 algebraic curves and surfaces exactly. (circle, ellipse, cylinder, cone…)
- Efficient and stable methods exist for refining the piecewise polynomials represented by splines
  - Knot insertion (Oslo Algorithm, 1980)
  - Degree elevation
  - Combinations
- NURBS is an industry standard and a standard for data exchange

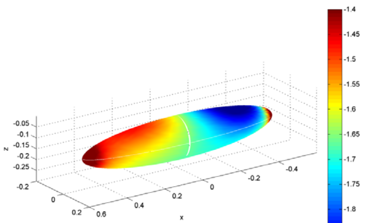
A 3D isogeometric model ≠ A boundary represented solid

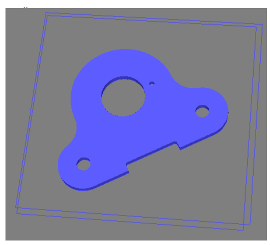


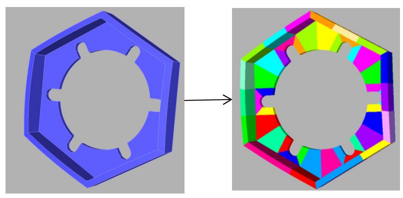
- Analytic surfaces – may be represented by NURBS
- Trimming – must be replaced by
  - Block structuring
  - T-splines or LR splines
- The volume is represented by its outer shell – needs a:
  - Trivariate representation
  - Boundary element method where the Greens function applies
  - Shell formulation

Approaches to handle trivariate cases

- Isogeometric boundary method applied to a submerged ellipsoid represented by 4 NURBS patches. Source distribution. Performed in EXCITING (EU-project in the Transportation program)
- Immersed Boundary Methods (Immersed domain). See Design-through-analysis Methodology based on Adaptive Hierarchical Refinement of NURBS, Immersed Boundary Methods, and T-spline CAD Surfaces and references therein. D. Schillinger, L. Dede, M.A. Scott, J.A. Evans, M.J. Borden, E. Rank, T.J.R. Hughes
- Block structured trivariate representation







B-rep model

Topology

Geometry

solid brep

Is limited by

shell

Defined by a number of

face — Shape given by — surface

Limited by

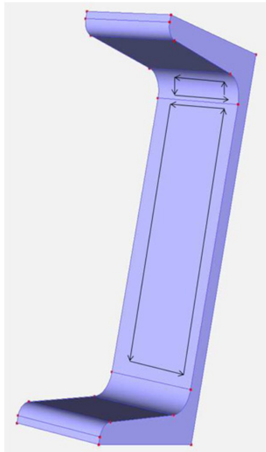
loop

Defined by a number of

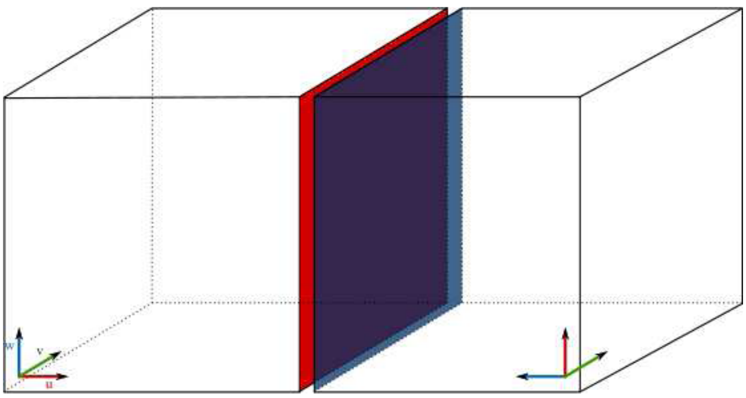
Adjacency is represented at this level: edge — Shape given by — curve

Limited by

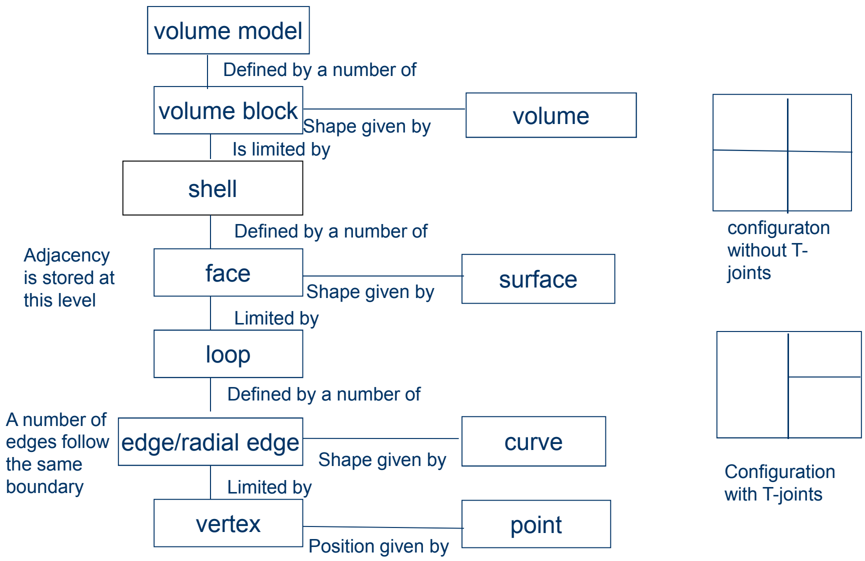
vertex — Position given by — point



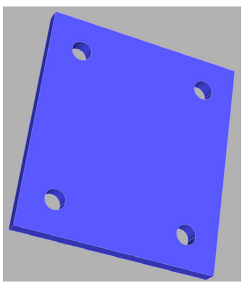
A volume model



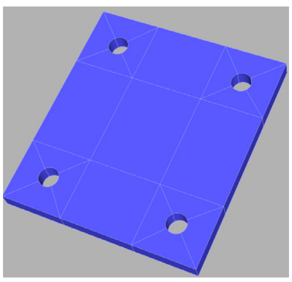
An Isogeometric Block Structured Model



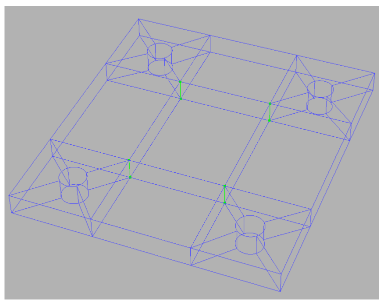
Block structured volume model from CAD solid



The CAD solid. The initial trimmed planes and cylinders are represented as trimmed spline surfaces

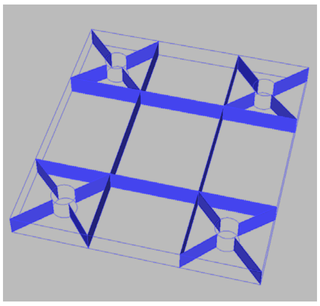


The outer shell of the CAD model is divided further to let each (trimmed) surface have 4 boundary curves and make sure that the surface set has no T-joints

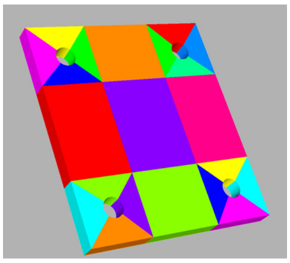


Extra edges are added to the wireframe of the surface model to get all edges needed in the final volume model.

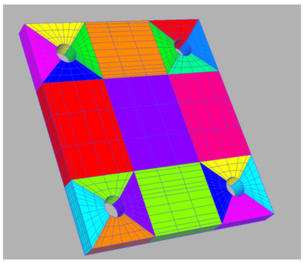
Finalizing the volume model



Adding surfaces internal to the solid to get all surfaces surrounding all volume blocks. The new surfaces are added to the current surface set from which a number of trimmed volumes are extracted

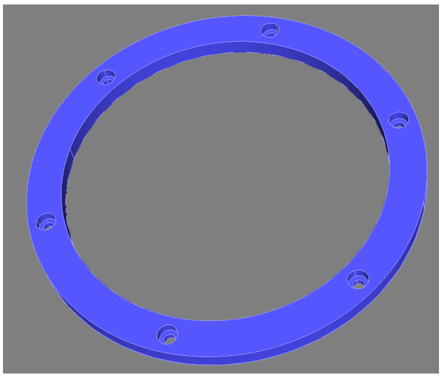


The spline volume blocks. They are created from trimmed volume blocks by approximating the boundary surfaces and interpolating them with the spline volumes

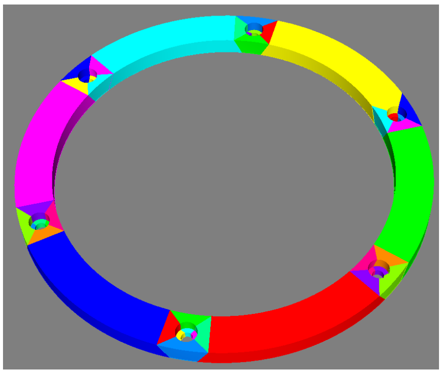


The control polygon illustrates correspondence of coefficients across block boundaries

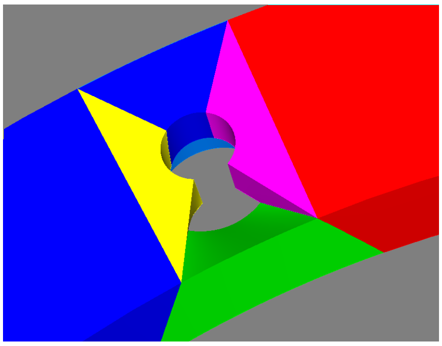
Holes with sharp edges



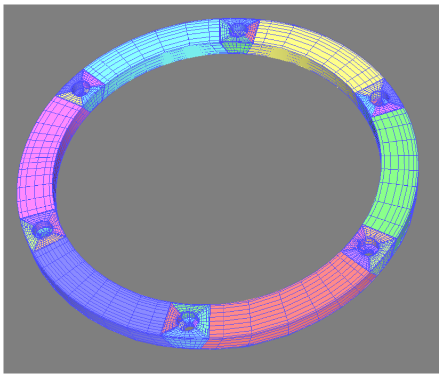
The initial model represented as trimmed NURBS surfaces



The block structured isogeometric model



A detail around a hole. One block is removed for visibility



The spline spaces illustrated by the control polygons of the boundary surfaces

A volume entity corresponding to a face

Face representation

- Geometric model: surface model
- The face is a face_surface or advanced face
- Adjacency represented by neighbouring faces pointing to the same edge
- Geometry represented as
  - Elementary surface
  - B-spline surface
  - Bounded surface
  - …
- Limited by edge loop
- B-spline surface exists

Topological volume

- Geometric model: need volume model
- Need a solid_volume (a solid_model with geometry)
- Adjacency represented by neighbouring volumes pointing at the same face
- Geometry represented as
  - Elementary volume
  - B-spline volume
  - A bounded volume does not make sense
- Limited by a face set (shell)
- B-spline volume exists

Comments

- The solid_volume is very similar to a manifold_solid_brep, but
  - The trivariate geometry representation is missing in manifold_solid_brep.
  - One solid_volume is a manifold, the volume model is not.

Representation of adjacency

Surface model

- Two faces point to the same edge
- The edge probably has a geometric representation, possibly as surface_curve
  - intersection_curve
  - seam_curve
  - …
- At most two curves in the parameter domain (pcurve) in a surface can be represented

Volume model

- Two solids point to the same face
- The face probably has a geometric representation
- volume_surface does currently not exist, nor do
  - intersection_surface
  - seam_surface
- More than two faces point to the same edge
- A corresponding surface_curve needs to represent more than two pcurves

Shell models and mixed models

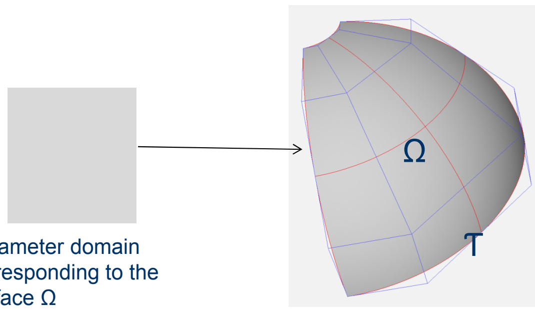
- Shell model
  - Can be represented by a non-manifold surface model (more than two pcurves in surface_curve is convenient)
  - Surfaces have thickness. This is not particular for the isogeometric case
- Mixed model
  - Non-manifold
  - The topology can be represented provided that boundary faces and edges are divided where a lower dimensional entity is attached
- Do not know about any particular concerns for these models

Isogeometric analysis

Solve some differential equation:

$\Delta u + f = 0$ on a domain Ω

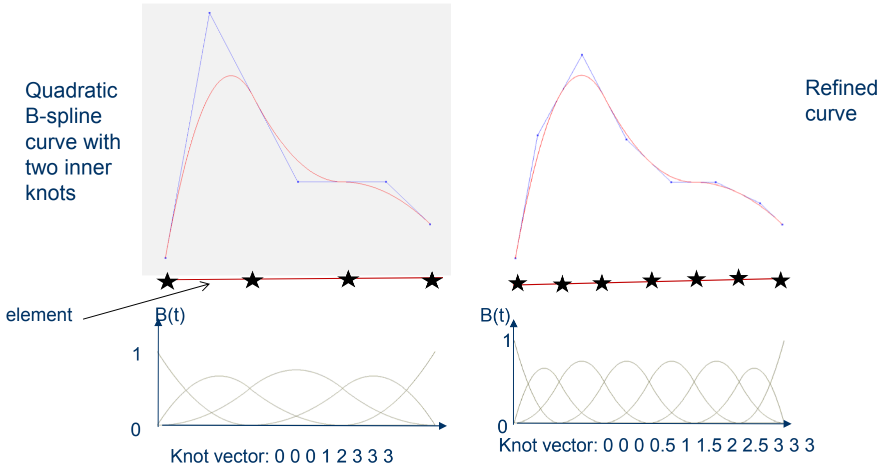
given some conditions on T which is the boundary of Ω.



Parameter domain corresponding to the surface Ω

The domain Ω is a NURBS representation of a portion of a sphere. It is a quadratic surface, refined once to get some more degrees of freedom

An approximate **u'** to the solution **u** is sought in the spline space used in the description of the domain Ω. The frame work is the same in isogeometric analysis as in traditional FEA, but the solution space consists of B-splines.



The solution

- The solution field is related to a geometry entity (curve, surface, volume) represented in the spline format.
- One geometry entity may have several solution fields related to different computations on the same geometry and to time dependent problems.
- The solution field is represented in the same function space as the corresponding geometry entity or a refined version thereof. As the shape of the geometry entity does not change with refinement, no accuracy is lost.
- Derived quantities (computed from primary solutions) do not necessarily share the same function space (different degree), but the knot spacing (elements) will be the same.
- Two solution fields related to the same geometry entity may have different polynomial degree when mixed methods are applied (for instance pressure and velocity in fluid flow).
- The knot vectors may differ, but the parameterization of the geometry entity and the solution field(s) correspond.

Boundary conditions

- Possible boundary conditions
  - Dirichlet
  - Neumann
  - Robin
  - Periodicity
  - Symmetry
- Associated to
  - Vertices (corner nodes)
  - Isolated points at boundary curves or surfaces
  - Boundary curves or specified parts of boundary curves
  - Boundary surfaces or specified parts of boundary surfaces
- Can be represented as
  - Relations between two boundaries
  - Explicit values (point constraints, constant conditions)
  - A spline entity in the spline space of the associated boundary entity
  - A relation between spline entities (Robin)

Relation to AP209 and Part 104

- The finite element model (fea_model?) is equal to the (possibly simplified) design shape which again is equal to the idealized analysis shape.
- **State**: an aggregation of information about the analysis variables of a model that describes the model at an instant.
- A node ≈ a coefficient
  - The coefficients are governing the geometry, not interpolating it
  - The coefficient is less explicitly represented than the node
  - There is no connection between the solution and the geometry representation for refined solution spaces, derive quantities or mixed methods
- An element ≈ a knot interval
  - This is the standard interpretation in isogeometric analysis
  - The knot interval is only implicitly defined by the knot vector
  - There is no connection between the solution and the geometry representation for refined solution spaces
  - Material properties are connected to elements in Part 104
- The geometry representation and the solution fields can always be connected through parametriziation

- Both a node_group and an element_group can in some sense be associated with an isogeometric block (a NURBS curve, surface or volume), but the correspondance is not very clear.
  - An analysis result corresponding to a group (field_variable_element_group_value) is in the isogeometric case not an aggregated result
- The type of boundary conditions and the connection to boundaries or parts of boundaries is not new, but the representation may differ
- A control for a finite element analysis describes the operations carried out upon the model. A finite element analysis application calculates the response of the model to these operations. Control ≥ / ≈ set of boundary conditions?
  - Symmetry control ≈ symmetry conditions (no_symmetry_control, cylindrical_symmetry_control)
  - Constraint ≈ Dirichlet boundary conditions? (point_constraint, curve_constraint, surface_constraint)
  - Control process ≈ Neumann boundary conditions? A control_process is the way in which the model is caused to depart from its initial state.

NURBS lack local refinement and modelling flexibility

- The regular structure of tensor product NURBS does not allow local refinement
  - 1988: Forsey & Bartels: Hierarchical B-spline refinement.
  - 1998: Rainer Kraft, Adaptive und linear unabhängige multilevel B-splines und ihre Anwendungen. PhD Thesis
  - 2003: T. Sederberg, T-splines
  - 2006: Deng, PHT-splines
  - 2010: Locally refined splines, addressing local refinement from the viewpoint of CAGD and Analysis
- The 4-sided (surface) or 6-sided (volume) structure of a NURBS entity lead to lack of flexibility in modelling of complex objects
- The tensor-product structure of surfaces and volumes is inconvenient in the context of diagonal features

Two basic approaches to local refinement of B-splines surfaces

Vertex grid refinement

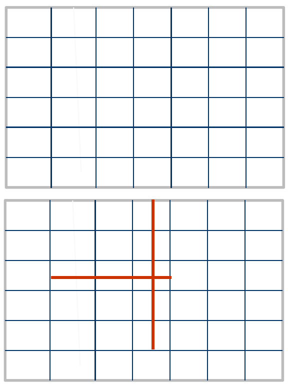
- Example: T-splines
- Insert new vertices in existing vertex grid
  - The insertion has to adhere to a set of rules
- Deduct spline space from vertex grid

Spline space refinement

- Example: LR-splines
- Specify refinement by knot line segment insertion
  - The segment has to at least span the width of one tensor product B-spline blending function
- Deduct vertex grid from spline space

Local refinement 2-variate spline spaces

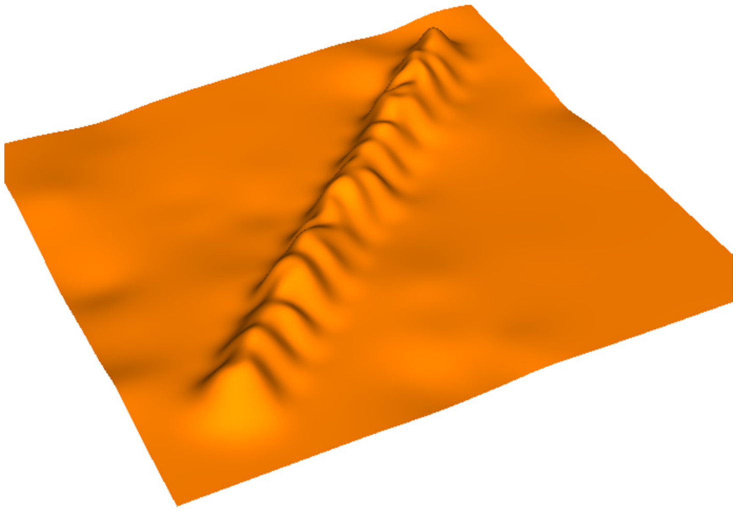
- Tensor product B-splines is an organization of 2-variate polynomial patches in a knotline grid
- T-splines, PHT-splines and LR-splines address local refinements of these



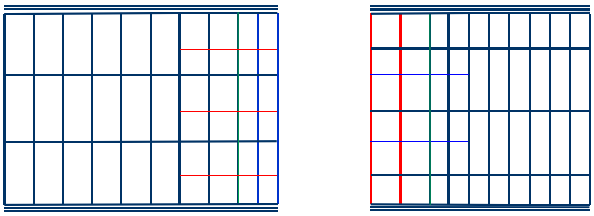
The T-splines technology is proprietary (owned by T-Splines Inc., Autodesk).

The LR-splines concept contains both T-splines and other approaches. Thus, only LR-splines will be considered in this context.

Added random values to coefficients of refined basis functions



C^1 Stitching of 2-variate B-splines Bi-quadratic case



1. Adapt the edge knotlines of A to B
2. Adapt the edge knotlines of B to A
3. Insert horizontal knotline segment from B in A
4. Insert horizontal knotline segment from A in B
5. Merge the parameter domains

LR-splines representation format

- LR-splines relate to geometry and solution fields, **not** to topology
- **Splines over a box partition**
- Representation format
- Coefficients, but not in a regular grid
- Knot vectors, but not a tensor product structure
- Polynomial degrees (constant within the surface/volume now, but might vary in the future)
- The parameter domain is the same as for an initial NURBS surface/volume when the approach is used for local refinement
- Not necessarily a united parameter domain when the approach is used for stitching
- No conclusion on the final representation format yet

Summary

- An isogeometric model with FEA information cannot currently be stored in the STEP format
- We focus on block structured isogeometric models
- Requested STEP extensions
  - Geometry: Entities corresponding to surface_curve for surfaces associated a volume. More than two pcurves for a surface_curve.
  - Topology: Possibility for accessing a geometric representation of a volume from a solid.
  - Analysis: Solution fields and boundary conditions related to spline entities. How should material properties be stored?
- LR-splines: Will be a request in the future