Geometry for simulation

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Tetrahedron Workshop VII - Barcelona

QUEEN'S UNIVERSITY BELFAST

SCHOOL OF
MECHANICAL AND
AEROSPACE
ENGINEERING

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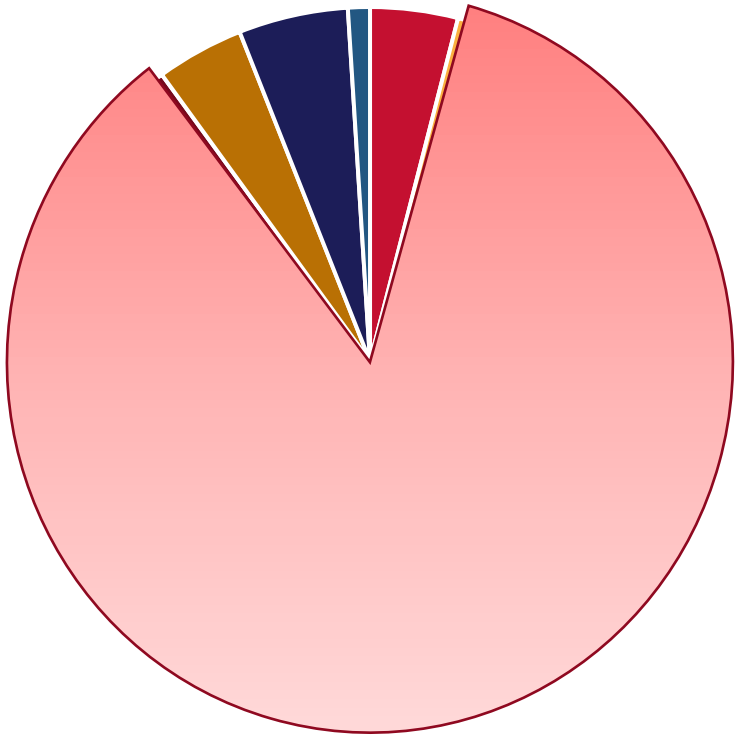
Biography

- **PhD (2003-2007)**
  - "Automated creation of mixed dimensional finite element models"
  - Supervised by Cecil G Armstrong
- **Post-doc (2007-2009)**
  - Automated FE model generation
  - CAD based optimisation
- **Academic staff (2009-)**
  - Automated Modelling & Simulation methods
- **Prof of Computational Design Engineering (2022-)**
  - Deputy Head of School

Talk overview

- What's this all about?
- Geometric reasoning
- Geometry handling
- Geometry learning
- Geometry perspectives

Phases of the simulation process

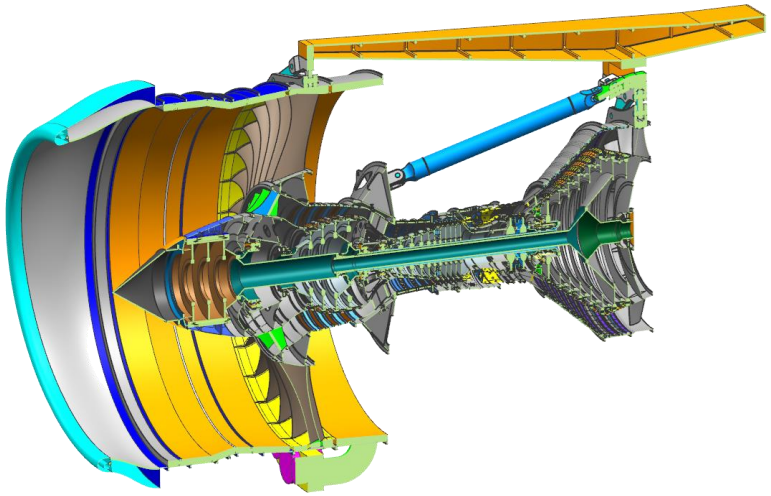


- Design solid model creation/edit
- Analysis solid model creation/edit
- Geometry decomposition
- Meshing
- Mesh manipulation
- Assign model properties
- Assemble simulation model
- Run Simulation
- Post process results
- Archive artifacts

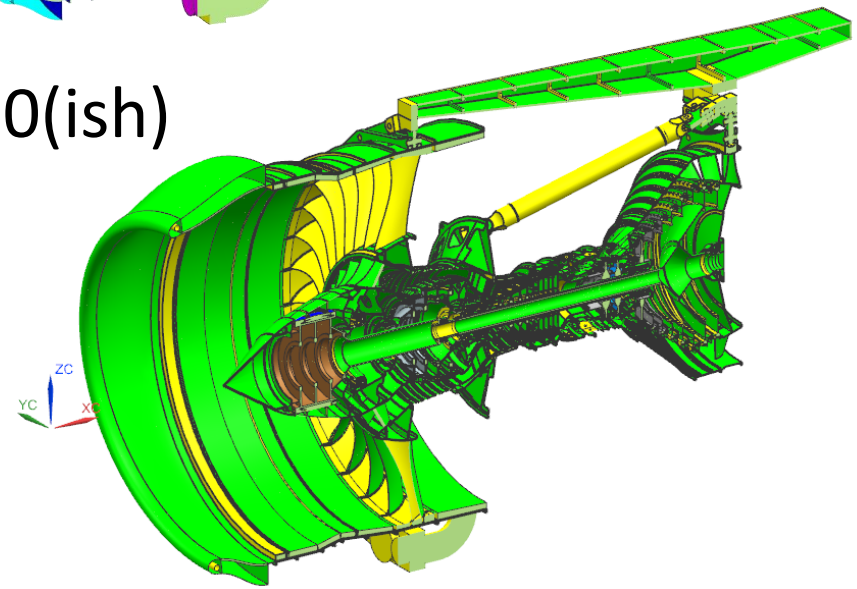
An Immersive Topology Environment for Meshing. Steven J. Owen Brett W. Clark Darryl J. Melander Michael Brewer Jason F. Shepherd Karl Merkley Corey Ernst and Randy Morris

What's this all about?

- We help to apply specific mesh styles/types to complex geometry models
- To do this, we isolate sub regions of the model we know suitable meshing strategies for



2020(ish)



2006

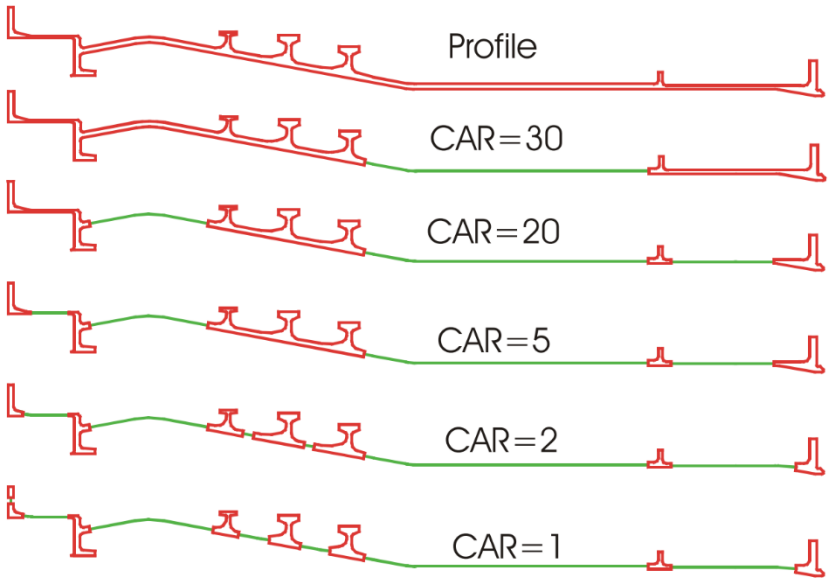


Figure 3.14 - Effect of critical aspect ratio on mixed dimensional model produced.

VIVACE model

VESTA Engine used with permission from Rolls-Royce

Geometric reasoning

Geometric Reasoning

- **Using information about the geometry of a CAD model to make decisions about how to prepare the model for simulation**

- **The key questions:**
  1. What operations do we want to automate?
  2. What information can help us automate the operation?
  3. How do we make robust decisions based on the information?
  4. How do we implement the update to the geometry model?

What operations do we want to automate?

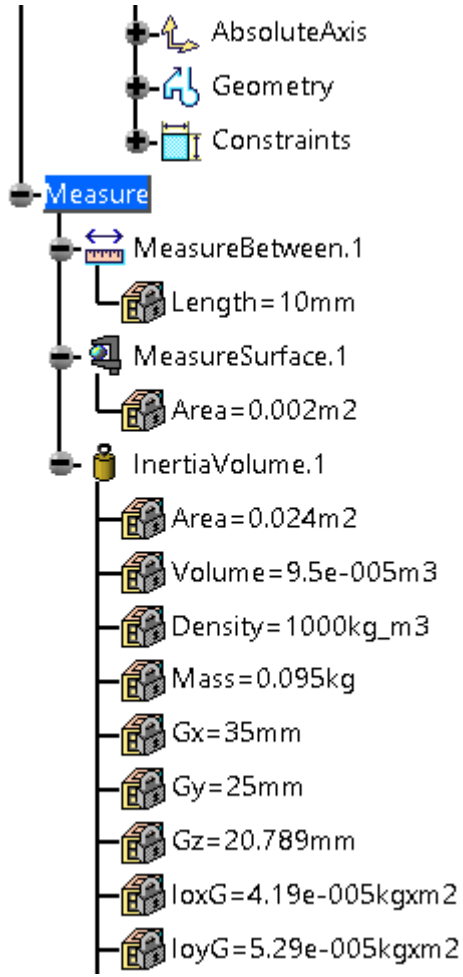
- **We want to automate tasks that are hard\take longest to implement**
  - Geometry repair
  - Defeaturing/idealisation
  - Mesh generation
  - Boundary condition application
  - Application of attributes (efficiently)

- **We also want to discover new ways of setting up the simulation model**
  - Can we build the geometry model with meshing strategies in mind?
    - i.e. changing/eliminating the decisions to be made!

Information from CAD systems

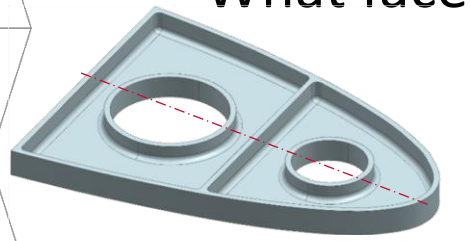
- **What CAD systems are good at informing us about a model:**
  - Properties of a body
    - e.g. CoG, volume
  - Properties of a face
    - e.g. Area, perimeter, Second Moments of Area
  - Properties of an edge
    - e.g. Length, tangent direction, Dia. of a circle,
  - Point locations or the distance between two points
  - Assembly measurements
    - Clearances or interferences

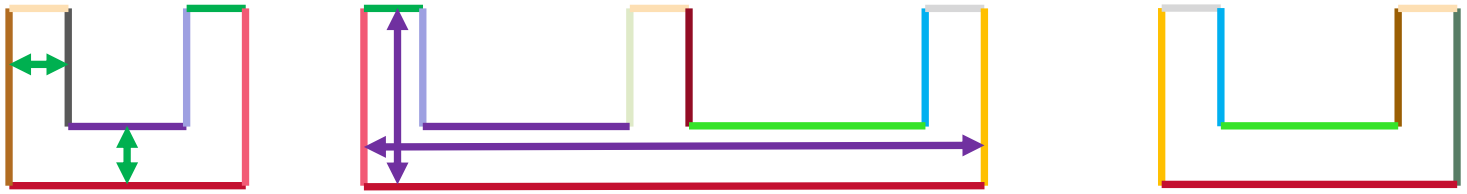
- **CAD systems are also good at supporting parametric model construction and subsequent updates**



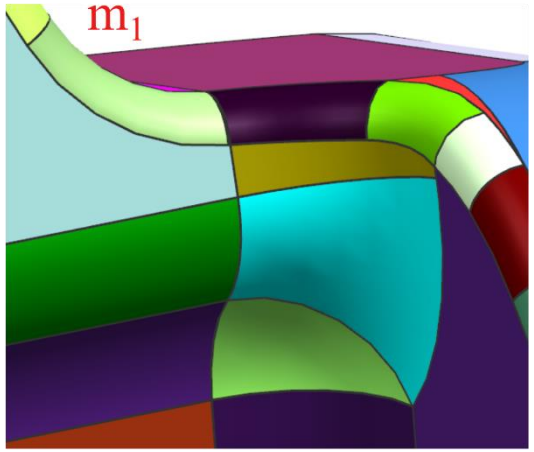
Information from CAD systems

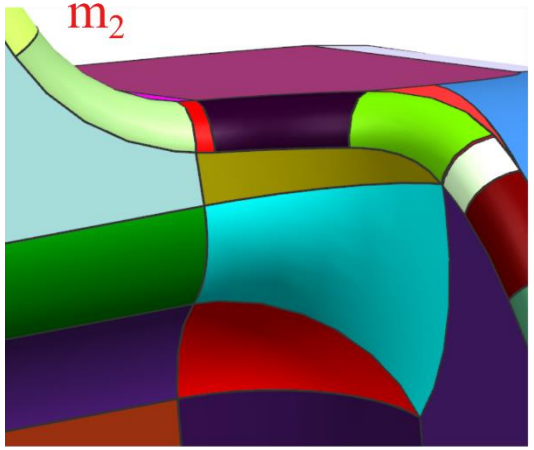
- **What are CAD systems are *not* good at informing about a shape:**
  - What the neighbours of a face (or edge) are
  - What faces/edges are opposite (in proximity) to each other





  - What has changed in the model after a modelling operation
  - What effect a change in the value of a parameter has on its shape/representation (or performance)
  - Making a change other than what it is parameterised to do

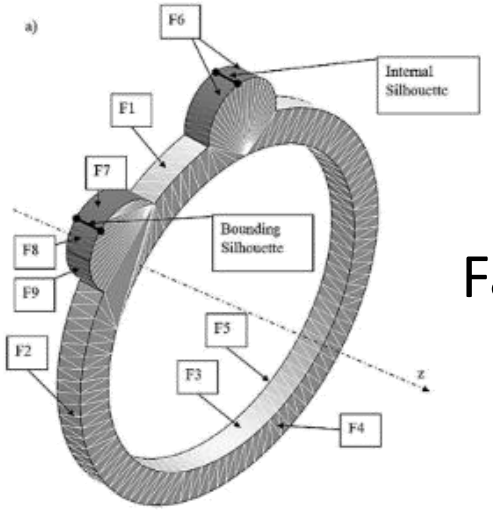


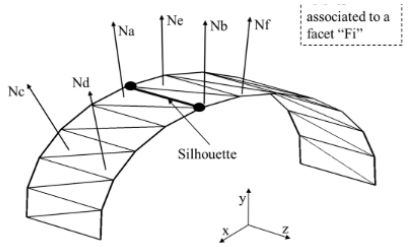


Impact of a parameter change

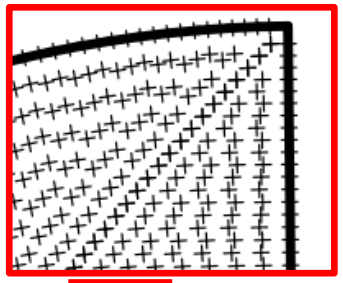
DOI: 10.2514/1.J058760

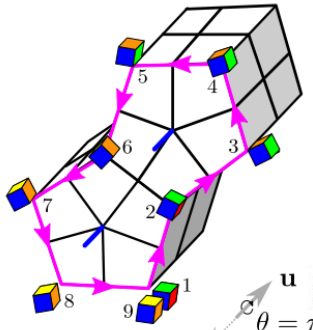
What other sources of information can help us?

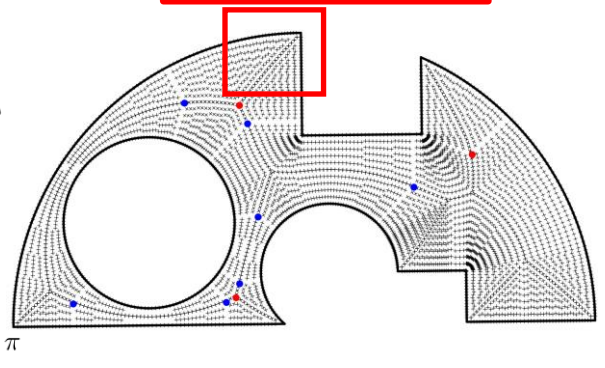




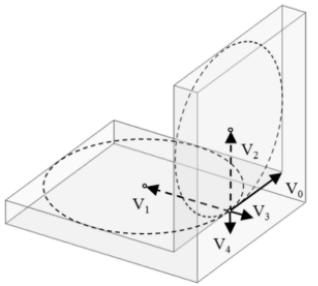
Facets

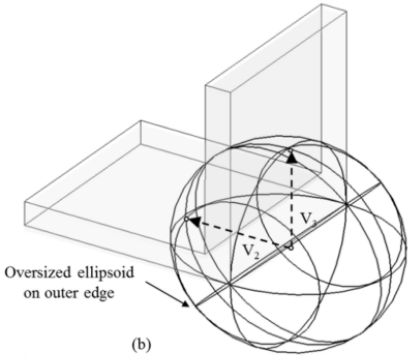


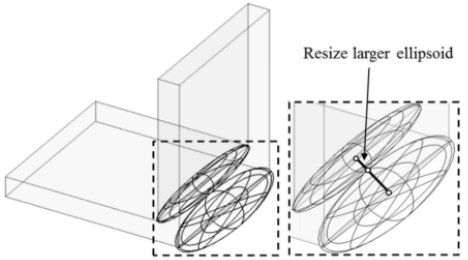




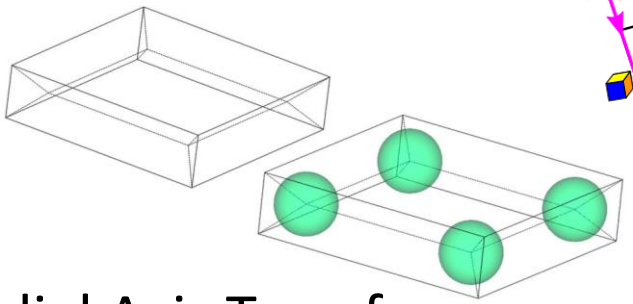
Cross/frame field



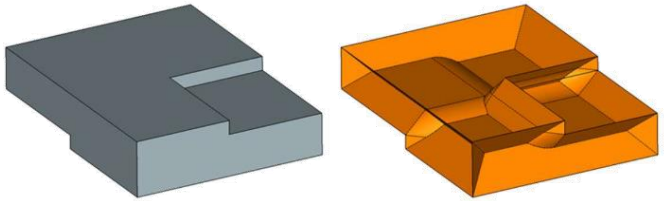


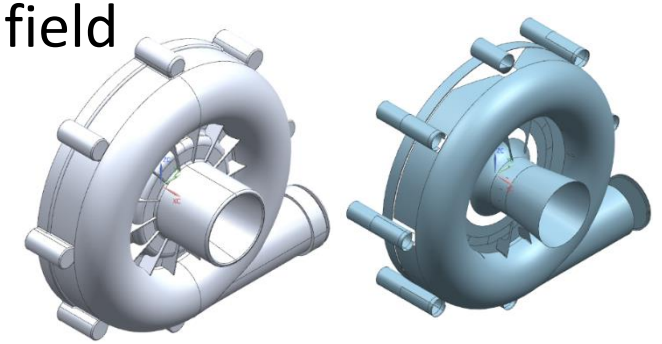


Ellipses

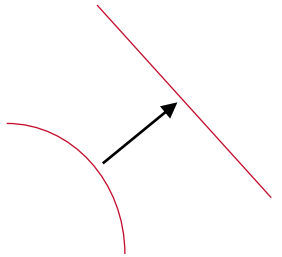


Medial Axis Transform





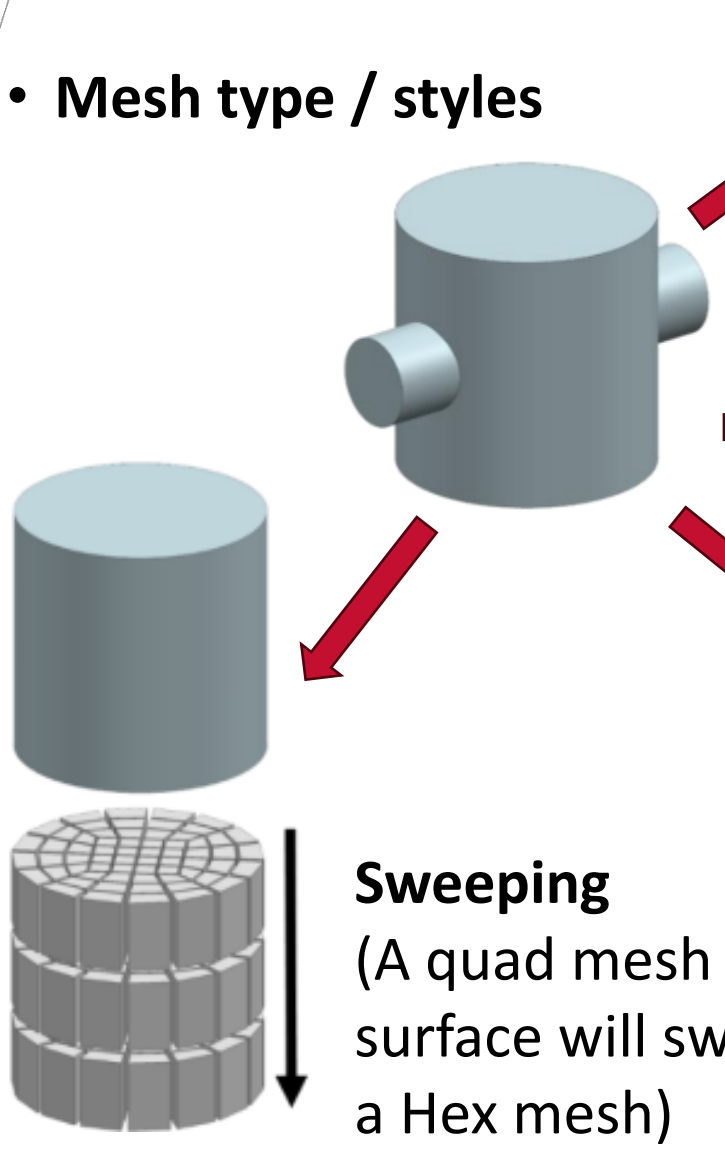
Mid-surfacing tools



Ray tracing

Meshing strategies we apply

- **Mesh type / styles**



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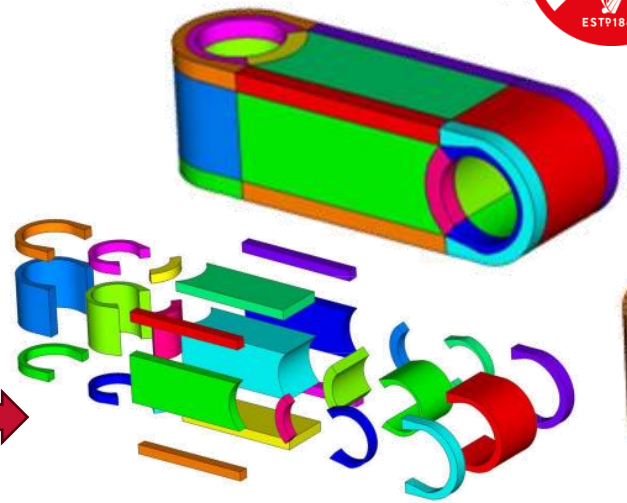
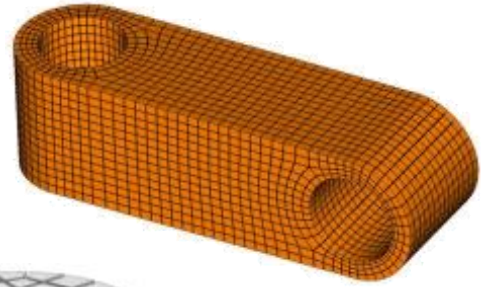
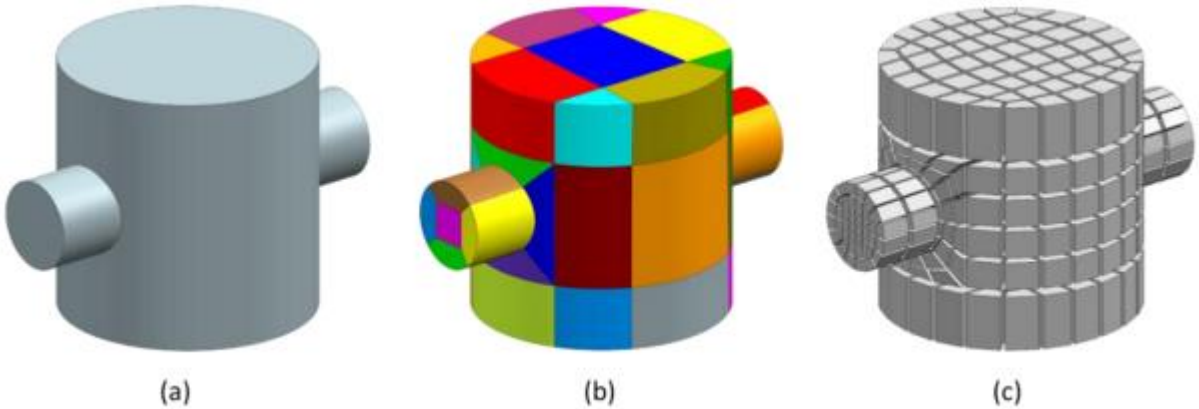


Multiblock
(Divide into 6 sided blocks)



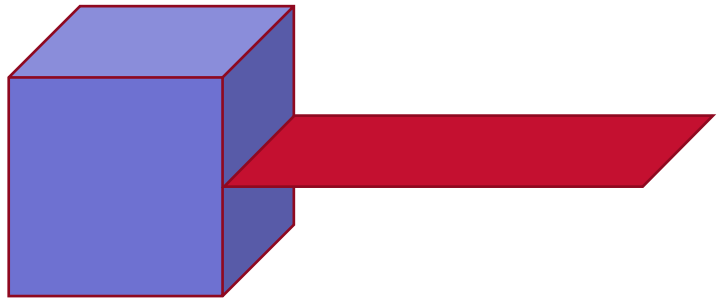


Sweeping
(A quad mesh on a surface will sweep into a Hex mesh)

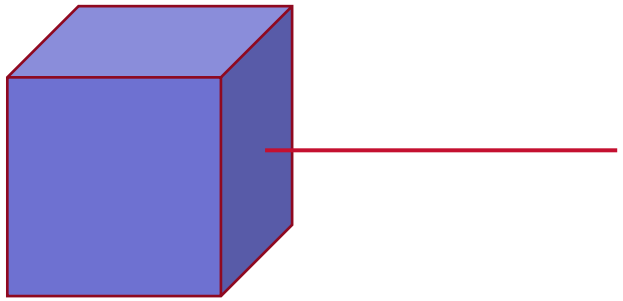
Decomposition (Splitting the model into sub-regions to which known meshing strategies (the other three) can be applied)

Dimensional reduction / mixed dimensional modelling

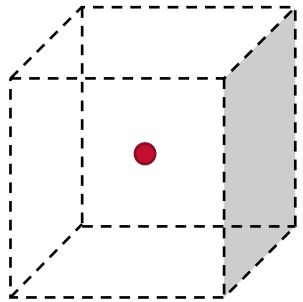
- **Reduced dimensional element types**



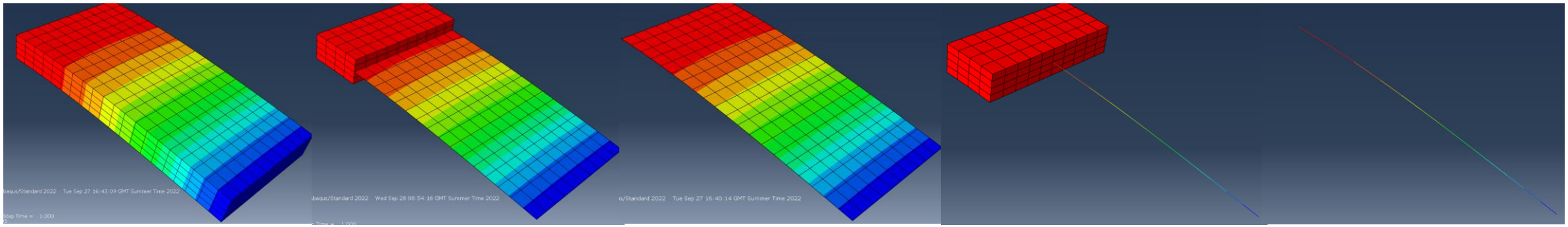
Surface models
-large lateral dims, small thickness
-meshed using shell elements



Line/wireframe models
-large length, small cross section
-meshed using beam elements

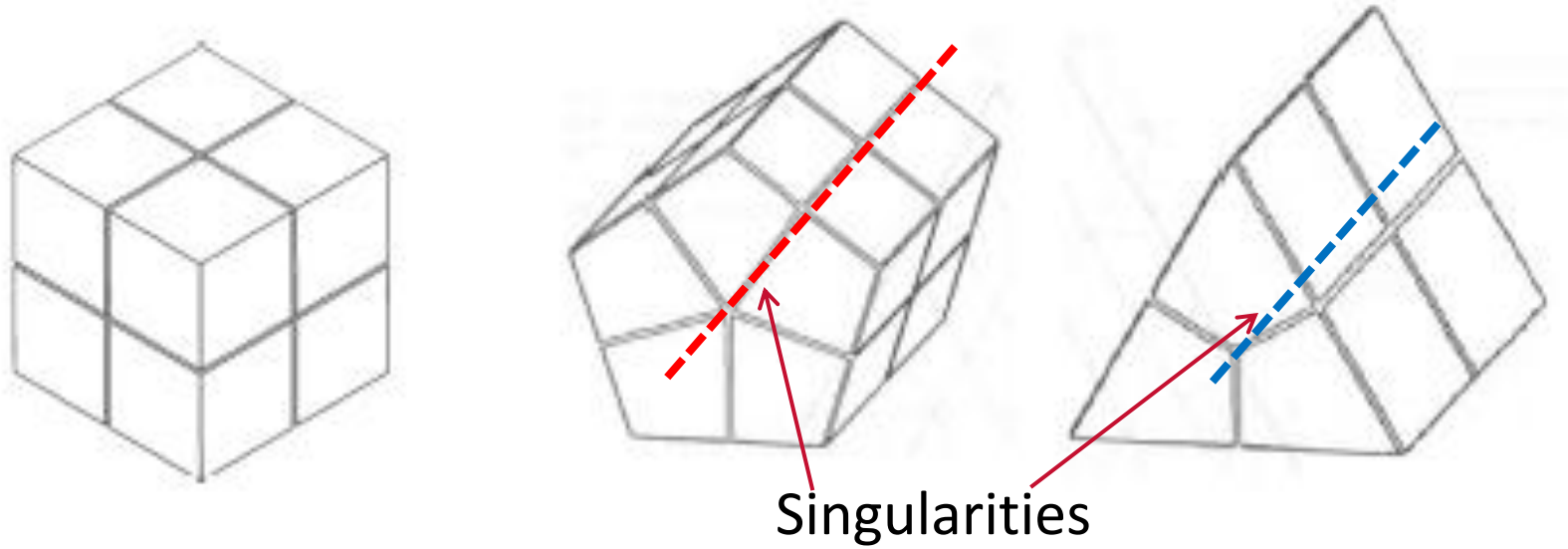


Point models
-similar dimensions
-point masses



Mesh singularities

- When creating a hex mesh for a complex shape, singularities are inevitable
- Singularities are where more or less than four elements meet in the mesh

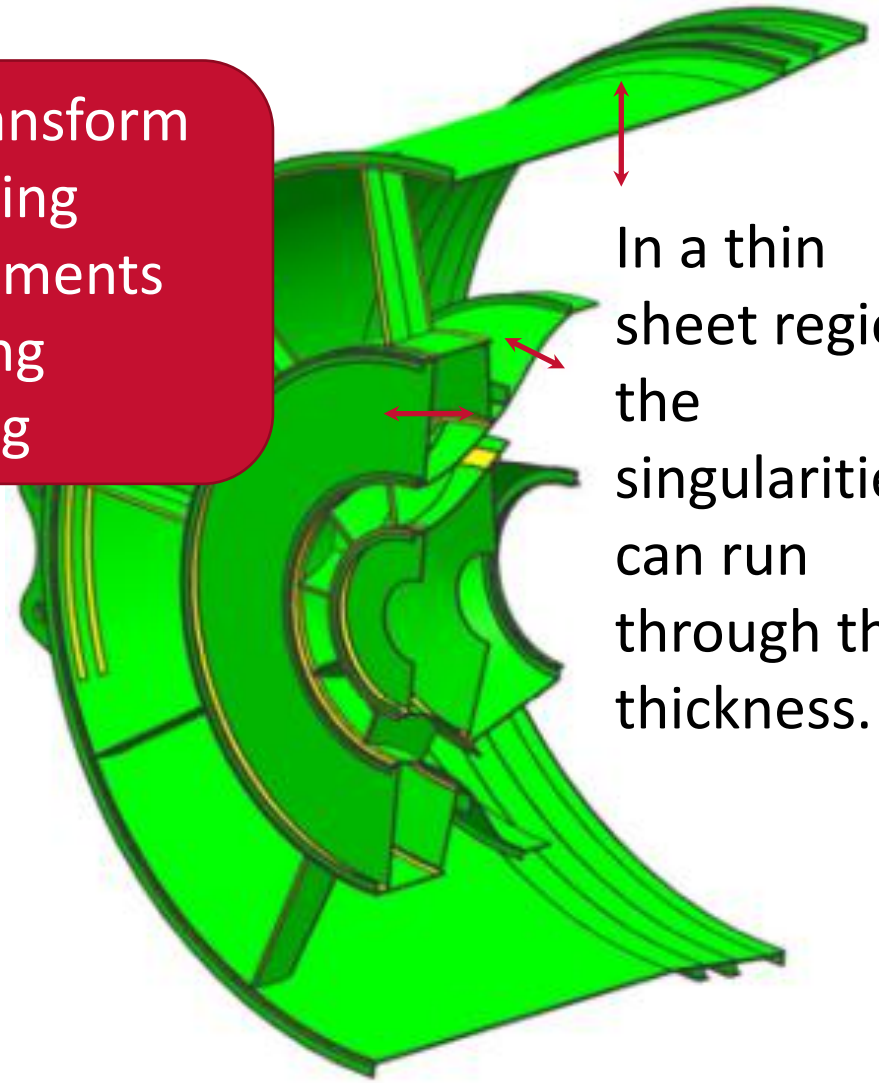


- By tracking the possible orientations, and numbers, of singularities we get information on how to decompose the model

QUB applications – thin-sheet regions

- **Geometric Reasoning rationale:**
  - Identify regions which ar
    relative to their lateral di
  - Mark which faces are the
    faces
  - Mark which faces run thr
    thickness of the region
- **Meshing rationale**
  - Replace with surfaces and shell mesh
  - Hex mesh by sweeping a quad mesh applied to one of the large end faces through the thickness

Medial Axis Transform
Mid surfacing
Area measurements
Ray tracing
Offsetting



In a thin sheet region, the singularities can run through the thickness.

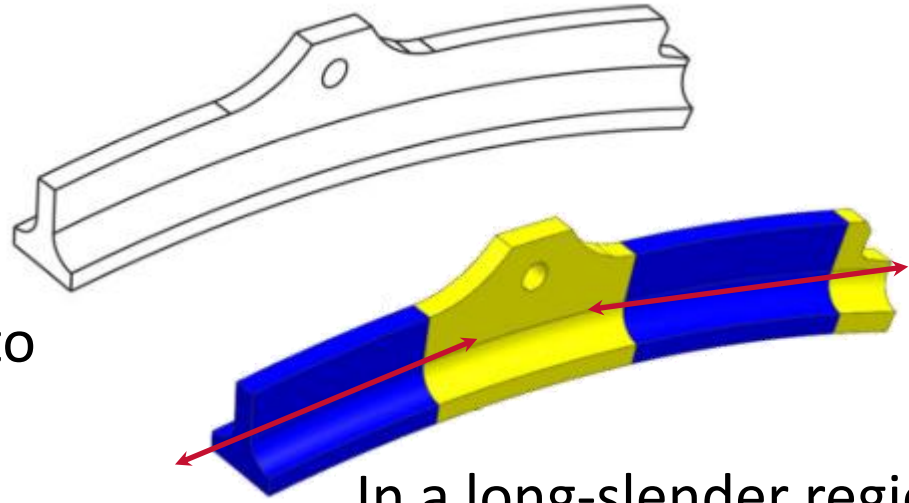
DOI: 10.1007/s00366-017-0550-x

CRESCENDO Engine used with permission from Rolls-Royce

QUB applications – long slender regions

- **Geometric Reasoning rationale:**
  - Identify regions which have a small but relatively consistent cross-sectional profiles relative to their length
  - Mark the end faces
  - Mark faces which run along the length
- **Meshing rationale**
  - Replace with lines/curves and mesh using beam elements
  - Hex mesh by sweeping a quad mesh applied to an end face along the length of the region

Ellipses
Medial Axis
Length measurements
Topology (neighbours)

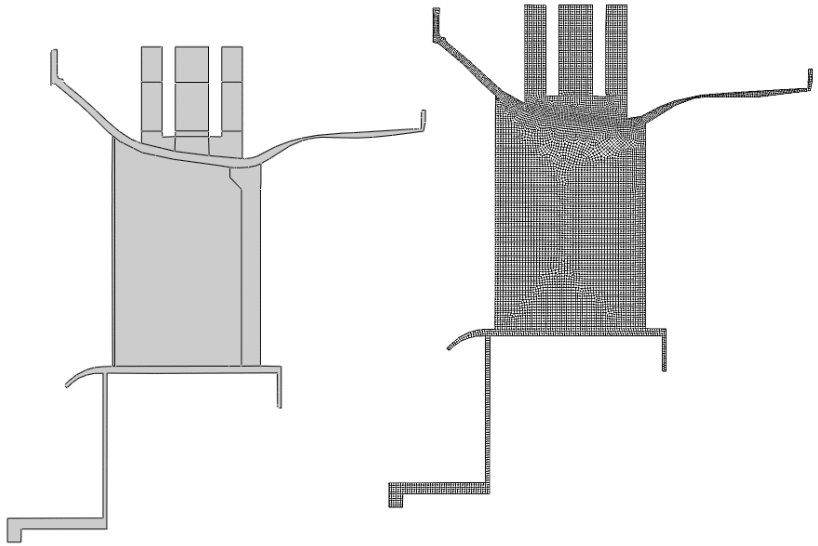


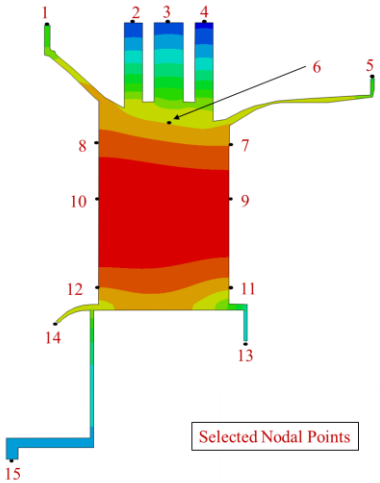
In a long-slender region, the singularities can run along the length.

DOI: 10.1007/s00366-017-0550-x; 10.1007/s00366-012-0302-x

QUB applications – quasi-axisymmetric regions

- **Geometric Reasoning rationale:**
  - Create the axisymmetric profile for the component
  - Split into different faces
    - a region which occupies a different percentage of the circumference than its neighbours
    - a region which has a different exposed surface area than its neighbours





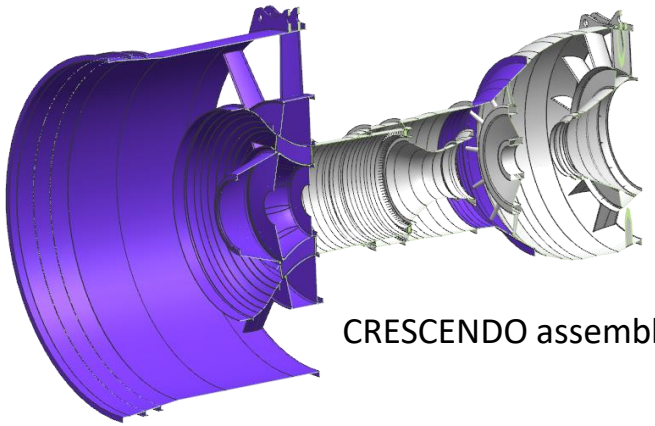
Facets
Topology
Sweeps
Boolean Operations

Thermal Overall Integrated Concept Aircraft

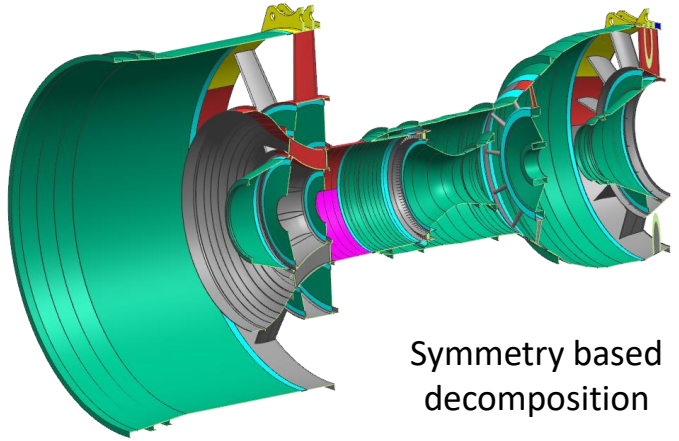
Singularities are in the out of plane direction (circumferentially)

QUB applications – Repeated geometric regions

- **Geometric Reasoning rationale:**
  - Identify regions which are repeated in the model
  - Mark each repetition of a region to its “master”
  - Record the transformation of the repetition relative to the master
- **Meshing rationale:**
  - Depends on the attributes of the master region



CRESCENDO assembly

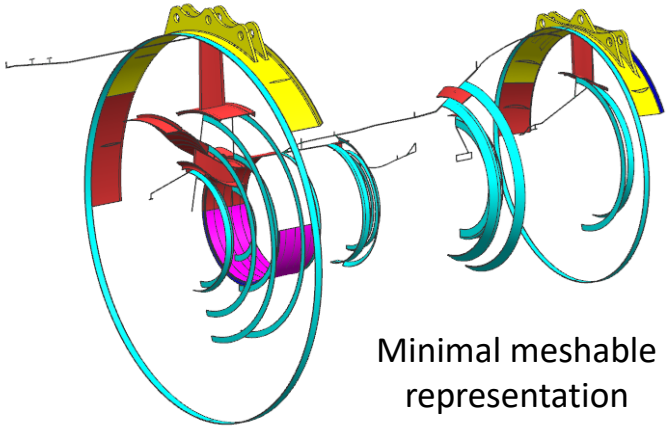


Symmetry based decomposition

Axisymmetric
Sweep / long-slender
Cyclic master
Residual / non-axisymmetric
Patterned
Block topology
Transition

CRESCENDO

60% - axisymmetric
28% - cyclic
5% - transition
2% - sweepable
1% - block topology
4% - residual



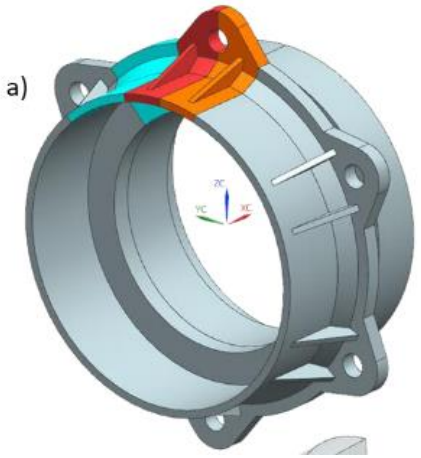
Minimal meshable representation

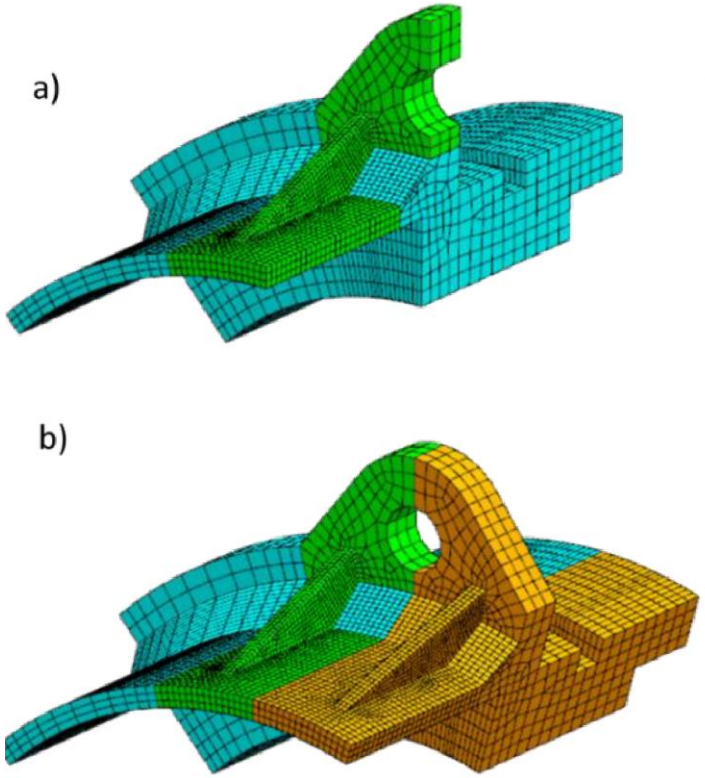
CRESCENDO Engine used with permission from Rolls-Royce

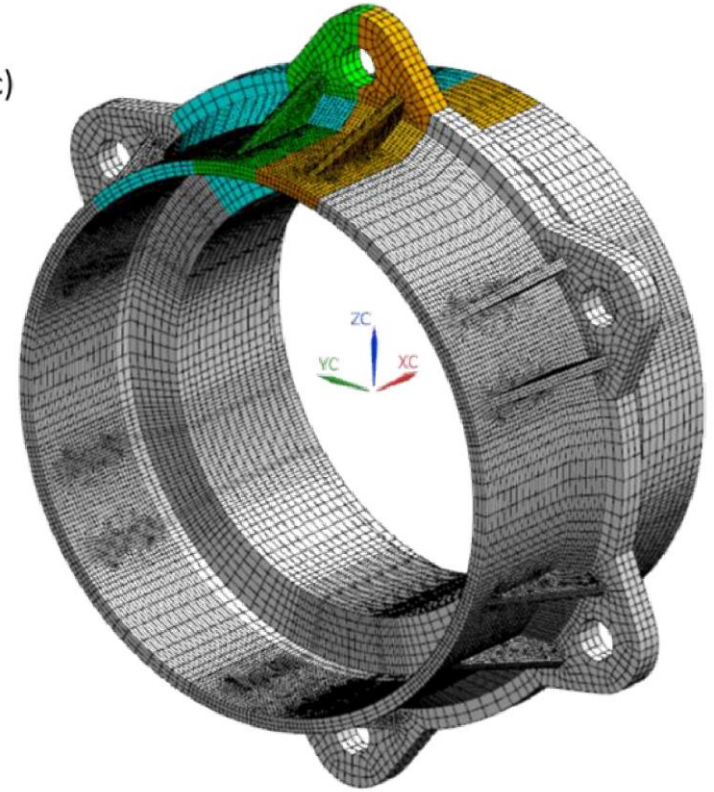
10.14733/cadaps.2019.478-495

QUB applications – Minimal meshable representation (MMR)

- **Mesh the minimal amount of the model possible**
  - We don’t mesh (or decompose) the same region twice!!
- **This has the opportunity to provide a meshing speedup, regardless of what your meshing requirements are**

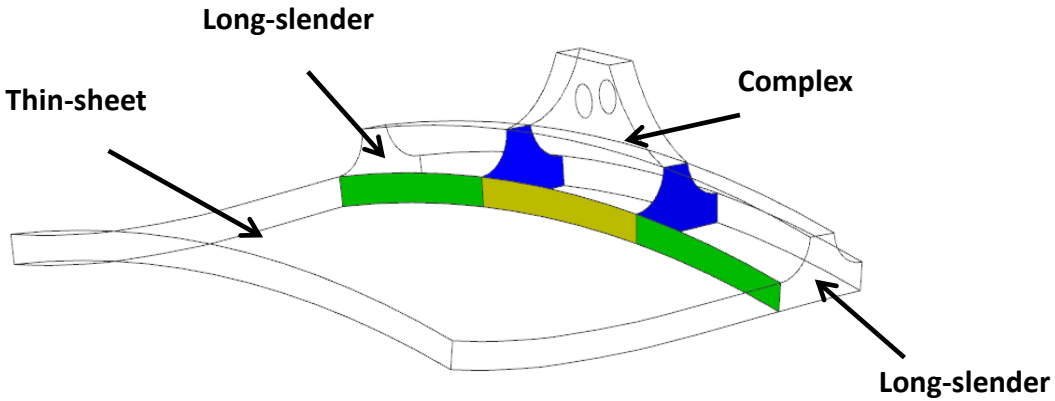


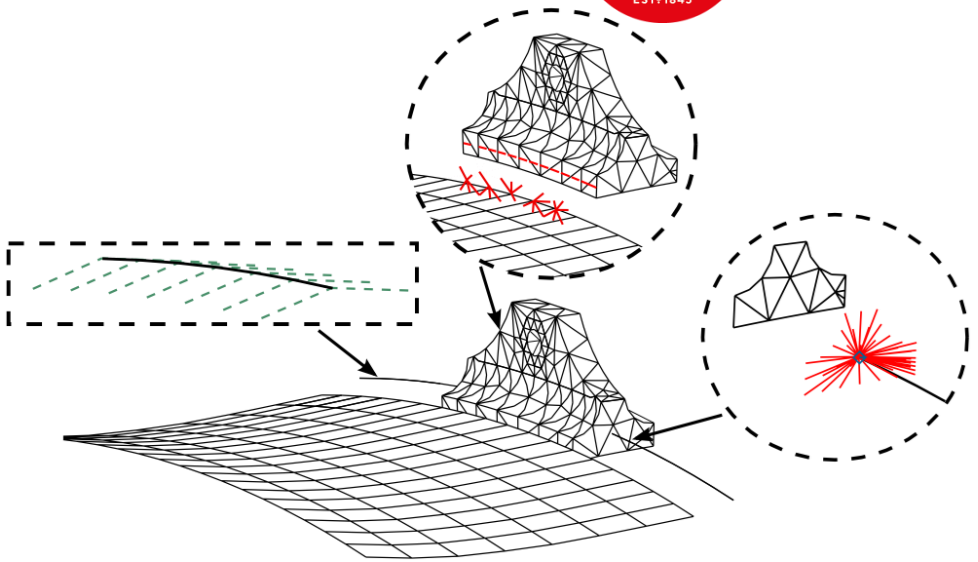


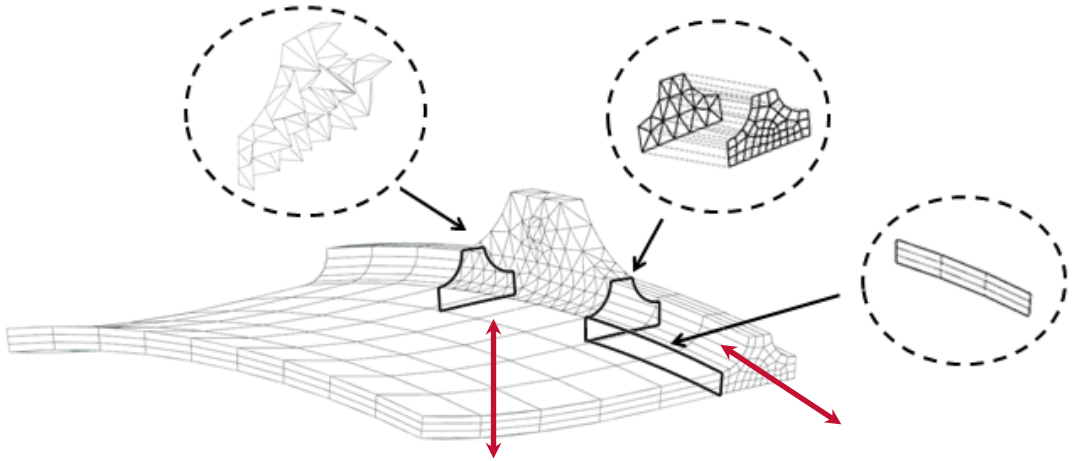


Meshing adjacent regions

- **When meshing adjacent regions, we can:**
  - couple them together,
    - behaviours of the coupled nodes are interpolated mathematically
  - ensure a common mesh at the interface, giving a contiguous mesh
    - only possible if each region has the same number of positive and negative singularities at the interface



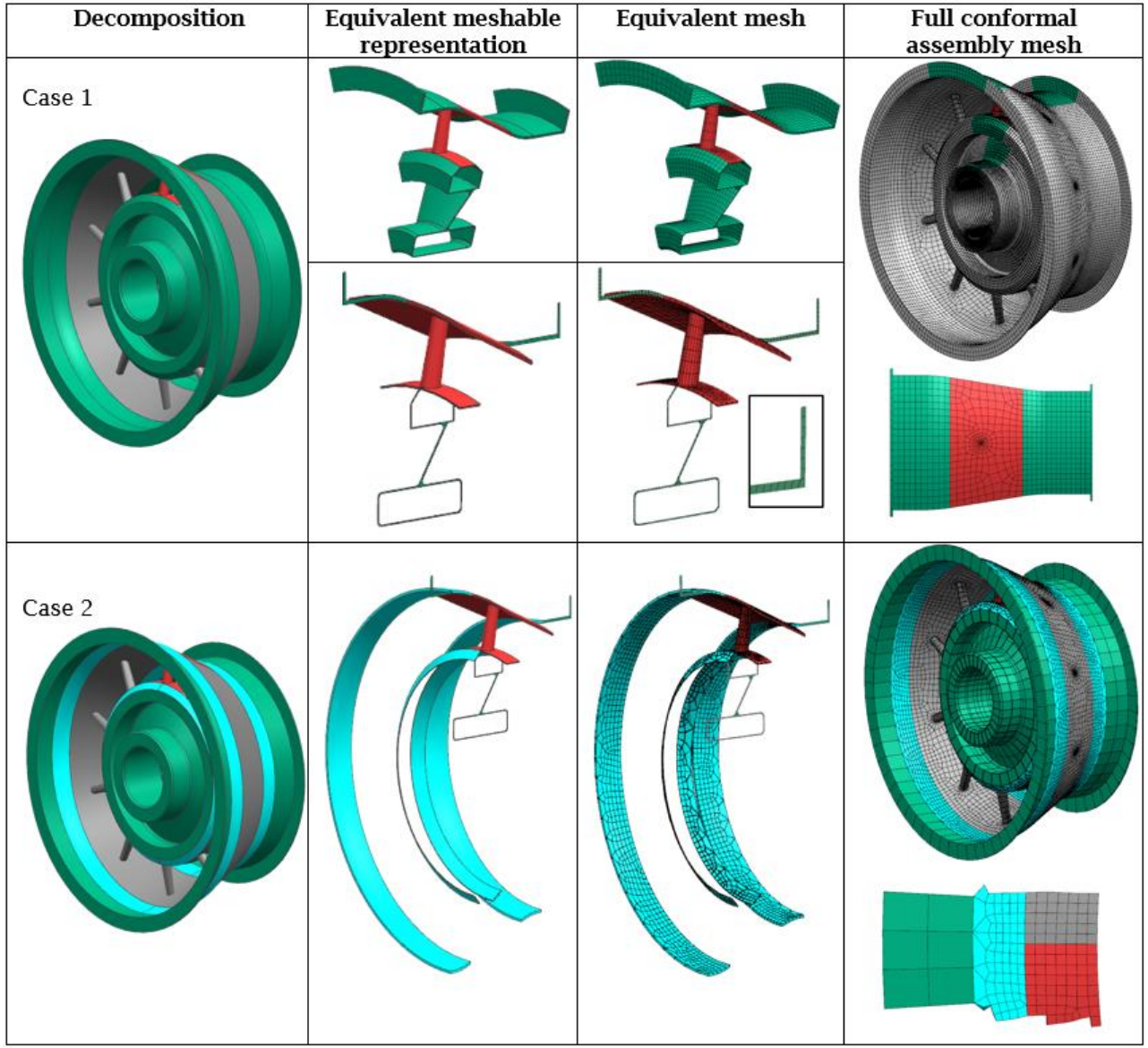




DOI: 10.1080/16864360.2015.1114391

Meshing minimal representation - transitions

Decomposing the model into cells we know how to mesh means each cell can be:
-meshed in parallel
-meshed using techniques suited/sized to the properties of the cell



Case 1 – fine mesh:

- MMR mesh - 2,719 hex elements
- MMR mesh - 823 hex and 110 quad elements are created.
- Component mesh - 38,870 hex elements

Case 2 – efficient mesh:
(uses bodies in transition regions)

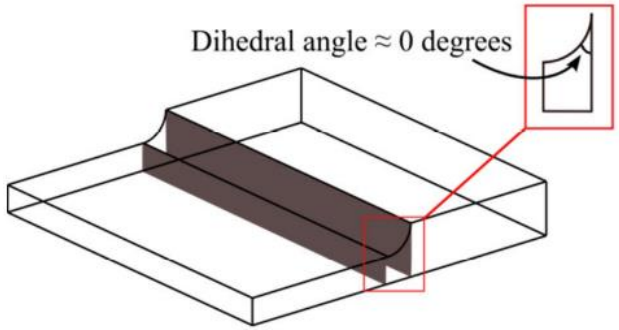
- MMR Mesh – 2,168 hex elements and 47 quad elements
- Component mesh - 12,024 hex elements

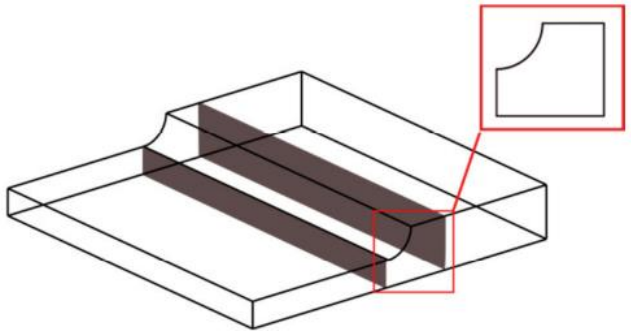
CRESCENDO Engine used with permission from Rolls-Royce

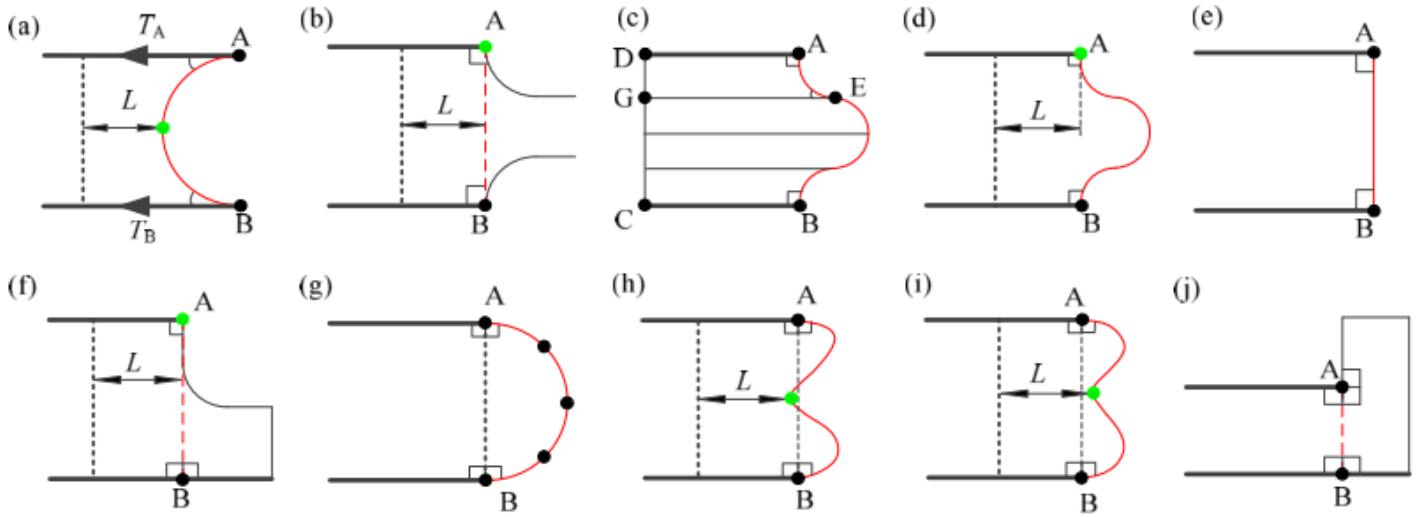
DOI: 10.14733/cadaps.2019.478-495

Post processing decisions

- **We need to ensure we don't cause issues/make things more difficult**
  - Often, we need to "update" our decisions before implementation:







DOI: 10.1007/s00366-017-0550-x

Comments

- **The decision to be made will differ for different simulations and applications**
  - It is difficult to determine completely generic solutions
  - Motivations change:
    - "Semi-autom g"
- **The most challengi**
  i. fact this is ab odel
     - local decisio
     - E.g. making a der of the model
  ii. quality of the
  iii. robustness o
  iv. when we modify the model, it can have significant impacts across the model lifecycle

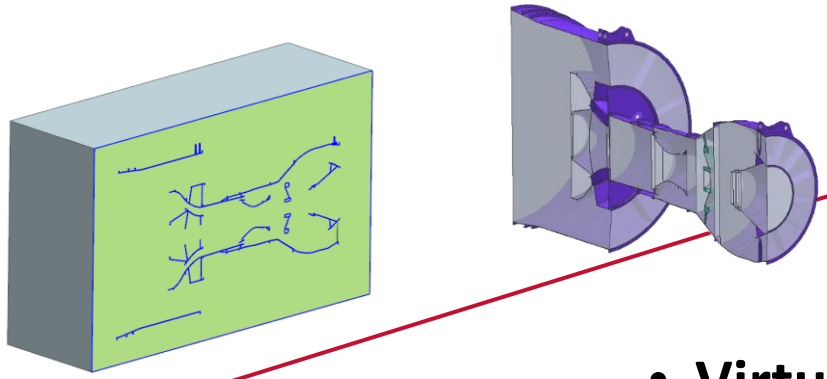
Earlier QUB work was hampered by geometry processing operations.

E.g. splits resulted in non-watertight bodies, sliver faces, short edges, changes to entity names/ids

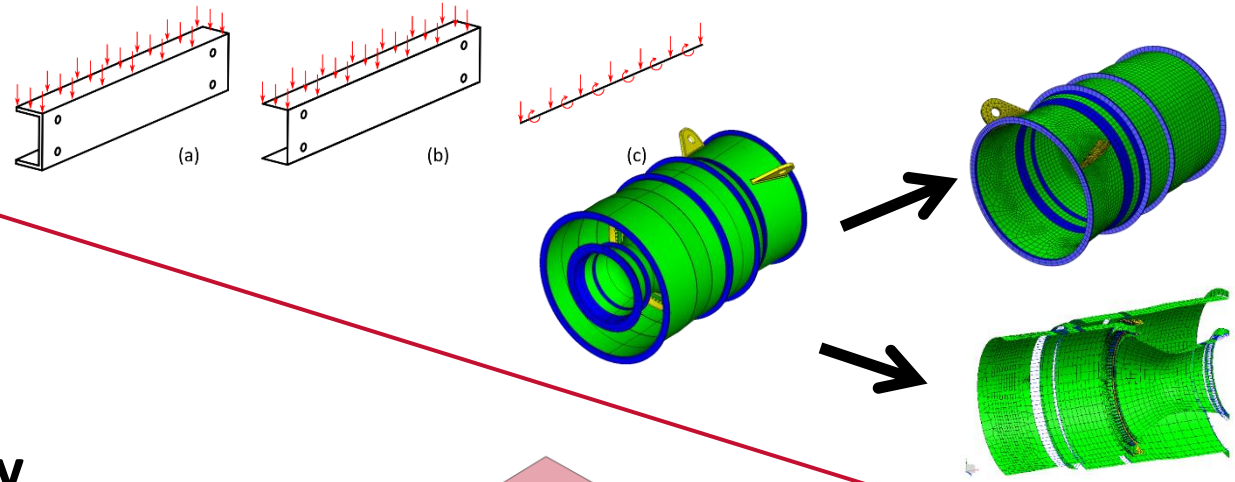
Geometry handling

Simulation Intent – enabling technologies

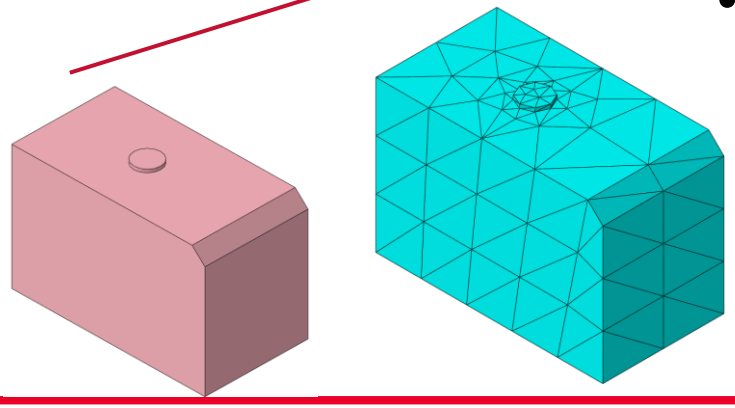
- **Cellular modelling**
  - Dividing space into cells of analysis significance
  - Provides a framework for capturing simulation Intent

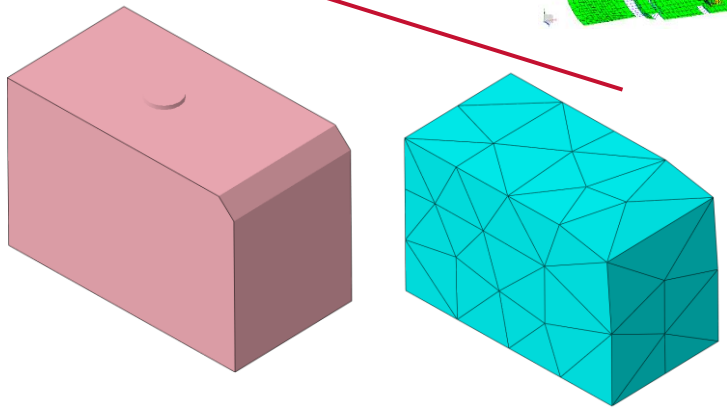


- **Equivalencing**
  - Capturing how cells, or groups of cells, are represented in different simulations



- **Virtual topology**
  - Updating the geometry representation of the simulation model, without modifying the geometry





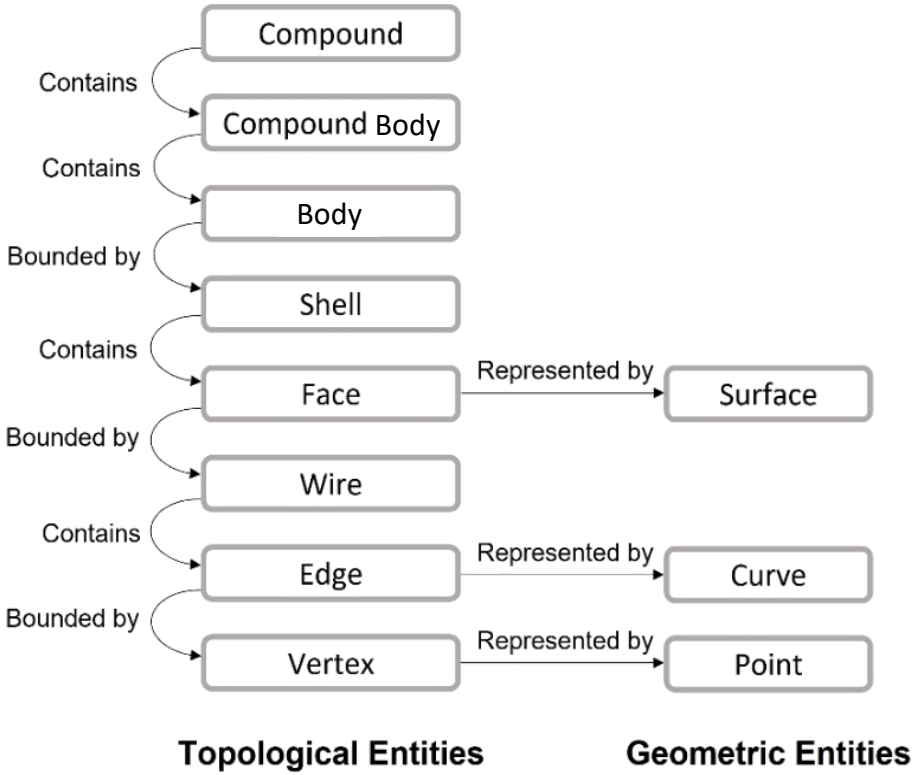
DOI: 10.1007/s00366-012-0302-x; 10.2514/6.2019-1720

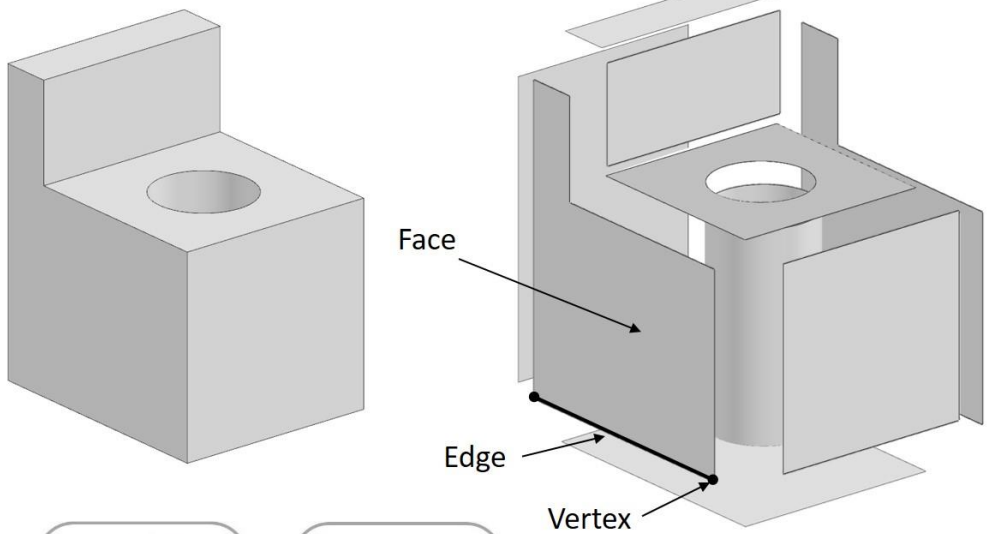
How to achieve it?

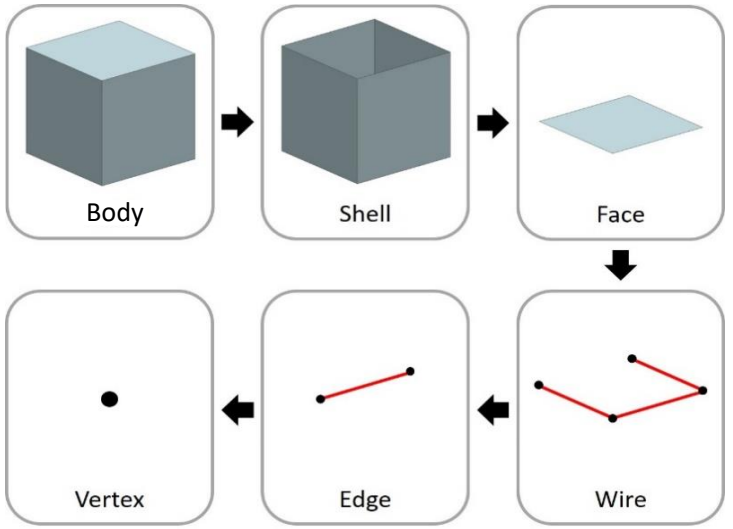
- **In QUB we retain a data-structure for the model, separate from that in the CAD (or CAE) system**
  - We use a SQL database (SQL Lite)
  - Data entries in the database are associated with the BREP and Simulation models
  - The structure of the database is used to link entities
  - Relations are used to hold attributes for entities
  - Queries on the database allow entities and relations to be retrieved
  - When we modify a model to prepare it for analysis, new entities, relationships and attributes are created in the database
    - They are not created in the geometry model!

Geometry in a CAD modelling system

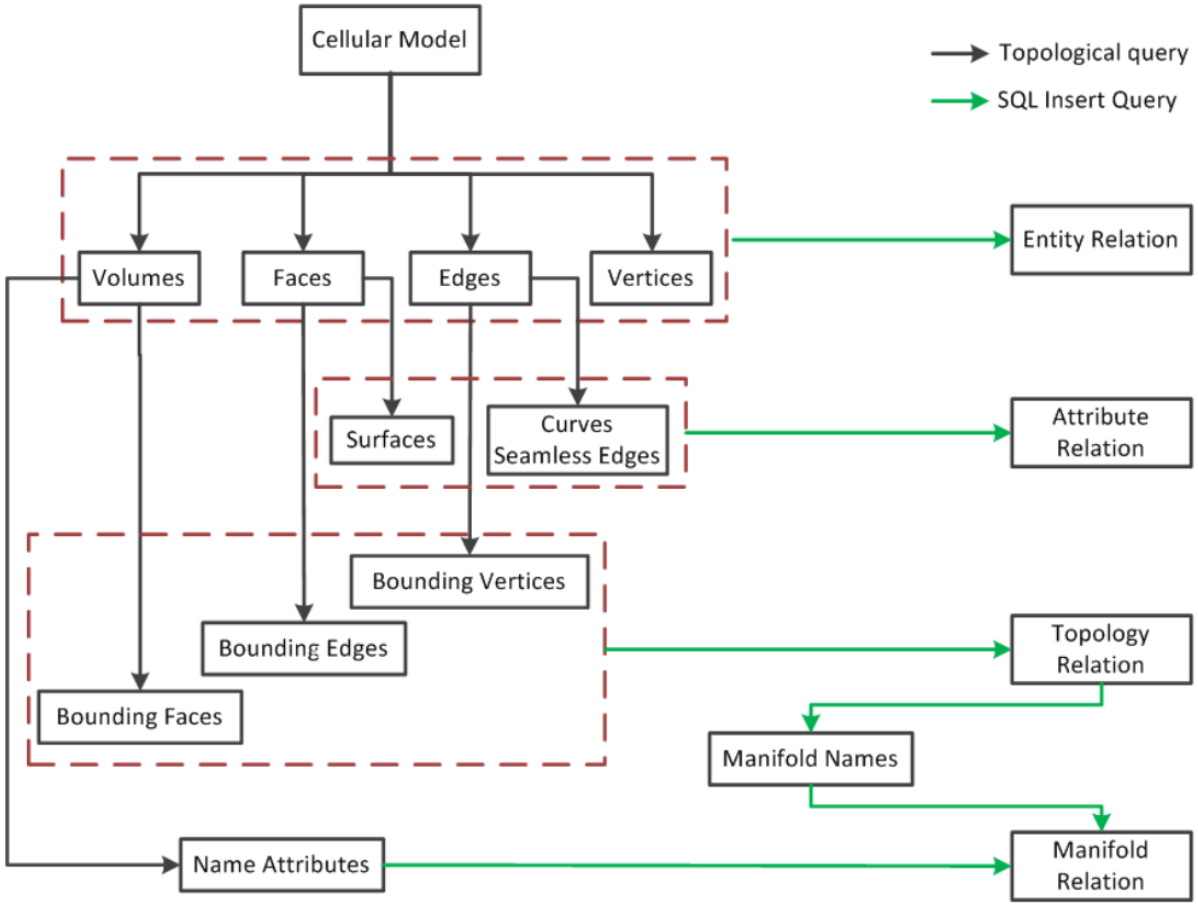
- **Most CAD modelling systems represent geometry as a Boundary Representation (B-Rep model)**







Database constructed round the BREP topology



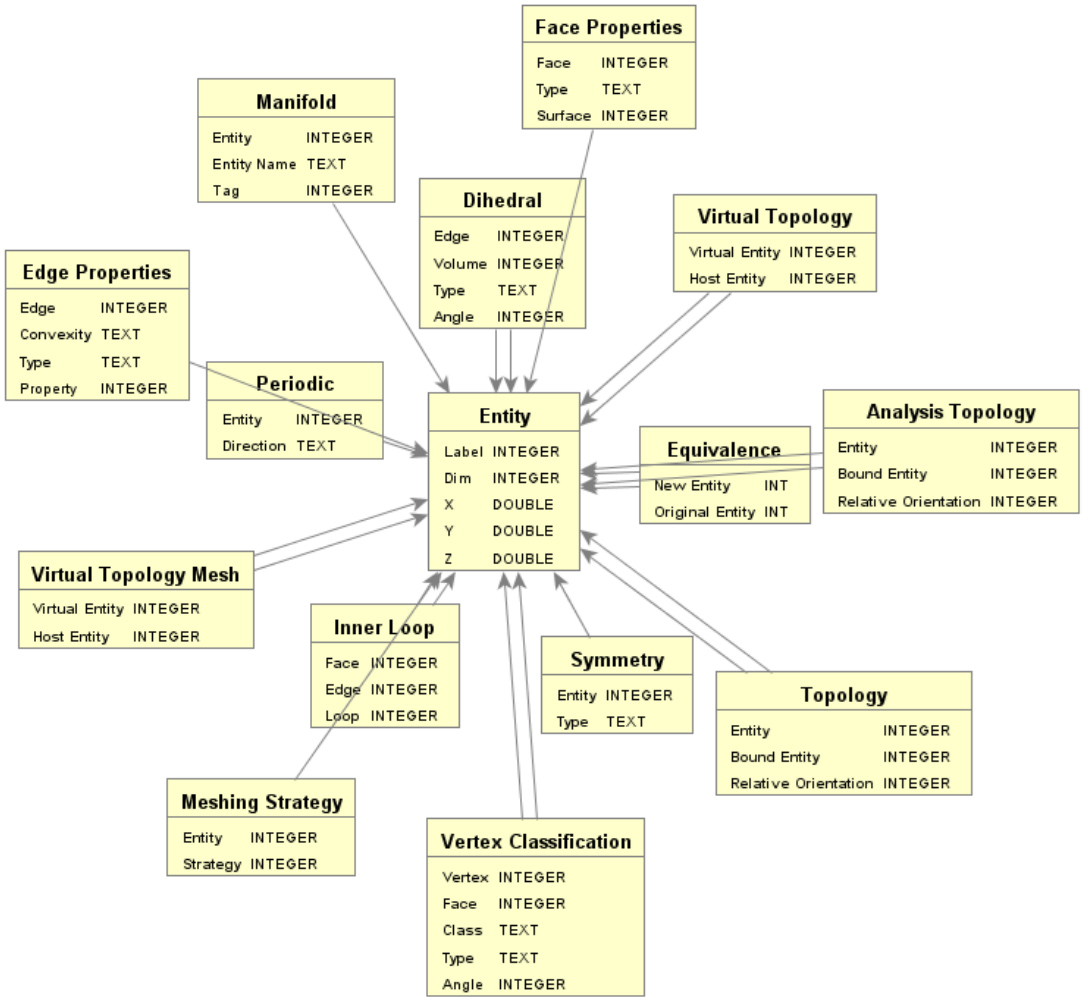
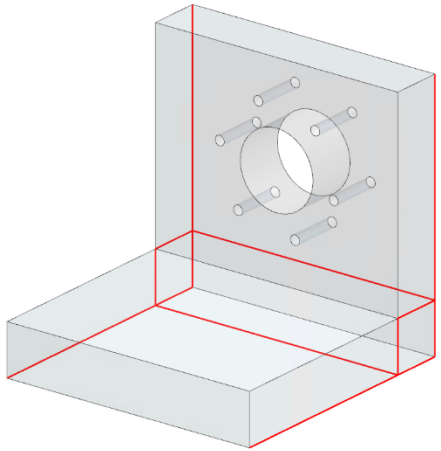


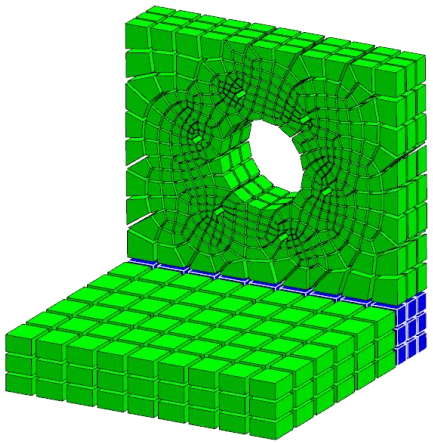
Figure 4-4 Topology extraction process

Virtual topology

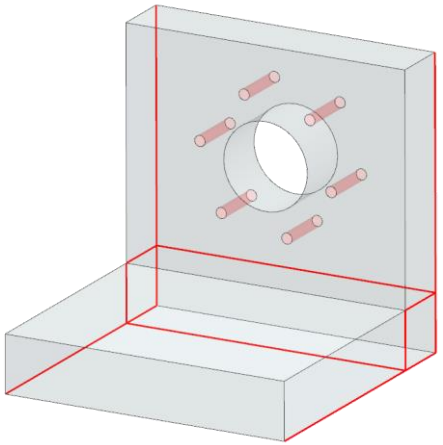
- **Virtual topology is a set of operators**
  - applied to the topology, without modifying the geometric description
    - E.g. Supersets, subsets, parasites, etc.
- **Common uses: preparing a model for simulation**



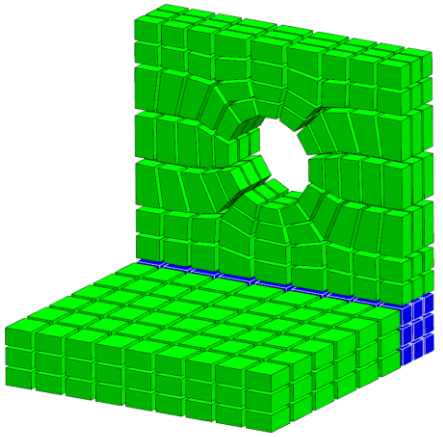
Model with hole features



Meshed model



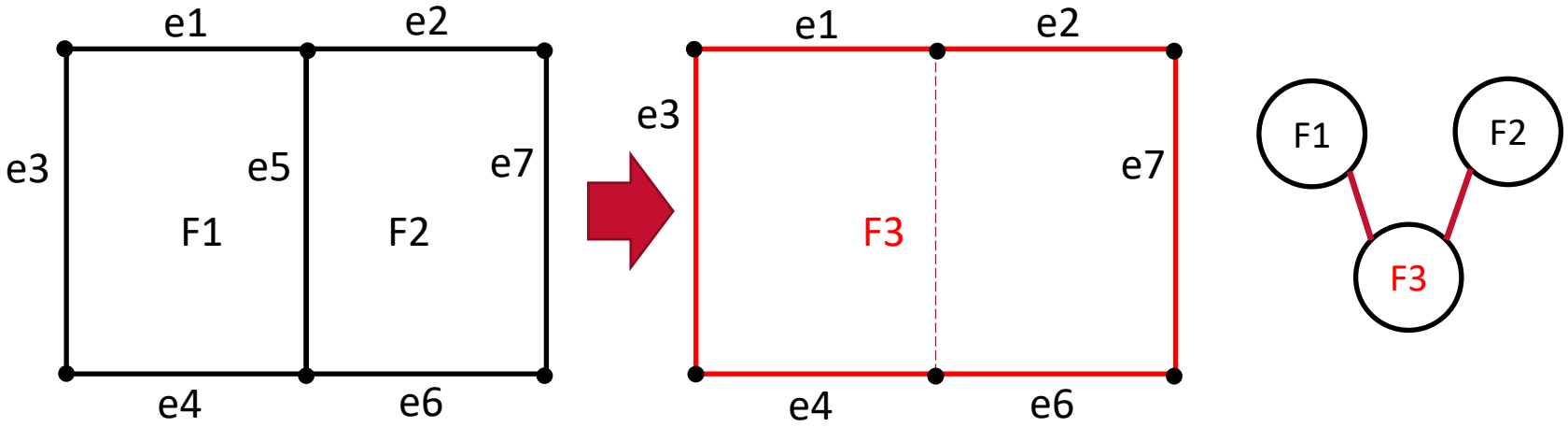
Select holes to apply VT

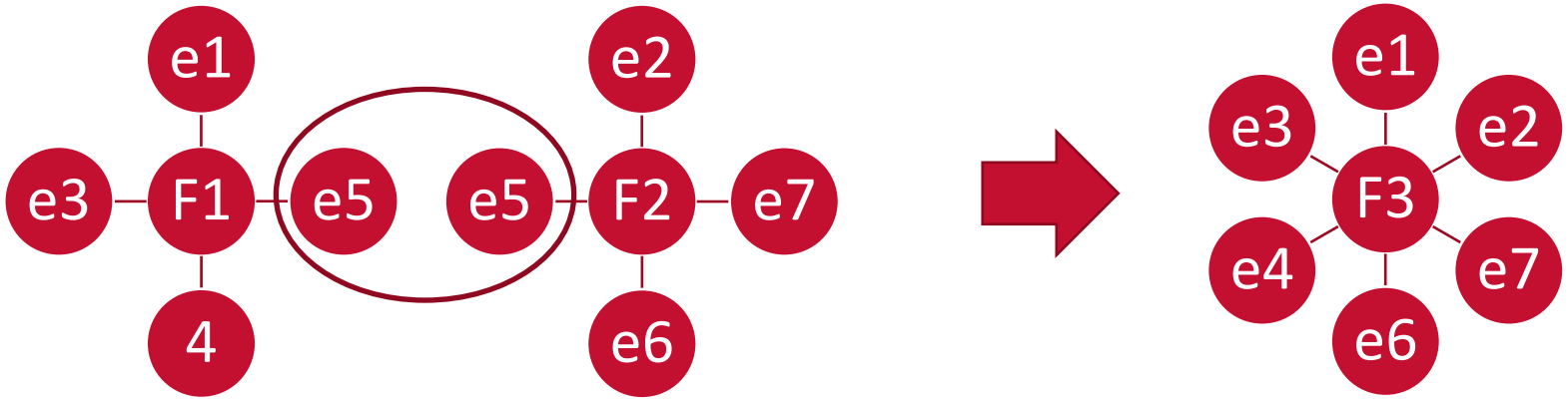


Mesh without hole features

DOI: 10.1142/S0218195900000188

Virtual topology – merging faces

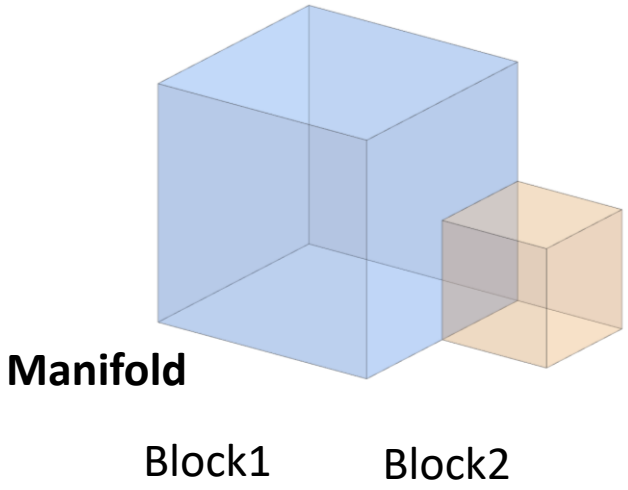


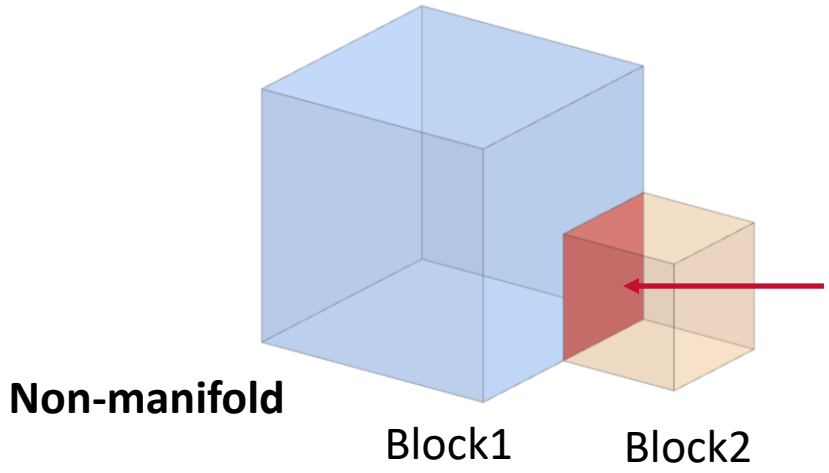


Topology of the faces

Interfaces

- **Manifold v non-manifold**
  - In a manifold model, each body is bound by a set of unique faces
  - In a non-manifold model, bodies can share the faces where they meet

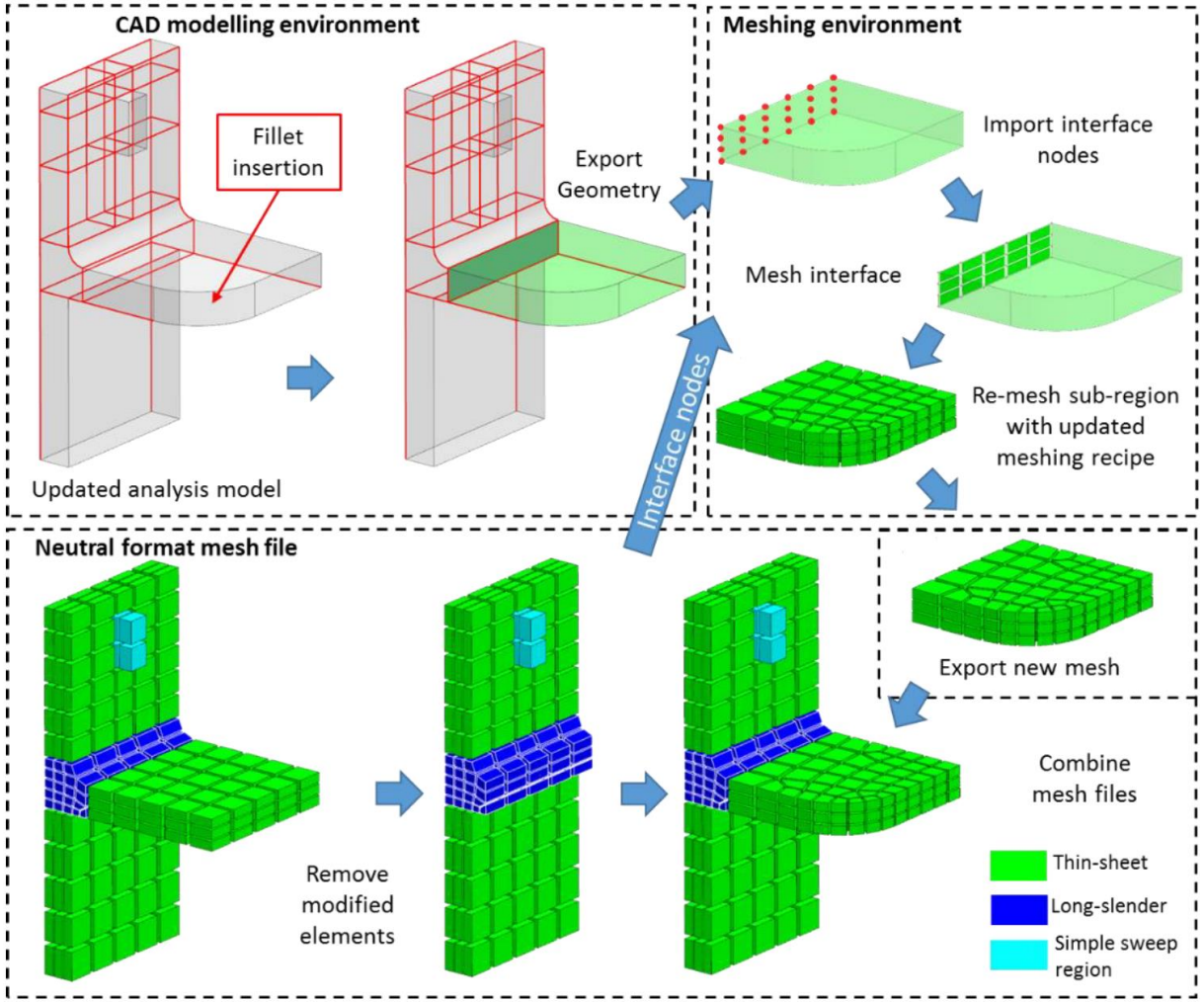




- A non-manifold model provides a robust framework to traverse a design
  - I.e. we know how to get from one cell to its neighbours
- Also achieved by recording when faces in the model are duplicate

Analysis topology

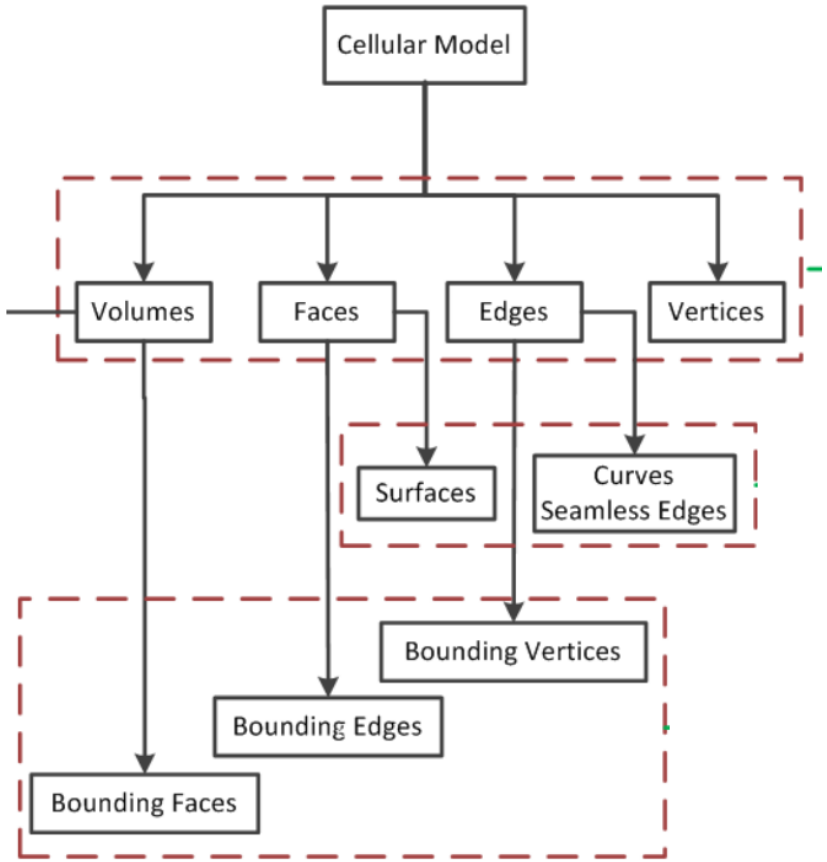
- **QUB apply virtual topology operators to create an Analysis Topology**
- **Analysis topology:** topological description used for simulation
- **Multiple Analysis Topology descriptions can exist for the same product**
  - These are equivalent representations
  - Can be reapplied after an update
- **The QUB cellular model is Analysis Topology**
  - virtual topology operators create the cellular model
  - we do not split the geometry into an assembly of cells
- **This is now the basis of our geometric modelling work!**



Geometric learning

BREP graph structure

- The structure of the model in the database is in effect a graph
- Simulation attributes are recorded for graph entities
- We have used this graph structure as the basis for ontologies / machine learning / deep learning processes



Ontologies – application of rules on cellular model

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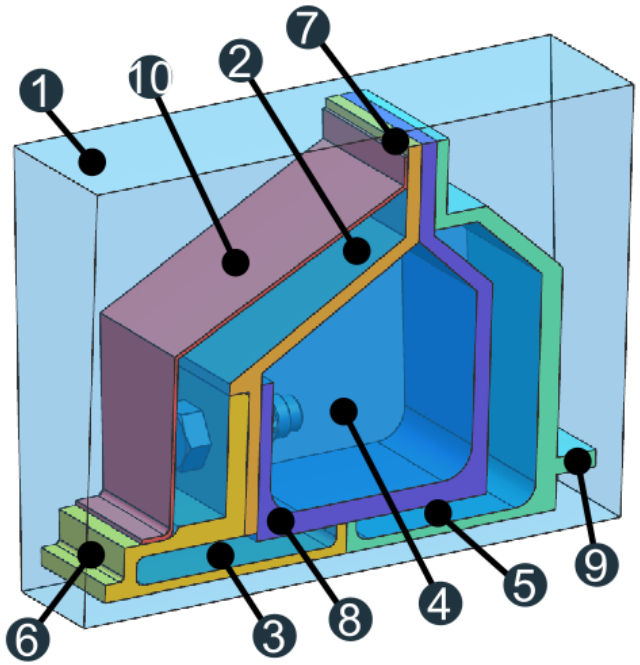
CAD - cellular model



1 2 3 4 5 Fluid domains

6 7 8 9 Casings structure

10 Heat shield

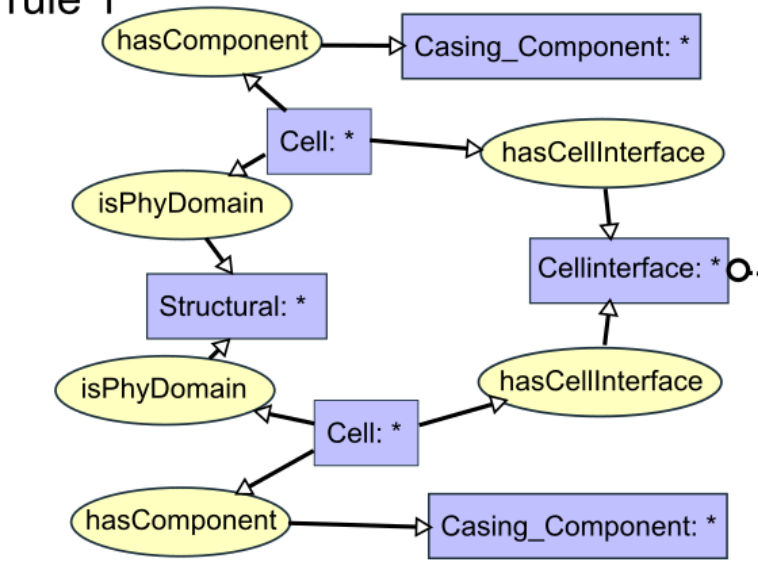
Ontology's rules

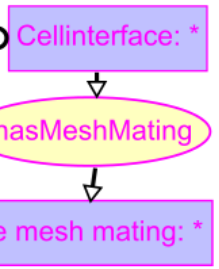
Hypothesis

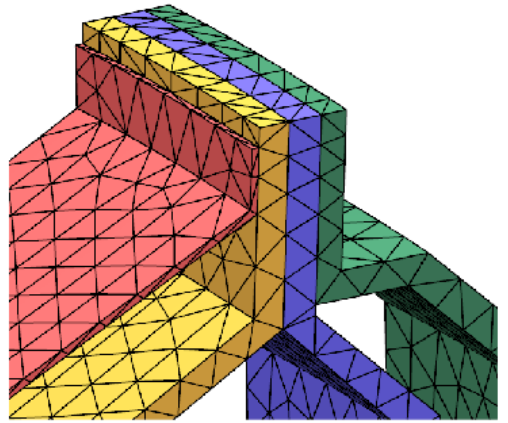
Conclusion

FEM - model

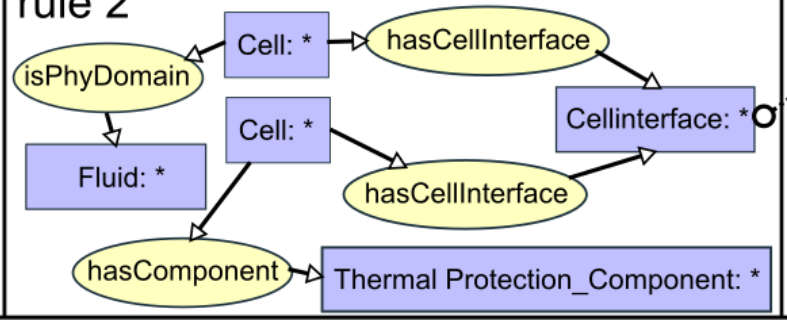
rule 1

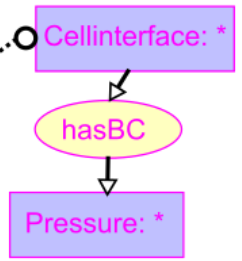


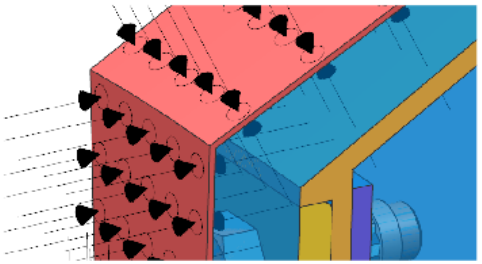




rule 2



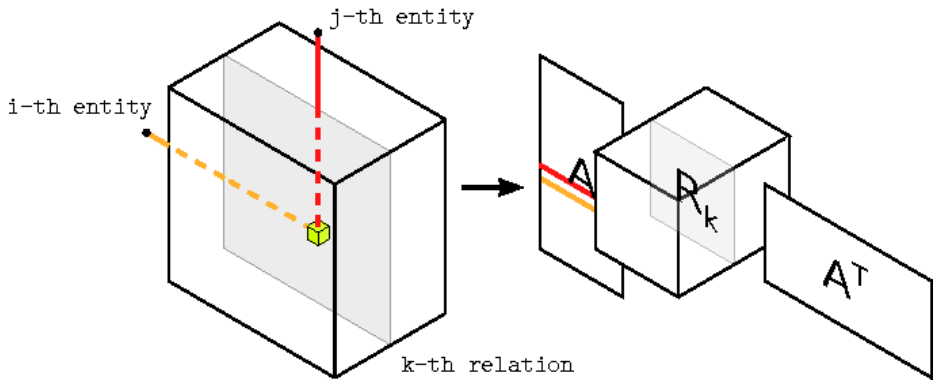




DOI: 10.1080/09544828.2019.1630806

Relational Learning

- Statistical analysis of relational or graph-structured data
- Can identify similar entities and repair duplicated, incomplete or missing relationships between entities
- QUB research applies relational learning to identify similarities in the B-Rep
- This is achieved by way of tensor factorisation, where each slice contains different information about the CAD model



Tensor Factorisation

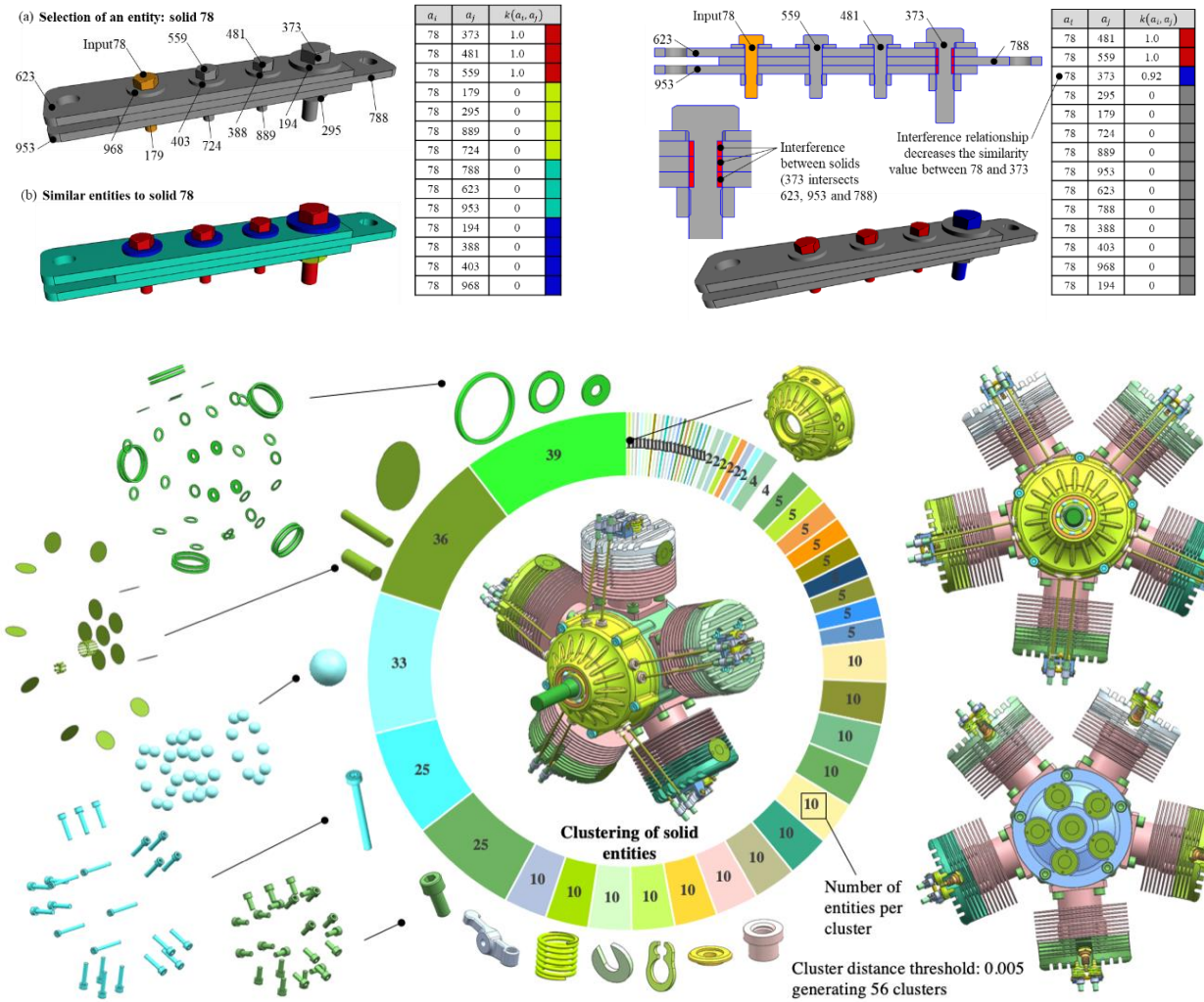
Frontal Slice, X_k	k^{th} Relation	i^{th} Entity/s	j^{th} Entity/s
X_0	Topological adjacency	Vertex, Edge, Face, Solid	Vertex, Edge, Face, Solid
X_1	Surface type	Face	Plane, Cylinder, Bezier, etc.
X_2	Edge type	Edge	Line, Circle, Bezier, etc.
X_3	Edge convexity	Edge	Convex, Concave, Smooth
X_4	Shape type	Vertex, Edge, Face, Solid	Vertex, Edge, Face, Solid
X_5	Edge length ratio	Face	Numerical Value
X_6	Number of bound entities	Vertex, Edge, Face, Solid	Numerical Value
X_7	Topological connectivity	Solid	Solid
X_8	Surface area to perimeter ratio	Face	Numerical Value
X_9	Interference type	Solid	Contact/Overlap, Gap

Tensor Slices [QUB FY student]

DOI: 10.1016/j.cad.2022.103372; 10.5281/zenodo.3653355

Relational Learning

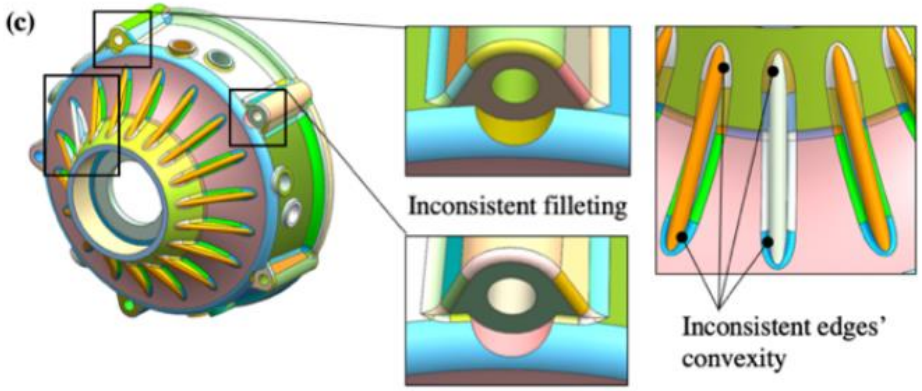
- User selects different entities in the CAD model (bodies, faces etc.) and similar entities will be highlighted in the CAD model
- Can select components in an assembly, faces in a model, or sets of faces in a model
- It does not require a dataset for training, unlike a neural network
- Able to run on very large CAD models



Examples of Similar Entities found by Relational Learning

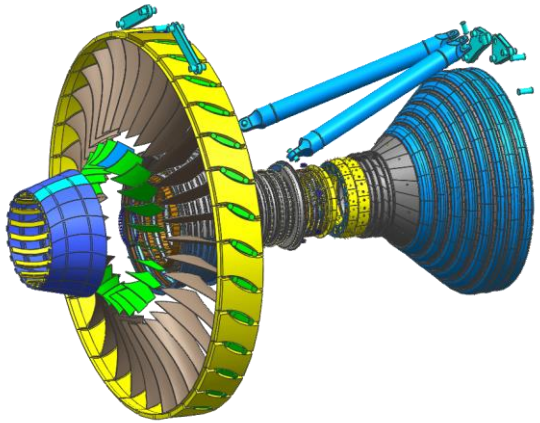
DOI: 10.1016/j.cad.2022.103372; 10.5281/zenodo.3653355

Identifying similarity in features

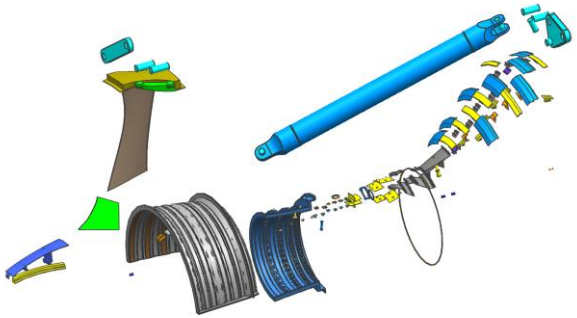


In the model above using relational learning has identified features that are similar but not identical

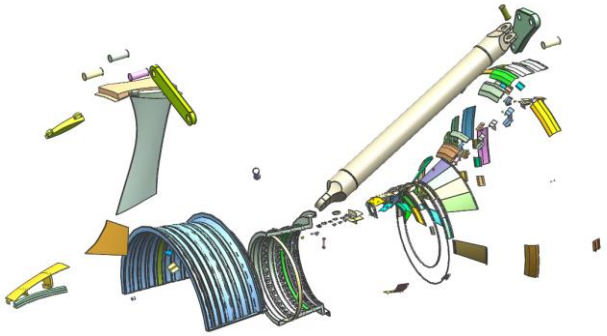
Can be used to reduce simulation pre-processing



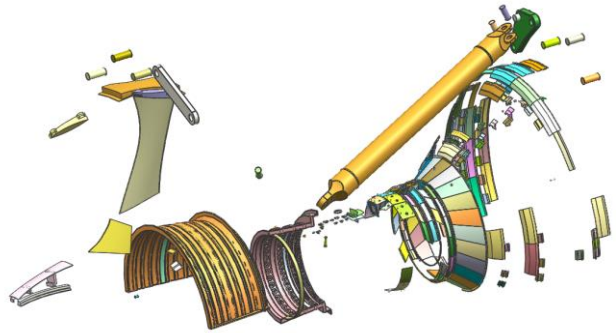
Annotated model: 148 classes



Tensor-based clustering: 186 clusters



Tensor-based clustering: 336 clusters

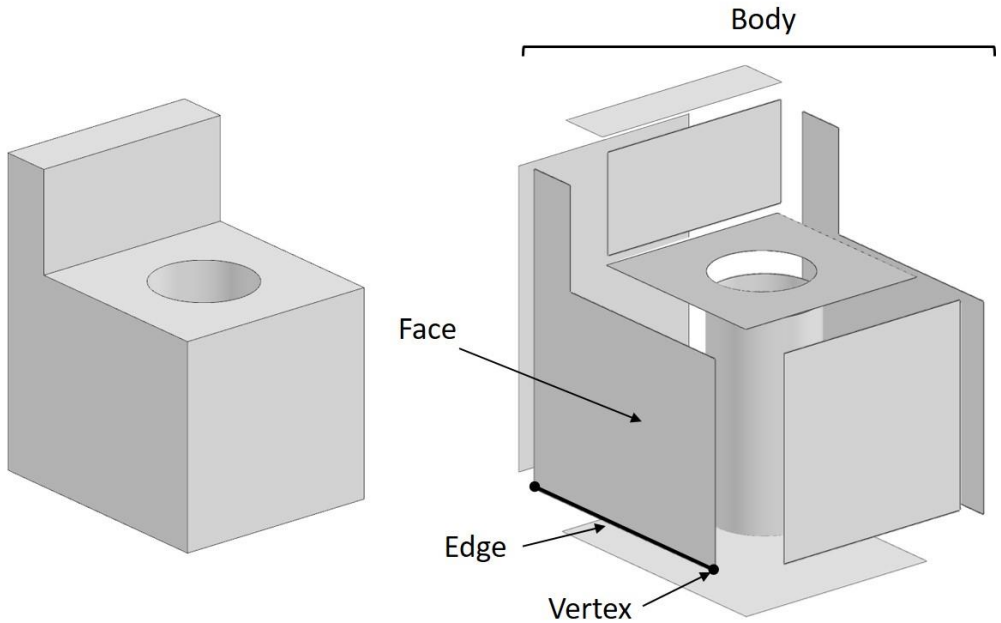


VESTA Engine used with permission from Rolls-Royce

DOI: 10.1016/j.cad.2022.103372; 10.5281/zenodo.3653355

Deep Learning for MCAD

- **Difficult to learn from the B-Rep directly**
  - Traditional CNNs (and other 3D shape NNs) require a fixed input size for each sample in the dataset
  - The B-Rep structure cannot guarantee this
    - A change in the number of B-Rep entities would change the whole semantics of the shape
  - Therefore, B-Rep is often converted into an alternative shape representation

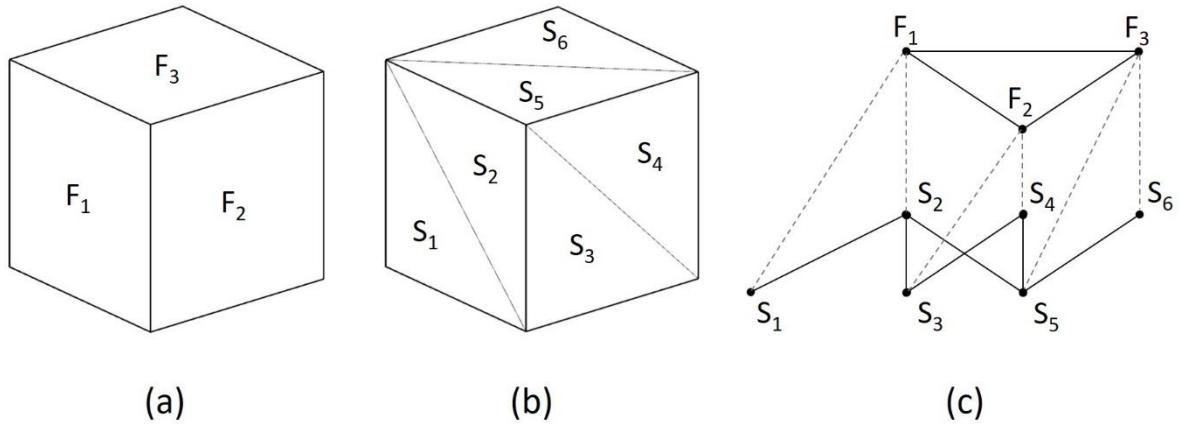


B-Rep CAD Model and B-Rep Entities

DOI: 10.1115/DETC2020-22355

Hierarchical B-Rep Graph (QUB approach)

- **A hierarchical graph made up of:**
  - the B-Rep face adjacency graph
    - To represent the structure of the model
  - a graph representing the facets of a surface faceting/mesh
    - To represent the geometry of the model

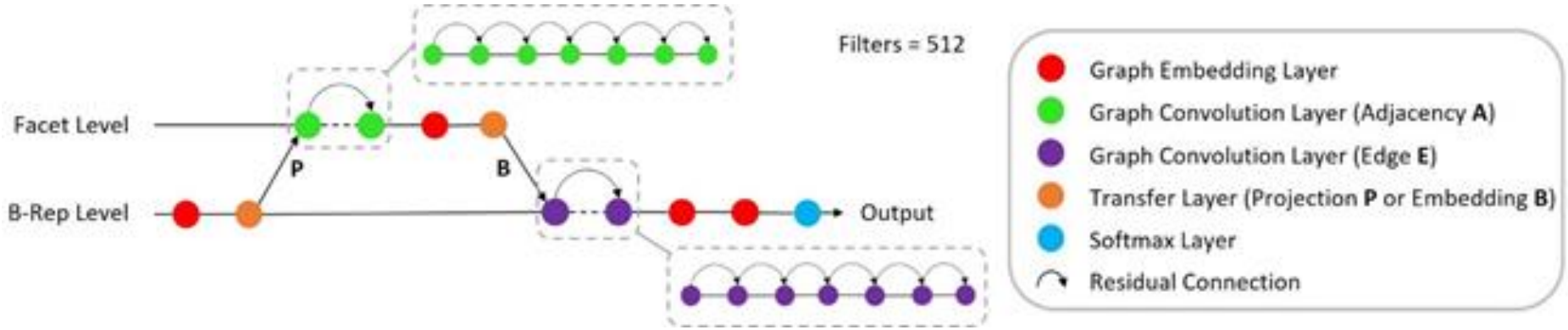


Hierarchical B-Rep Graph (a) B-Rep, (b) Facet/Mesh & (c) Hierarchical Graph

DOI: 10.1016/j.cad.2022.103226

The Hierarchical CADNet (QUB)

- **A graph convolutional neural architecture with two neural networks**
  - one to learn the facet/mesh level
  - one to learn the B-Rep face level
  - connections to transfer the information between the two
- **Neural Network can learn from a different input size from each sample**
  - More suited to B-Rep



DOI: 10.1016/j.cad.2022.103226

Application of Hierarchical CADNet on MFCAD++ Dataset

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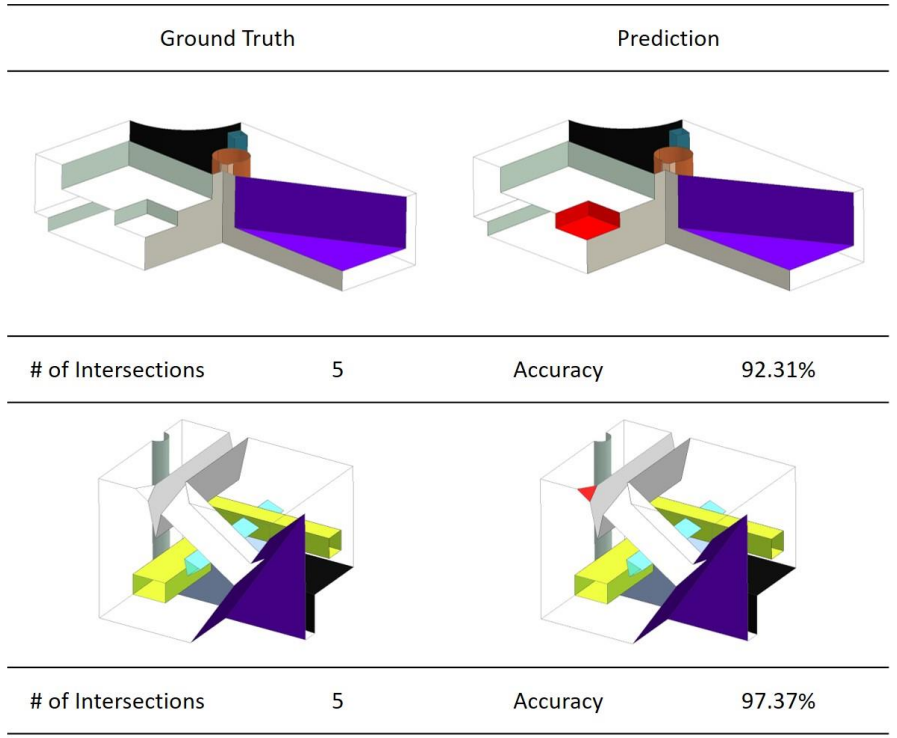
- **We got good results!**
- **We had to use it for identifying manufacturing features**
  - There are no simulation focused datasets available

Network	Accuracy Per Face (%)
PointNet++ [1]	85.88
DGCNN [2]	85.98
Hierarchical CADNet (Ours)	**97.63**

Results on MFCAD++ Dataset



Examples of Predictions of Intersections

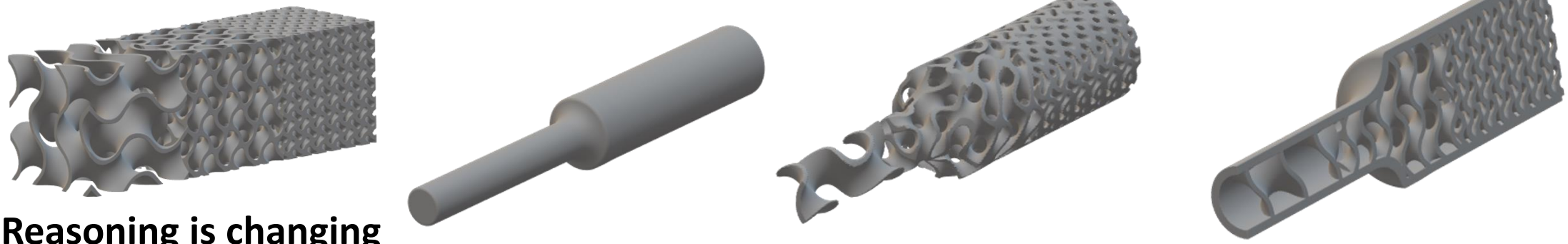
[1] Li CRQ, Hao Y, Leonidas S, Guibas J. PointNet++: Deep Hierarchical Feature Learning on Point Sets in a Metric Space. In: Conference on Neural Information Processing Systems (NIPS). 2017
[2] Wang Y, Sun Y, Liu Z, Sarma SE, Bronstein MM, Solomon JM. Dynamic Graph CNN for Learning on Point Clouds. ACM Trans Graph. 2018;38(5):Article 146.

DOI: 10.1016/j.cad.2022.103226

Geometry perspectives

The future

- **Geometry modelling is changing**
  - New CAD tools are becoming available
    - Some are focused on the hobby market
  - Implicit modelling (and others) are emerging



- **Reasoning is changing**
  - ML tools are changing how we reason
- **Design and manufacture is changing**
  - Generative design means designs are being created based on a mesh
  - Manufacturing processes are becoming less reliant on the traditional CAD route
- **People want to run bigger simulations**
  - New hardware architectures and solvers

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