Development of algorithms for generating connected midsurfaces using feature information in thin-walled parts

PhD Defense Presentation

by

Yogesh H. Kulkarni

Guided by Dr. Anil Sahasrabudhe (Guide) and Dr. Mukund Kale (Co-guide)

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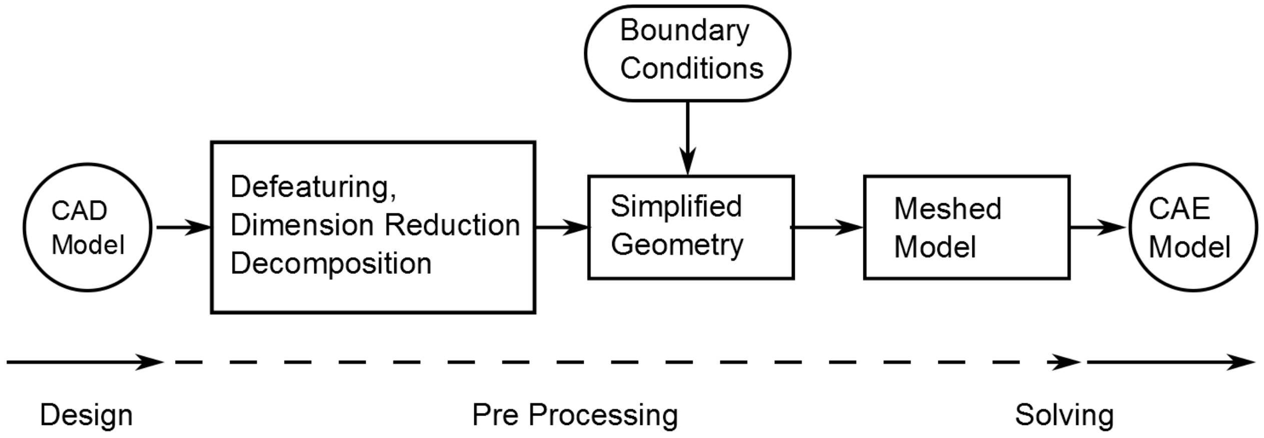
Agenda

- Introduction
- Literature Survey
- Proposed System
- Model Defeaturing
- Feature Generalization
- Midcurve-Midsurface Computation
- Topological Validation
- Case Studies
- Conclusions

Introduction

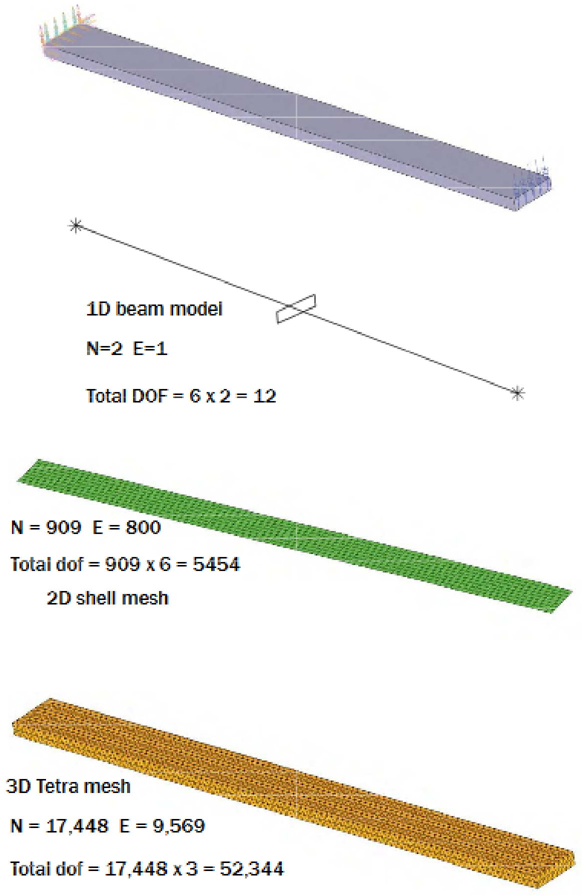
Introduction

- Necessity of Time-to-market
- Quicker validation
- Modern - Digital Product Development
- CAD-CAE Workflow
- Components of Model Simplification
- Dimension Reduction: Midsurface, Bar



Midsurface Advantages

- Thin-walled : Sheet Metal, Plastics
- Expensive Solid Mesh elements
- Advantages of Shell elements
- Comparison of results
- Lesser computations/time.

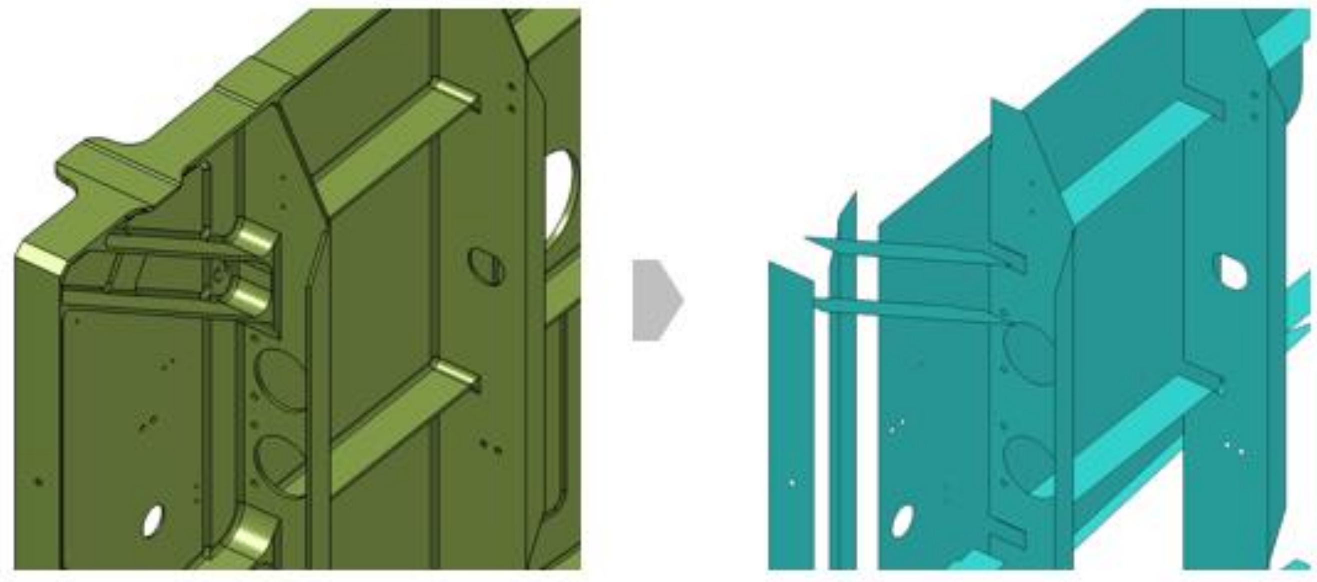


	thick	thin	very thin
Lengt / thickness	~5 to ~10	~10 to ~100	> ~100
physical characteristics	transverse shear deformations $\epsilon_{13} \neq 0$	negligible transverse shear deformations $\epsilon_{13} \approx 0$	geometrically non-linear

	Nodes	Elements	Stress N/mm²	Displacement mm
Analytical	–	–	105	4.23
1D	2	1	105	4.23
2D	909	800	103	4.21
3D	17,448	9,569	104	4.21

Motivation for Research in Midsurface

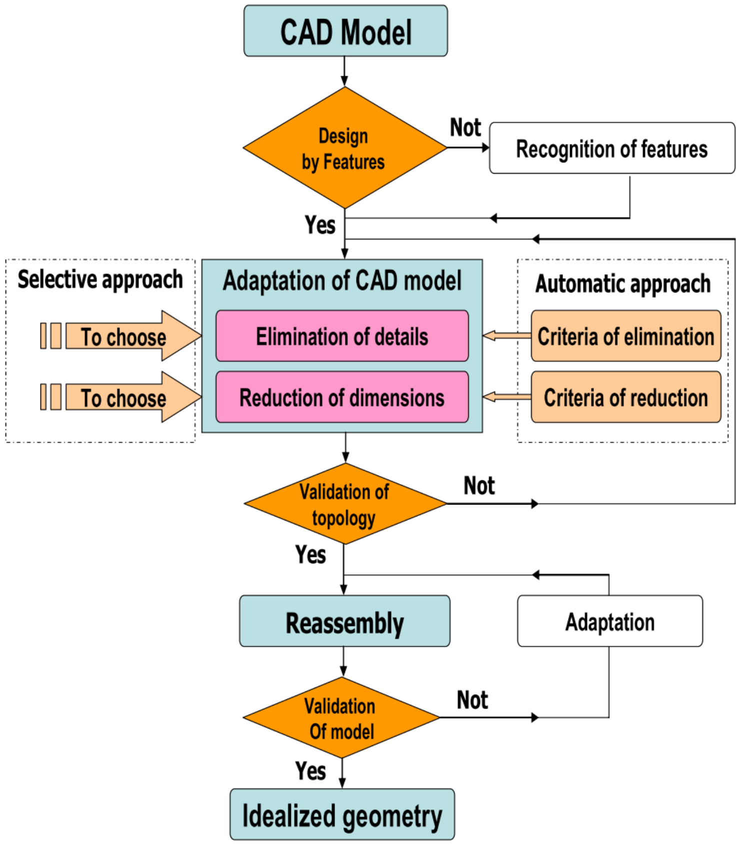
- 60%+ of analysist time for Idealization (Sandia report)
- Recent commercial results
- Varity of Midsurface Errors
- Process/tools of corrections
- Quality Midsurface, a must



Literature Survey

Traditional CAD-CAE Transition Approach

- Input formats
- Elimination of Details - Defeaturing
- Dimension Reduction – Medial computation
- Validation
- Output – Idealized Geometry



CAD Model Simplification

- Feature Recognition-based: Hamdi, Belaziz
- Decomposition-based: SH Lee, B Kim
- Feature-based: Dabke, Smit

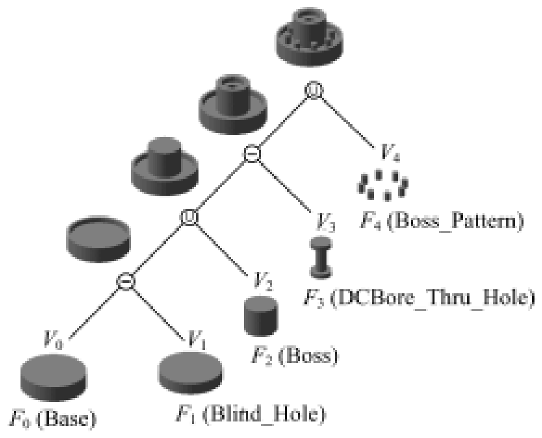


Fig.4 An example of feature-based solid modeling

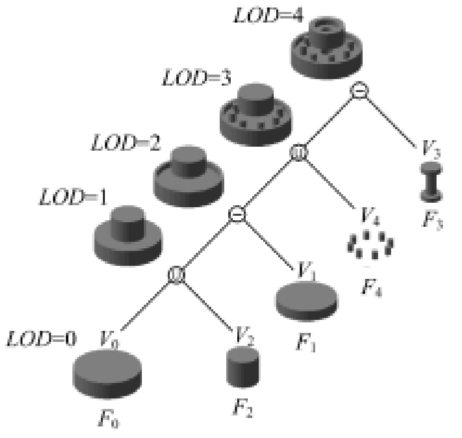
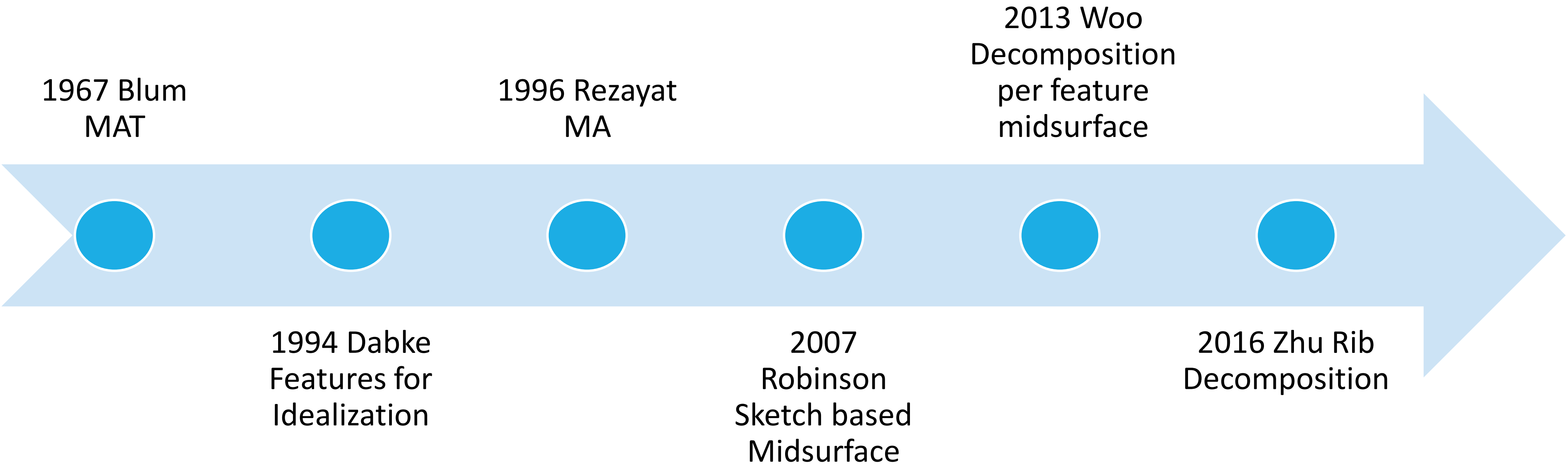


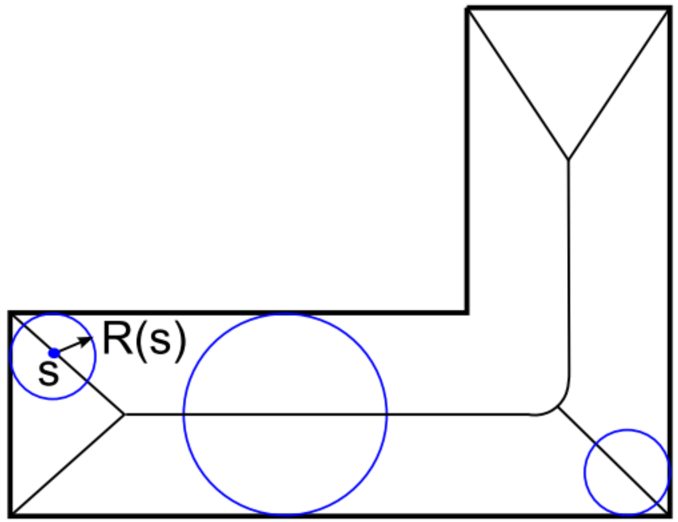
Fig.5 A rearranged feature tree and its results

Midsurface Development Milestones



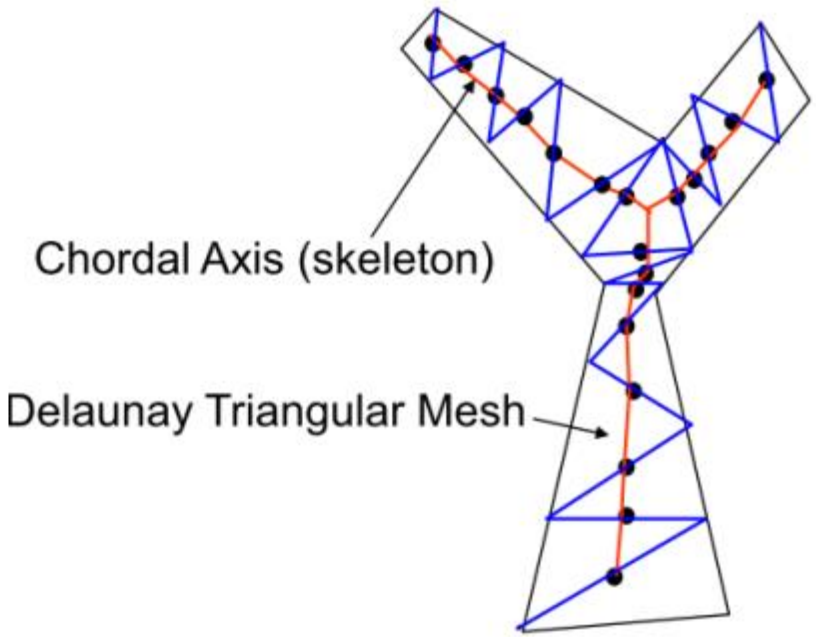
Medial Axis Transform (MAT)

- Blum, Robinson, Ramanathan, etc
- Maximal circle/ball, loci of centers
- Defined for any input shape
- Reversible
- Spurious Branches



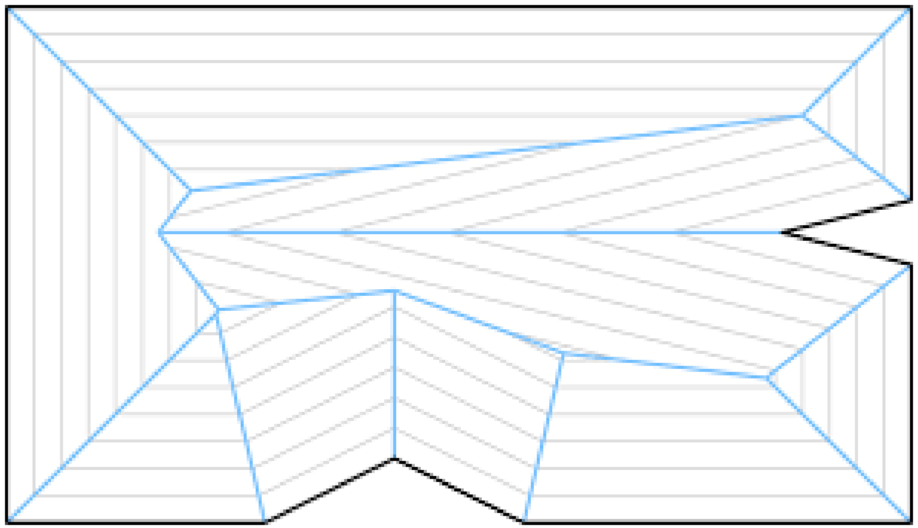
Chordal Axis Transform (CAT)

- Prasad, Quadros, etc
- Constrained Delaunay Triangulation
- Any input shape
- Missing ends
- Does not mimic well



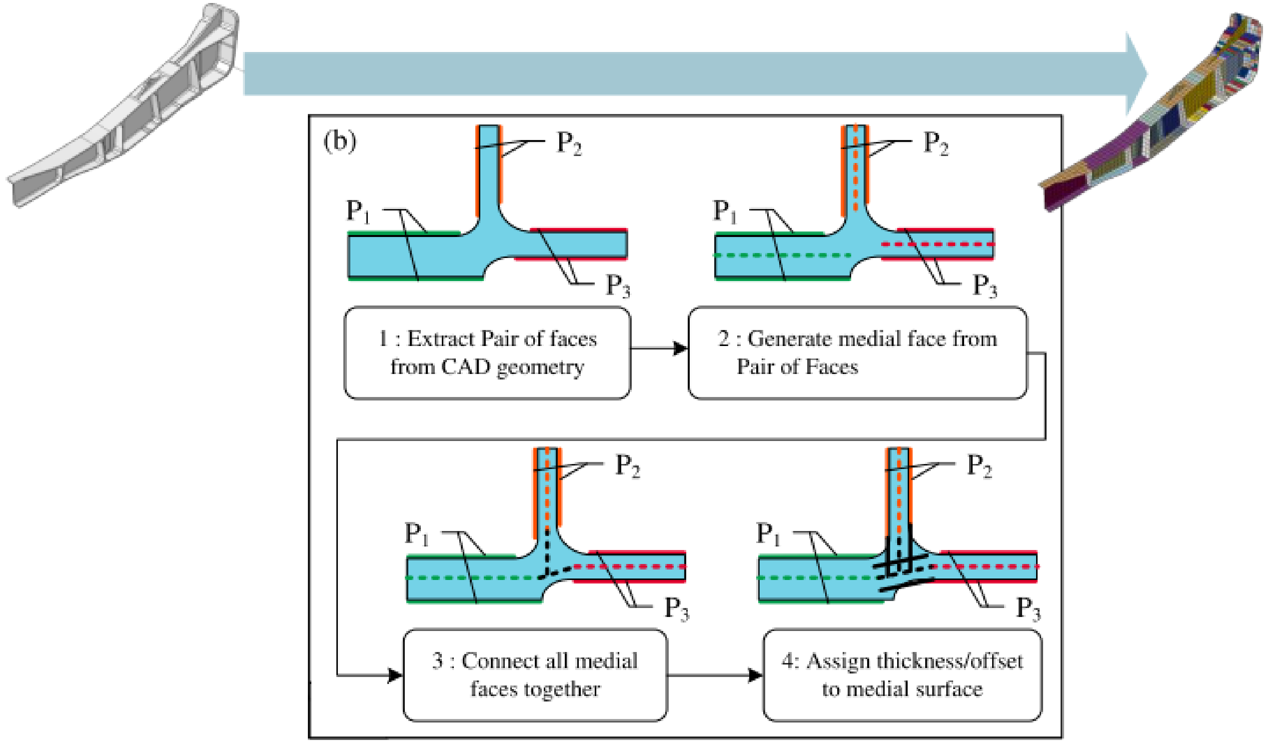
Thinning

- Montanari, Aichholzer, etc.
- Offset Inside
- Intersection events
- Spurious Branches



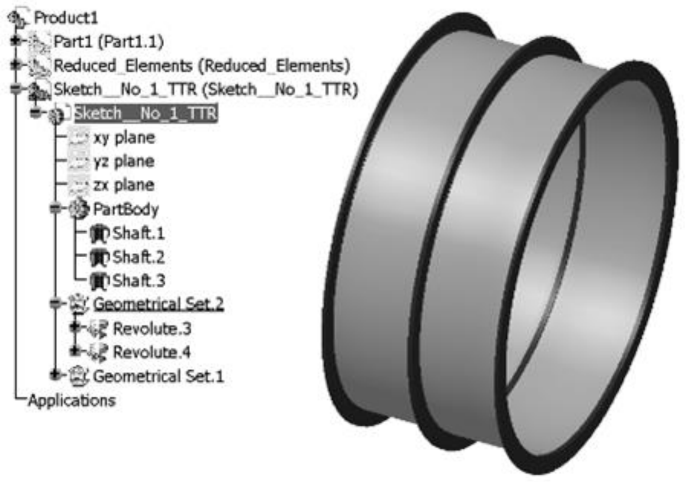
Midsurface Abstraction (MA)

- Rezayat, S Kim, Sheen
- Detect Face Pairs
- Midsurface Patches
- Extend – Trim
- Most representative
- Complex, with errors
- Commercially adopted



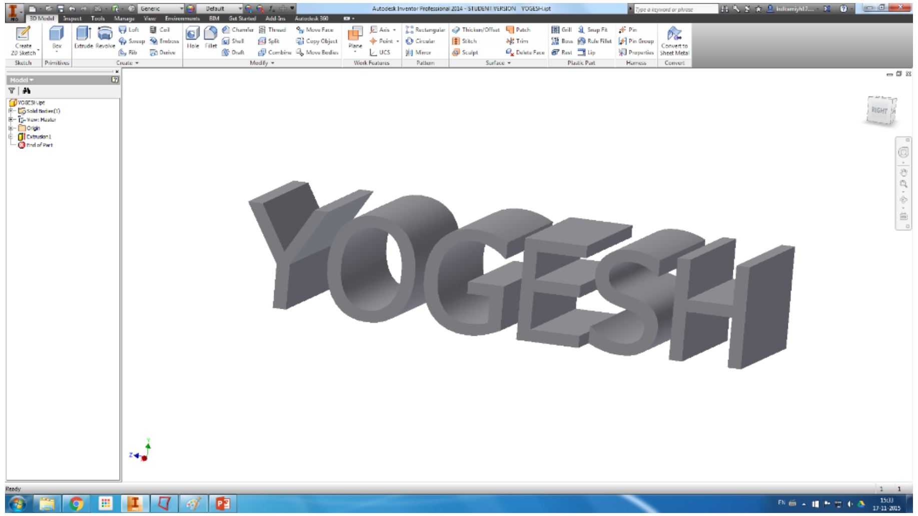
Feature-based Midsurface

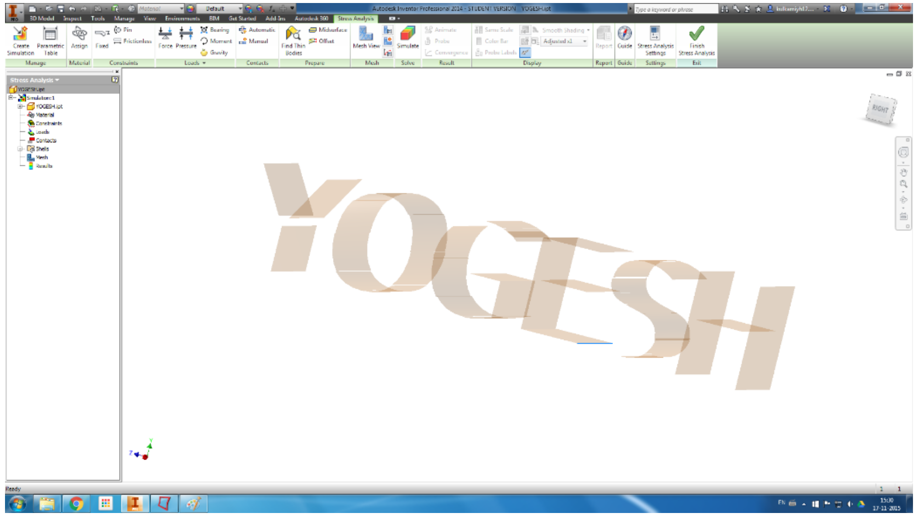
- Stolt, Robinson, Boussuge
- Single Feature + MAT
- Decomposition + Feature Recognition/MA
- No feature interaction

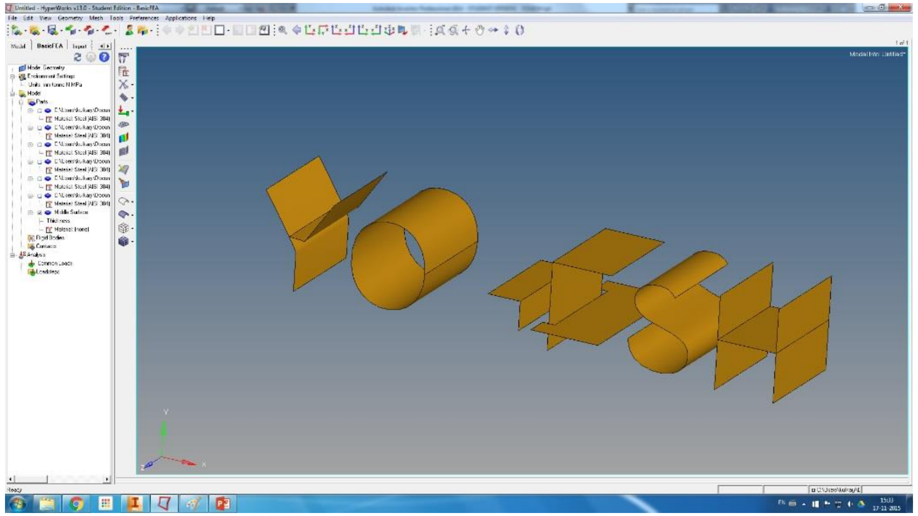


Commercial Midsurface

- CAD : Unigraphics NX, Inventor
- CAE : Hypermesh, MSc Apex
- MA based: Auto + Manual
- Quality issues







Observations from Literature Survey

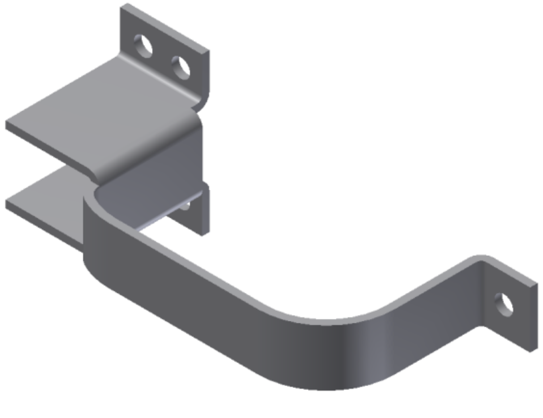
- Most are Brep based and very few leverage feature information
- Model Defeaturing
  - Selection of features to remove depends on domain, analysis type, etc.
  - Most approaches are feature recognition based and size based.
  - Feature based deterministic approaches are less, and they still use size criterion
  - Size based use full feature dimensions
- Midsurface Generation:
  - Formal approaches: any shape but need post processing
  - Heuristic approaches: More practical, but complexities in Pair detection, Joining
- Limited in the range of
  - input model geometries (say, only planar or analytic surfaces),
  - feature types (say, only extruded, positive primitives) and
  - connection types (say, only, parallel, or perpendicular)

Research Objectives

- To develop a system to generate a quality midsurface of feature based CAD model.
- To develop defeaturing algorithms to simplify CAD feature model while retaining the gross shape.
- To develop algorithms to transform existing sheet metal features to a finite set of generalized features.
- To develop algorithms for generating quality midsurfaces leveraging generalized feature based CAD model and cellular decomposition covering a wide variety of topological connectivities.
- To come up with an approach to topologically validate the generated midsurface.
- To implement a software system incorporating above algorithms and demonstrate the efficacy of the proposed approach.

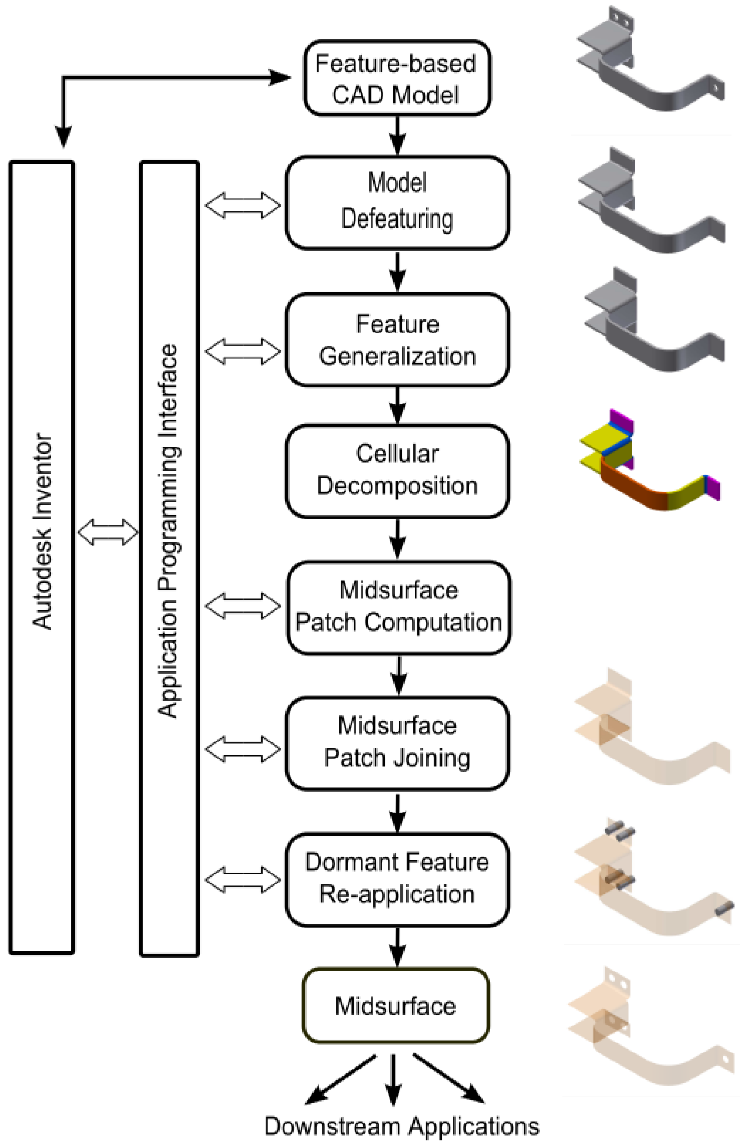
Research Scope

- Sheet Metal Parts: 40% Manufacturing parts
- Thin-walled Constant Thickness parts
- Feature based Autodesk Inventor CAD models



Proposed System - MidAS

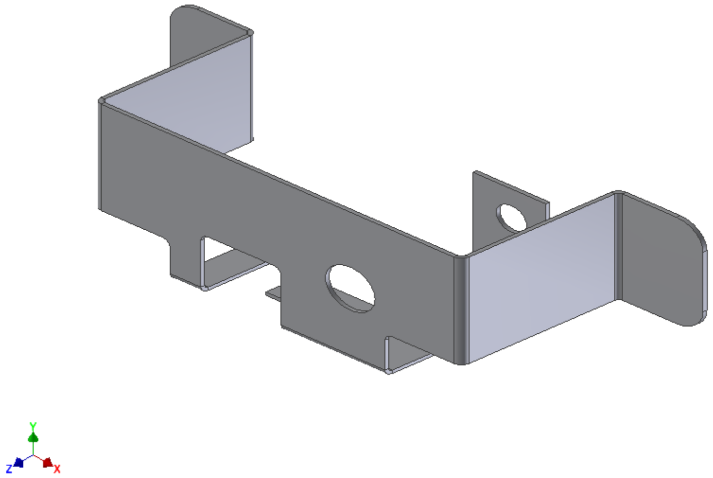
- Input: Feature based Autodesk Inventor CAD Model
- Each step, a module, OO Interfaces
- Model Defeaturing
- Feature Generalization
- Cellular Decomposition
- Midsurface Patch generation (incl Midcurve Computation)
- Dormant Features Reapplication
- Output: Midsurface

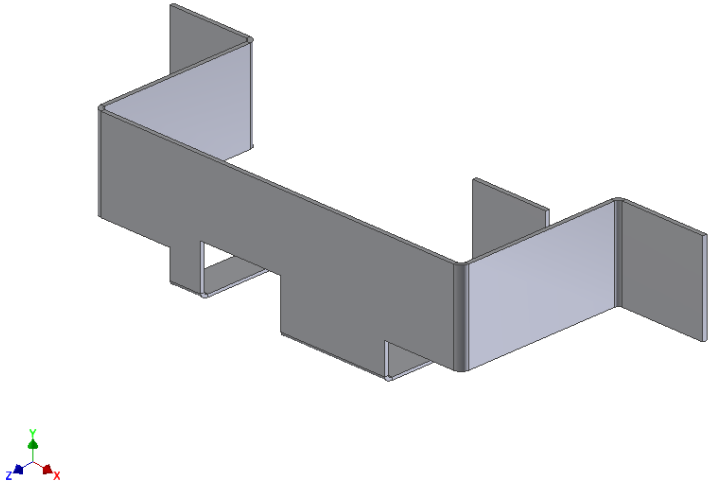


Model Defeaturing

Proposed Approach

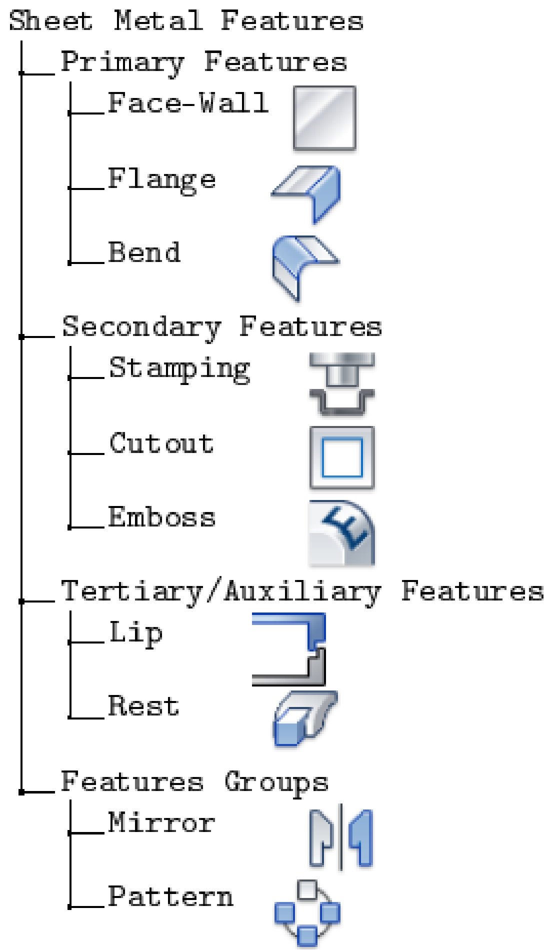
- Need: More features, difficult computation
- Objective: Remove irrelevant features, but retain gross shape
- Phase I: Sheet Metal Features Taxonomy based
- Phase II: Remnant Feature Size based
- Phase III: Dormant feature based





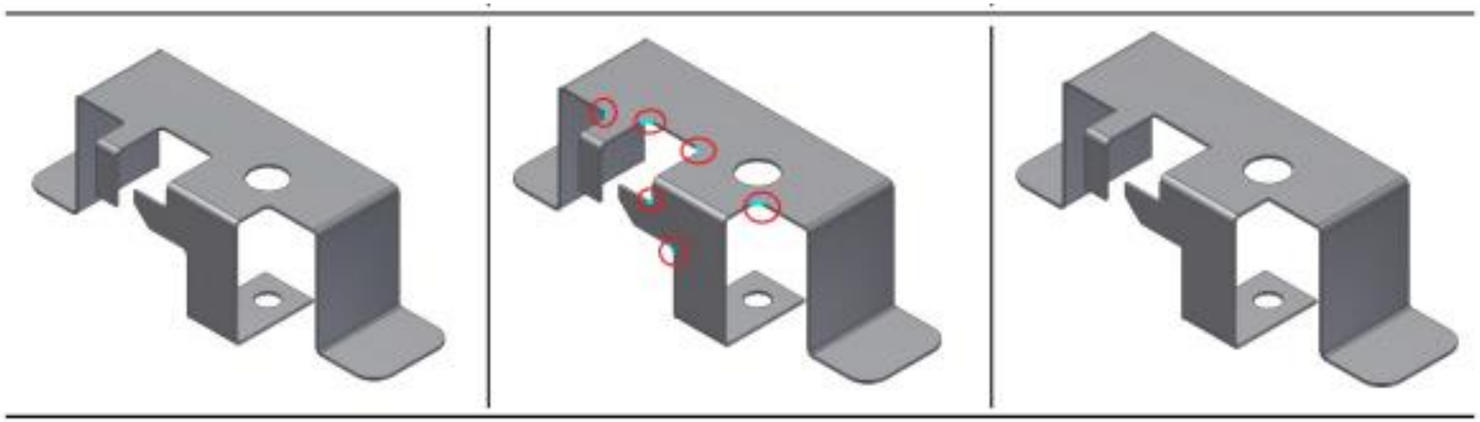
Sheet Metal Features Taxonomy

- Sheet metal features classified into categories .
- Primary (**P**) : Principal. Relevant.
- Secondary (**S**): Relevant if > Threshold.
- Tertiary/Auxiliary (**T**): Superficial. Irrelevant.
- Feature Groups (**G**): Collections Relevant if > Threshold.



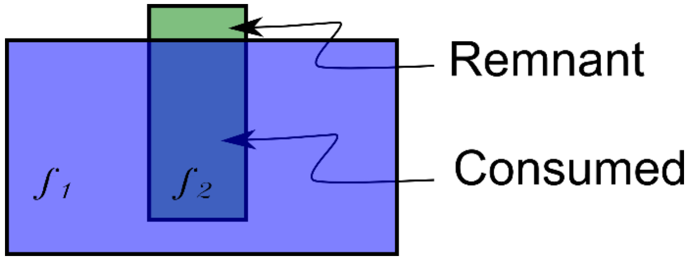
Phase I : Defeaturing based on Sheet Metal Feature Taxonomy

- Identification based on Taxonomy
- Primary features: Cannot be removed as they directly affect the gross shape
- Secondary and Group features: Removed if their sizes are below the threshold
- Tertiary features: Removed irrespective of their sizes



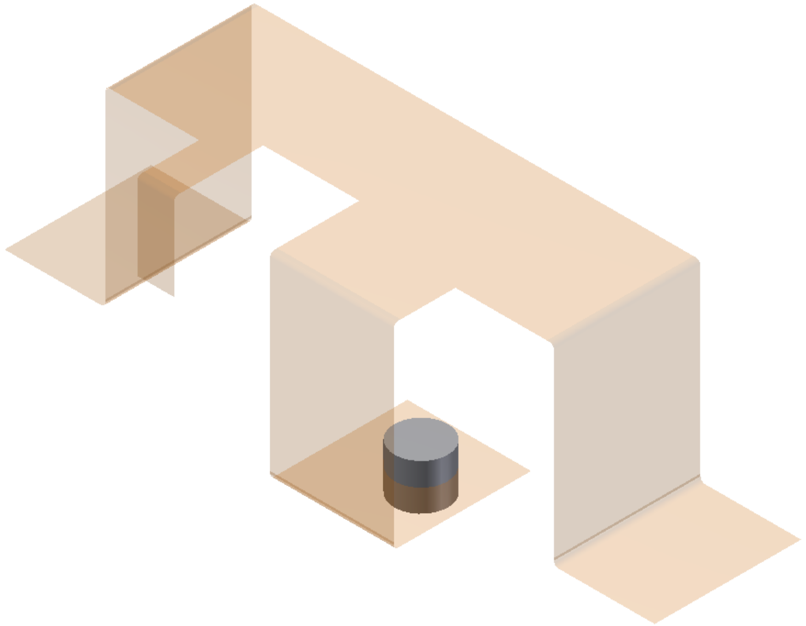
Phase II : Defeaturing based on Remnant Feature Size based

- Features when booleaned, are consumed
- Erroneous if defeaturing decision is based on full feature dimensions
- Approach to detect and compute size of the remnant size of features
- Size criterion: summation of face areas



Phase III : Defeaturing based on Dormant features

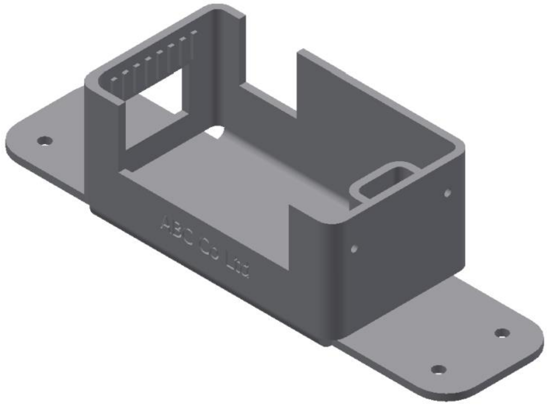
- Large Negative but relevant features
- Hindrance to midsurface computation
- Tool bodies cached
- Re-applied after Midsurface computation

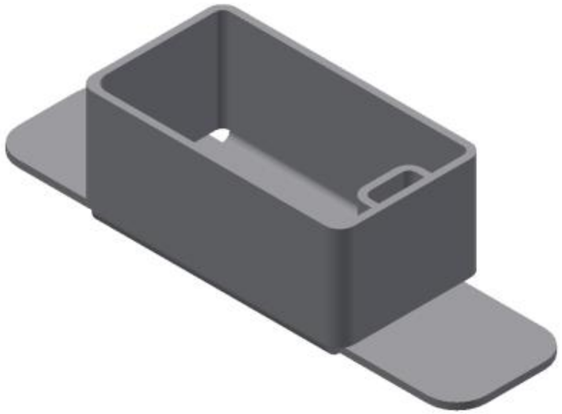


Effectiveness of Model Defeaturing

Metrics: Percentage reduction in the number of faces.

$$pR = (1 - \frac{rF}{nF}) \times 100$$





$$pR = (1 - \frac{64}{259}) \times 100 = 75.29\%$$

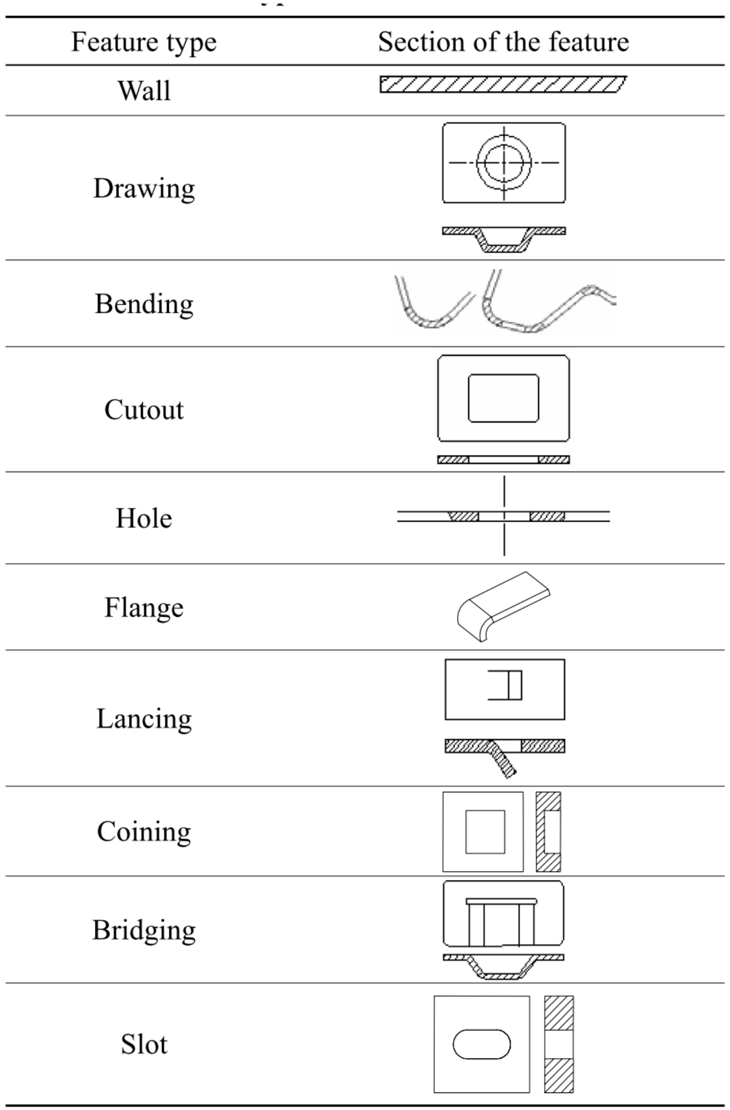
Summary: Model Defeaturing

- Limitations of existing approaches:
  - Feature Recognition unreliable
  - Dominance of size based selection
  - Wrong size computation
  - Loss of negative relevant features
- Contributions
  - Sheet Metal Features Taxonomy based Approach
  - Remnant Feature Approach
  - Dormant Feature Approach
  - Effective reduction in Features/faces, while retaining the Gross Shape

Feature Generalization

Proposed Approach

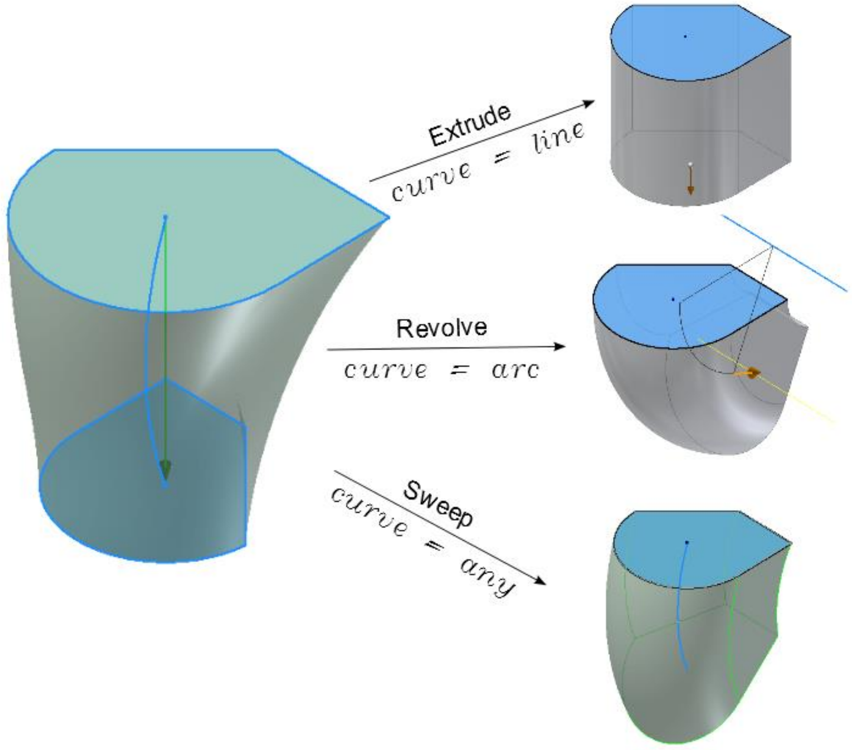
- Need: Presence of a large variety of types of features
- Challenging to develop feature based algorithms
- Proposed: New CAD representation with Loft as genialized feature form
- Objective: To transform given feature tree to generalized feature tree
- No loss of ‘feature’-ness
- No loss of re-generation



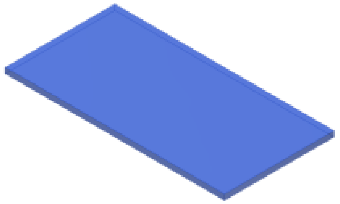
Proposed New Form Features

- ABLE:
  - Affine Transformations
  - Booleans
  - Lofts
  - Entities
- CAD model as list of ABLE entities

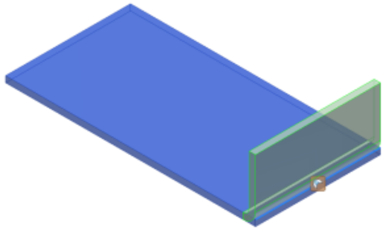
$$\Omega\mathcal{L}^{subtype,3}[\{0, guide, 0|C_{0,1,2}\}((sketch)^{<1-n>})]$$



Wall - Loft equivalent

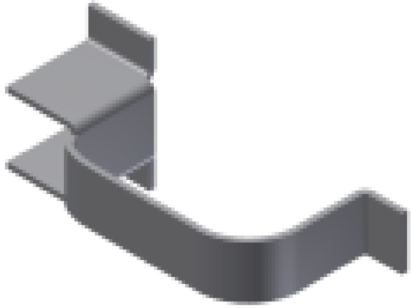
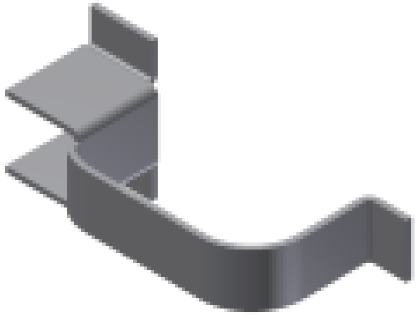
	**Face, Wall**	**Extrude** is created by extracting *sketch* of the "Wall" feature and giving sheet metal thickness as the distance for extrusion. $\Omega\mathcal{L}^{EnD,3}[\{0, thickness, 0\|C_0\}((sketch)^{<1>})]$ Where, $sketch = \Pi\mathcal{C}^{S,1}[\{\}(profile)^{<1><2-n>})]$ $profile = \Pi\mathcal{C}^{P,1}[\{0, 0, C_{0\|1\|2}\}(curve)^{<1-n>})]$ $curve = \Omega\mathcal{L}^{C,1}[\{0, 0, C_{0\|1\|2}\}(\bar{s})^{<1-n>})]$

Flange - Loft equivalent



	Flange	**Sweep** is created by creating *guide* using bend radius, offset distance and a planar rectangular profile as *sketch*. $\Omega\mathcal{L}^{SnD,3}[\{0, guide, 0 \vert C_0\}((rectangle)^{<1>})]$

Transformation to ABLE

CAD Features	Model	$\mathcal{ABLE}$ Features	Model
SheetMetal_Simple_UBracket2Sides_defeat Folded Model View: Master Origin Contour Flange2 Flange6 Flange7 Flange10 Flange11 End of Folded		SheetMetal_Simple_UBracket2Sides_able.ipt Folded Model View: Master Origin Extrusion2 Sweep1 Sweep2 Sweep3 Sweep4 End of Folded	

Transformation in ABLE representation

- $Extrusion2 = \Omega\mathcal{L}^{EnD,3}[\{0, edge1, 0|C_0\}((sketch1)^{<1>})]$
- $Sweep1 = \Omega\mathcal{L}^{SnD,3}[\{0, guide1, 0|C_0\}((sketch2)^{<1>})],$
  $\Omega\mathcal{B}^{U,3}[\{\}(model, Sweep1)]$
- $Sweep2 = \Omega\mathcal{L}^{SnD,3}[\{0, guide2, 0|C_0\}((sketch3)^{<1>})],$
  $\Omega\mathcal{B}^{U,3}[\{\}(model, Sweep2)]$
- $Sweep3 = \Omega\mathcal{L}^{SnD,3}[\{0, guide3, 0|C_0\}((sketch4)^{<1>})],$
  $\Omega\mathcal{B}^{U,3}[\{\}(model, Sweep3)]$
- $Sweep4 = \Omega\mathcal{L}^{SnD,3}[\{0, guide4, 0|C_0\}((sketch5)^{<1>})],$
  $\Omega\mathcal{B}^{U,3}[\{\}(model, Sweep4)]$

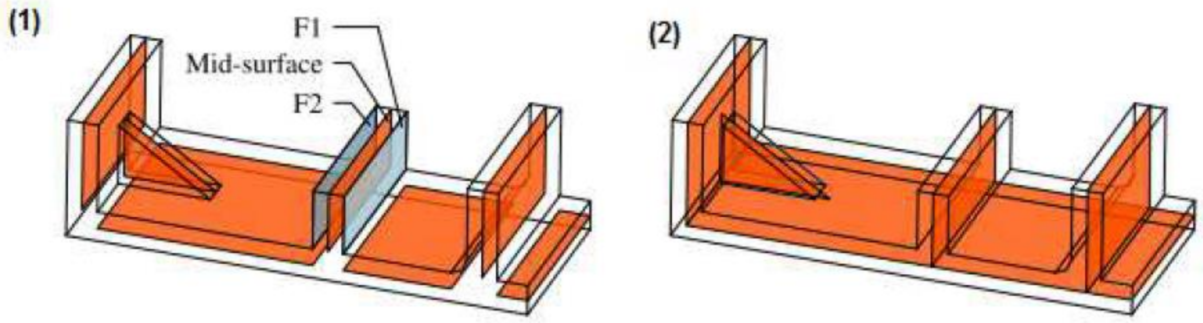
Summary: Feature Generalization

- Limitations of existing approaches:
  - Plethora of feature types
  - Lack of generic notation for CAD features/entities
- Contributions:
  - New representation scheme for Feature-based CAD
  - Loft as generalized feature form
  - Sheet Metal features as Lofts

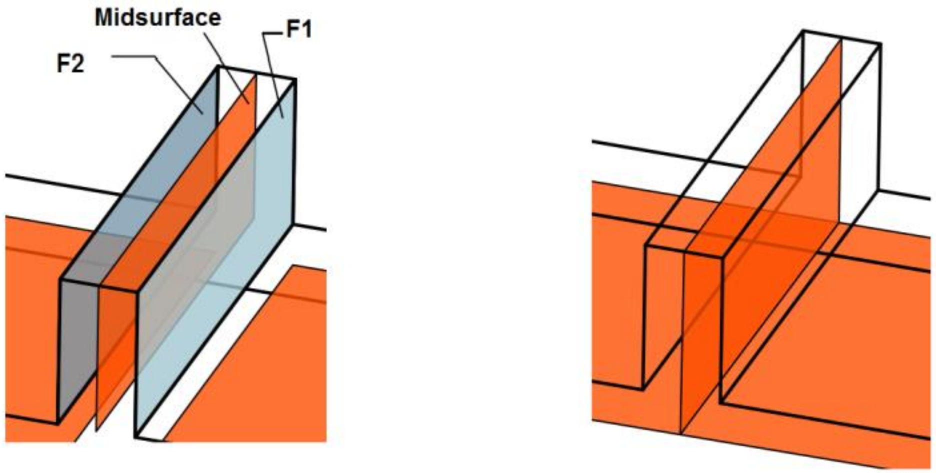
Midsurface Generation

Existing Approach - MA

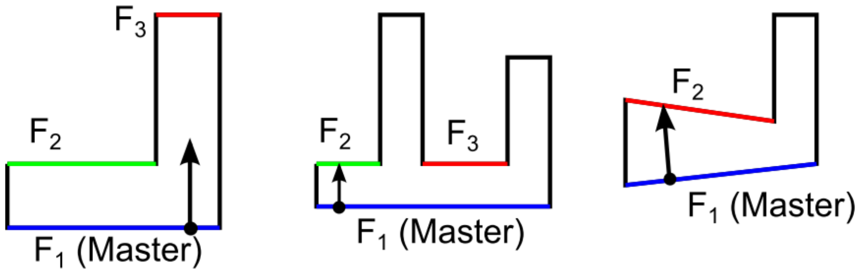
- Limitations
  - Face Pairing challenges
  - Patch Joining challenges
- Proposed Cellular decomposition
- Cell classification, delegation



(a) Full model view

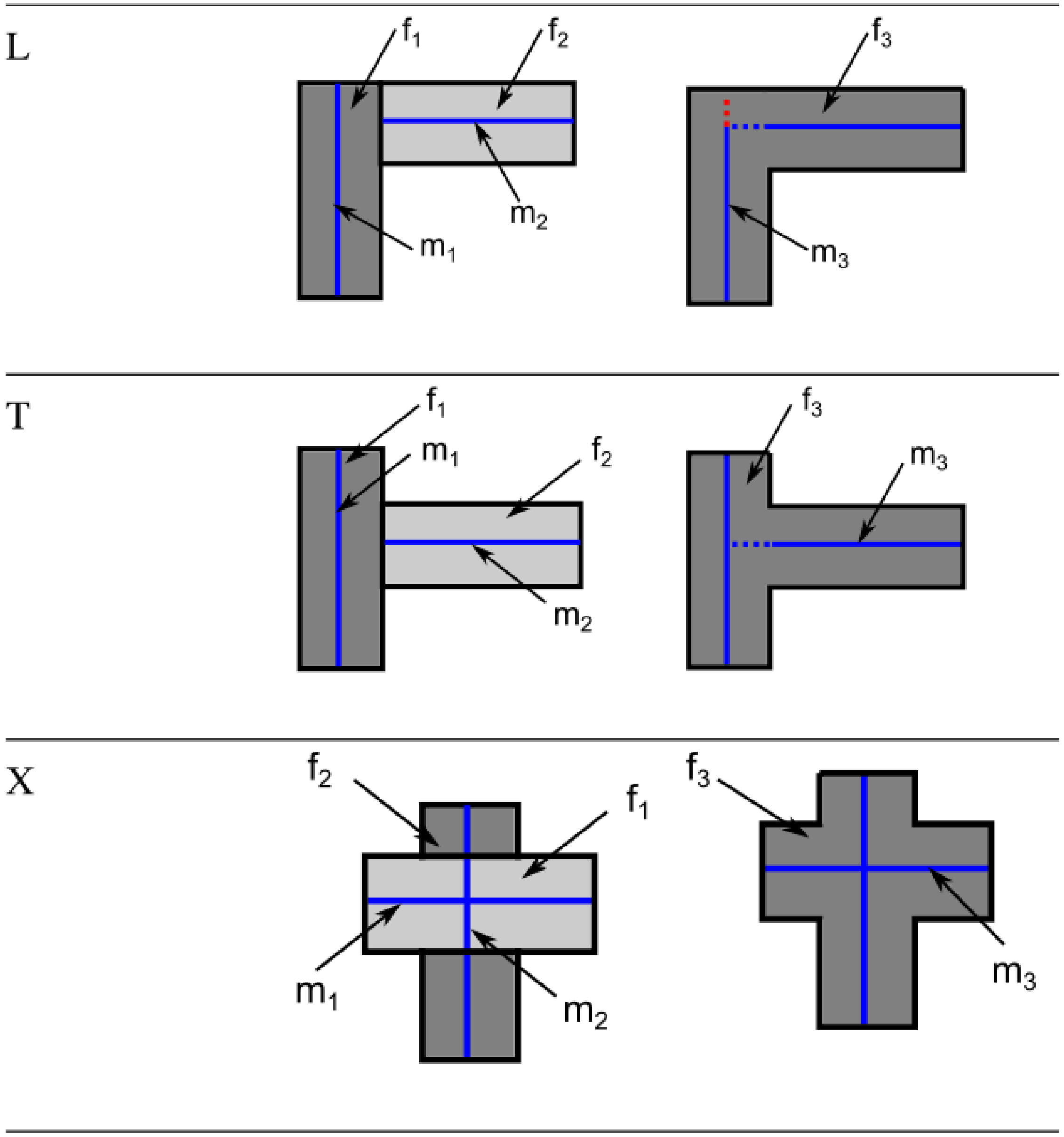


(b) Magnified view



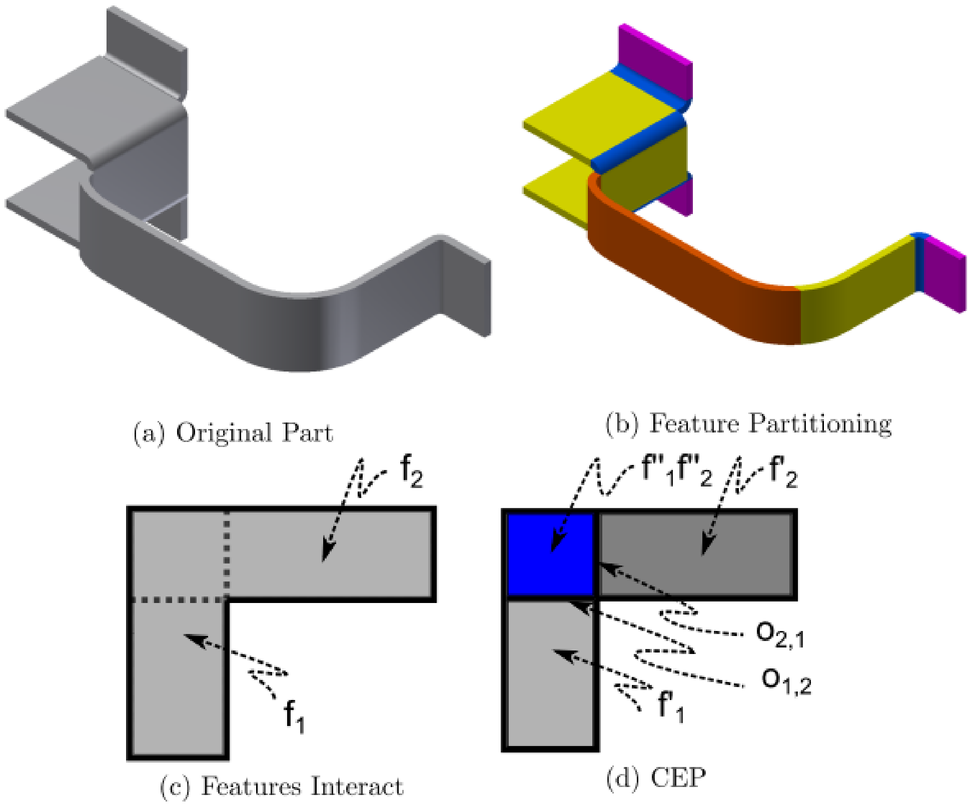
(a) Missing target (b) Multiple targets (c) Angled targets

Interface Configurations



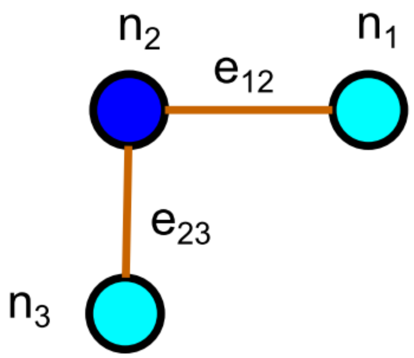
Feature-based Cellular Decomposition

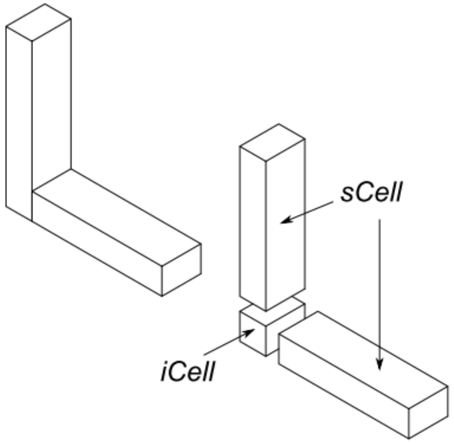
- Features Boolean types are changed from Union to “New”
- Concave Edge partitioning in the feature influence zone.
- Result:
  - non overlapping cells with feature owners
  - Face interface between cells
- Graph: Cells at nodes and overlapping faces at edges
- Classification:
  - Solid Cells (Scells)
  - Interface Cells (iCells)



Proposed Approach

- Graph to bring connectivity information
- Makes overall complexity of original part irrelevant
- Rules:
  - sCells compute Midsurface patches
  - iCells join incident midsurface patches
- Delegation of computation
- Generic and not type spec

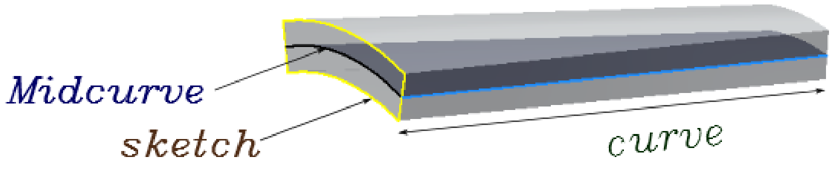


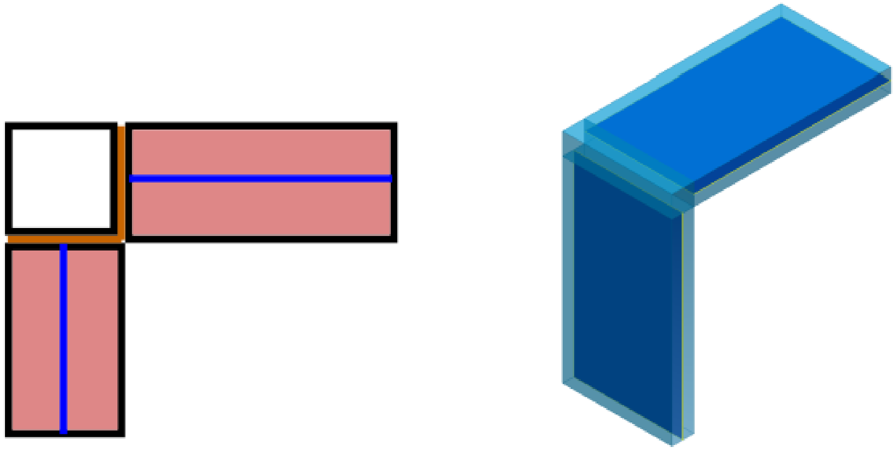


- $n_1 = sCell_1 = f'_1$
- $n_2 = iCell_1 = f''_1 f''_2$
- $n_3 = sCell_2 = f'_2$
- $e_{12} = O_1$
- $e_{23} = O_2$

Midsurface Patches in Solid Cells

- Two cases
  - **Offset**: profile >> guide : offset the profile face
  - **Midcurve**: profile << guide: compute midcurve, sweep



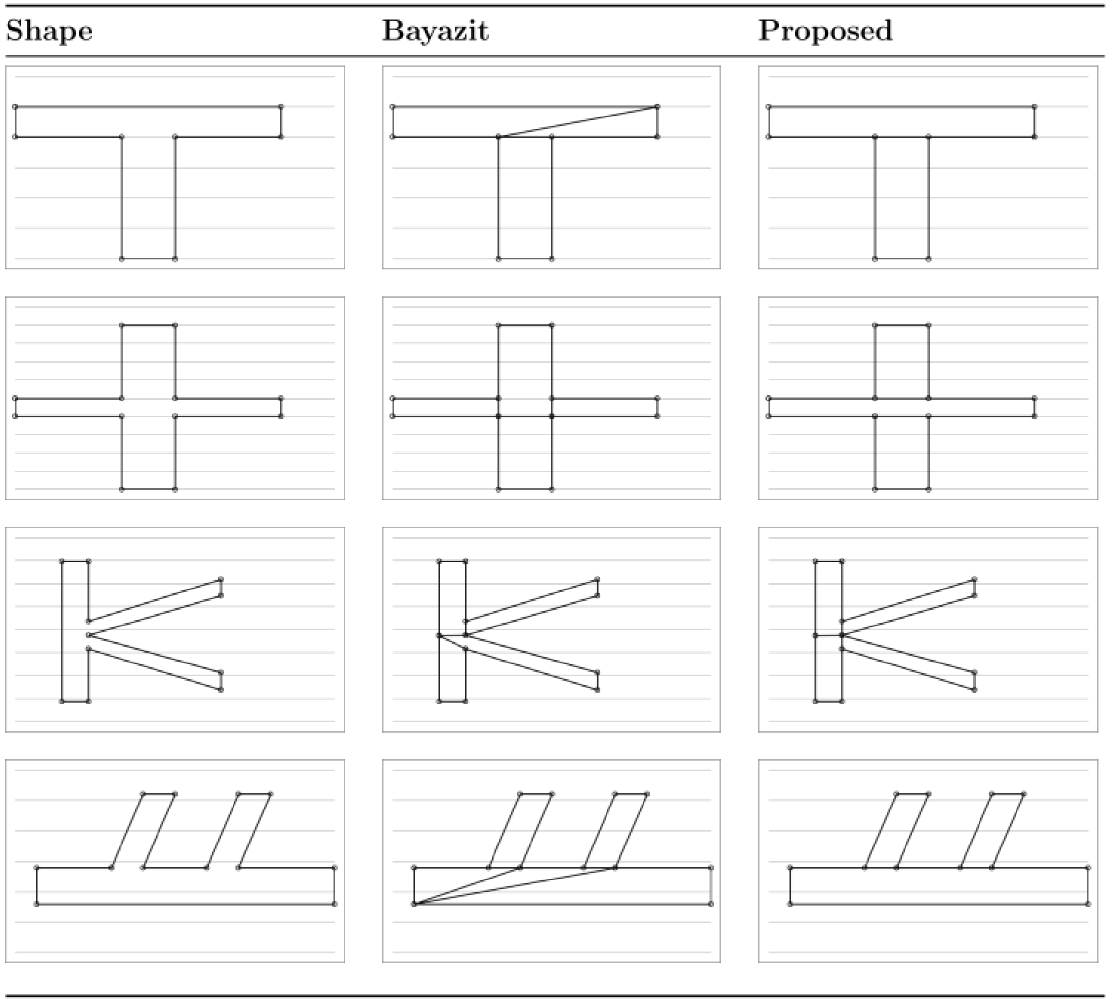


(a) Patches, 2d view (b) Patches, 3d view

Generation of Midcurve

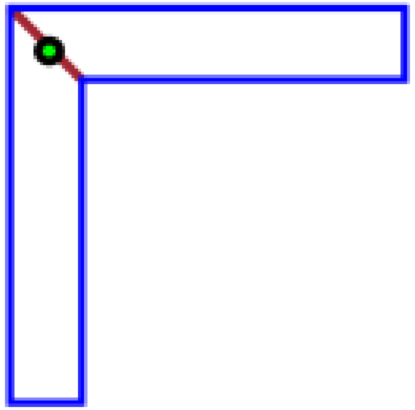
- Partition given shape into sub-shapes
- Midcurves can be generated for each sub-shape.
- Such individual Midcurves are joined

Polygon Decomposition

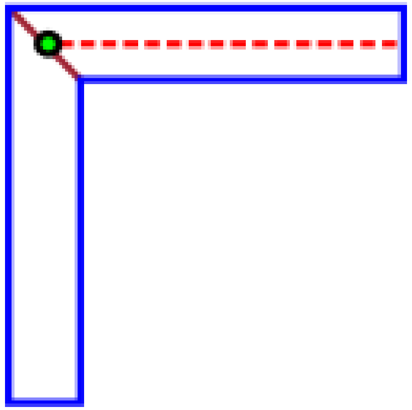


Midcurve Computation

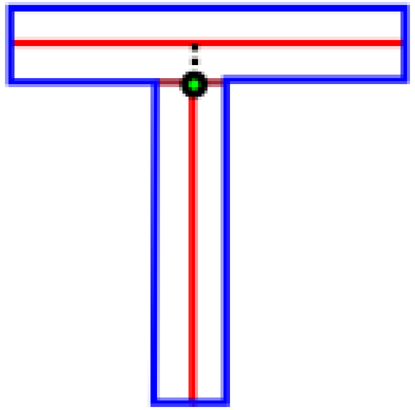
Each partitioning edge inserted during the decomposition is called as a 'chord'.



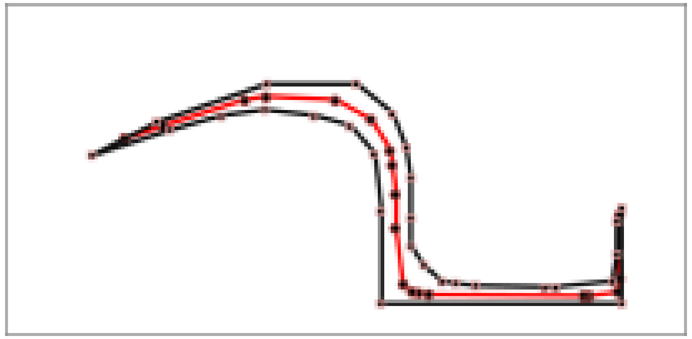
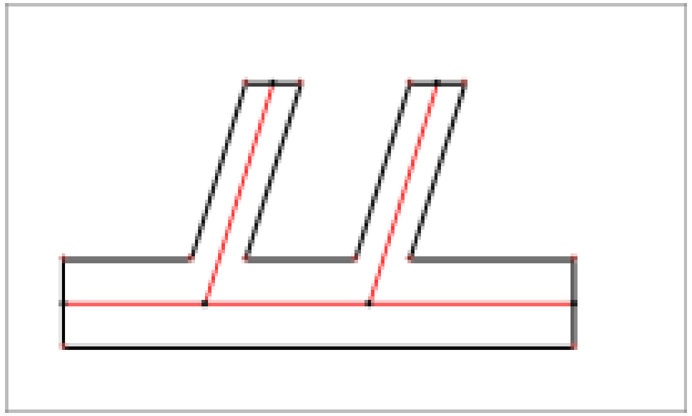
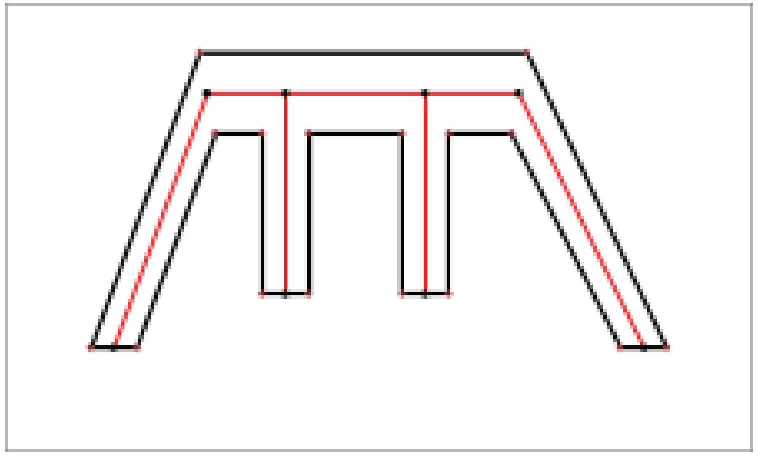
Midcurves are generated for individual polygons that are longer lengthwise on both sides of the 'chord'.



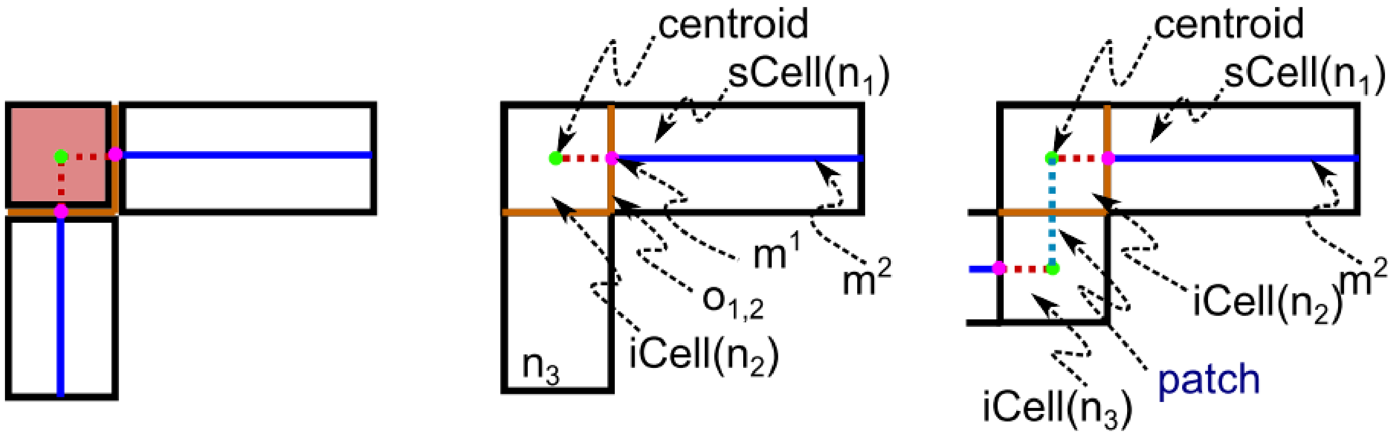
When curves do not meet at the chord', they are extended upto the midcurve.



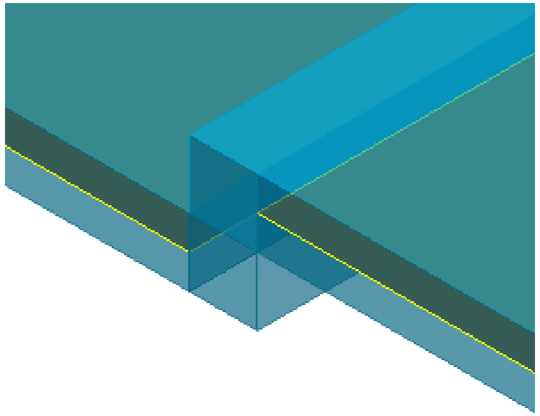
Results

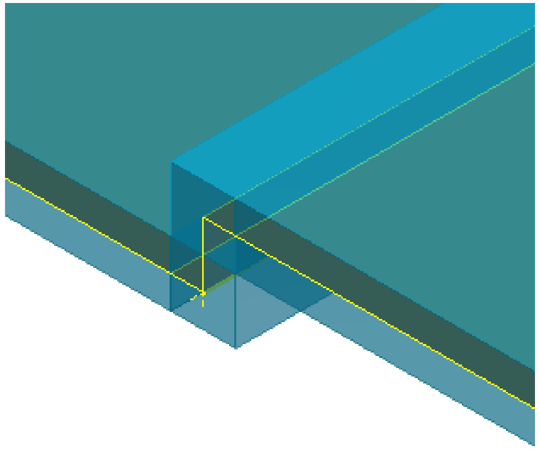
Glass profile by Fischer [11].	Profile by Ramanathan [24].	Plastic Part profile by Sheen [29].
		

Connecting Patches

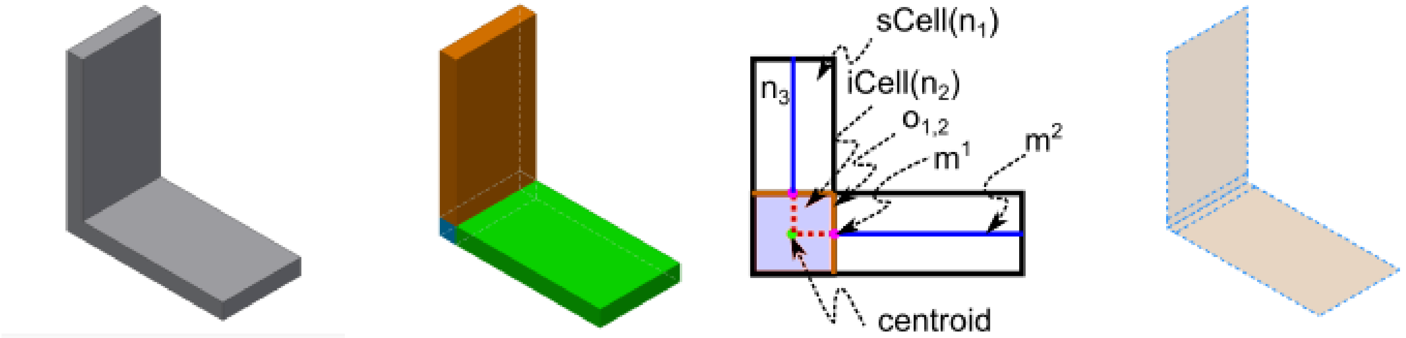


(a) Expected adjustments (b) $sCell - iCell$ scenario (c) $iCell - iCell$ scenario



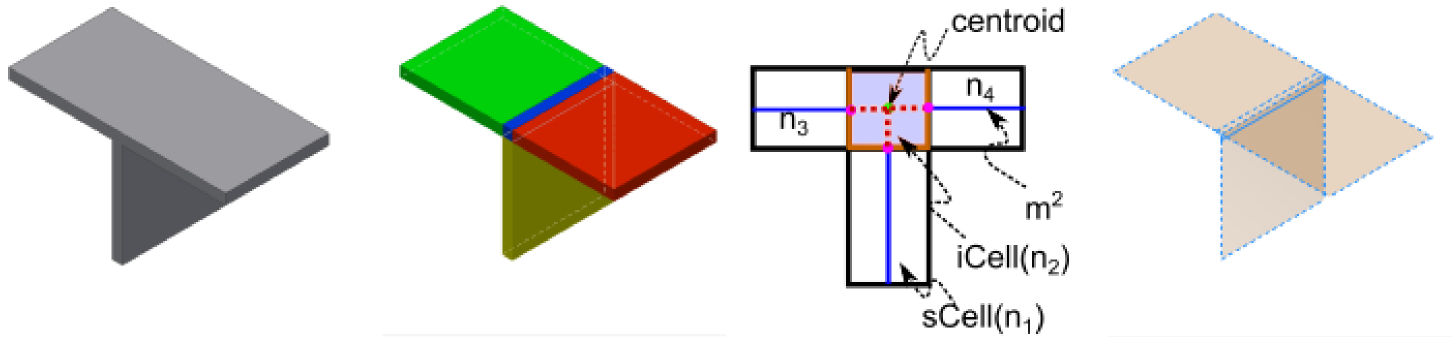


Connection Scenarios

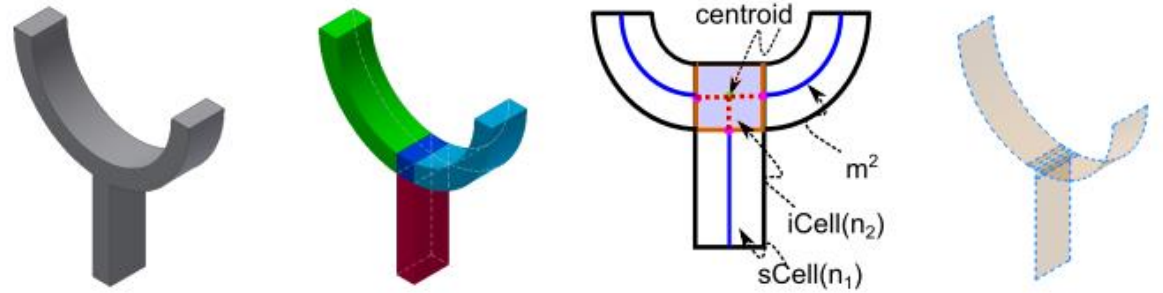


(a) Model (b) Decomposition (c) 2 *sCells*, 1 *iCell* (d) Midsurface

Figure 16: Midsurface for L Model

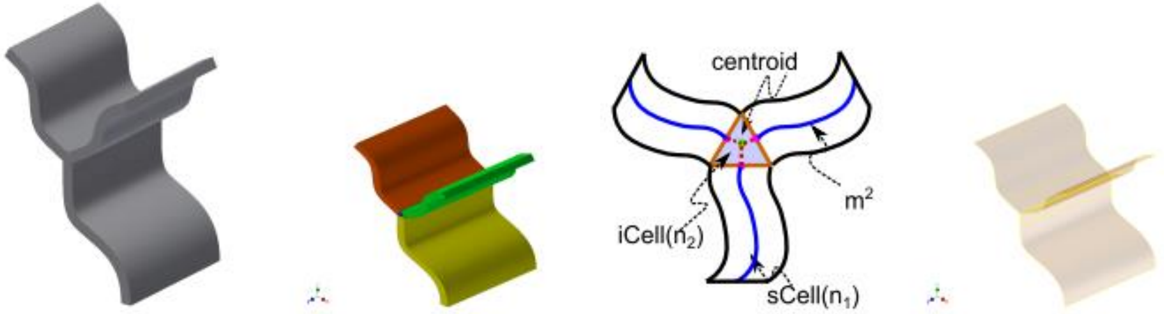


(a) Model (b) Decomposition (c) 3 *sCells*, 1 *iCell* (d) Midsurface



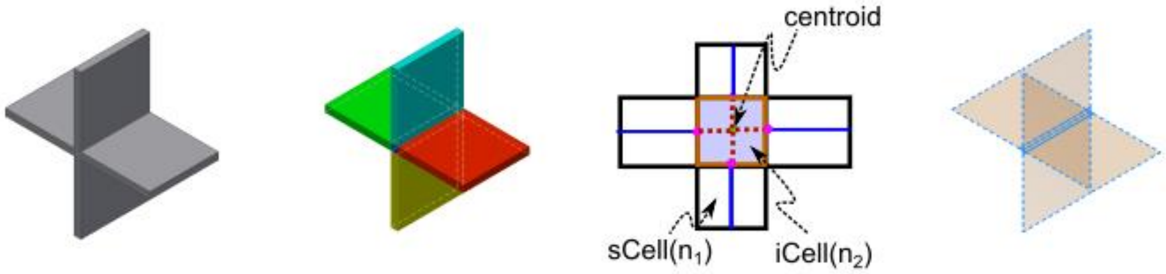
(a) Model (b) Decomposition (c) 3 *sCells*, 1 *iCell* (d) Midsurface

Figure 18: Midsurface for Curved Y Model



(a) Model (b) Decomposition (c) 3 *sCells*, 1 *iCell* (d) Midsurface

Figure 19: Midsurface for Wavy Model

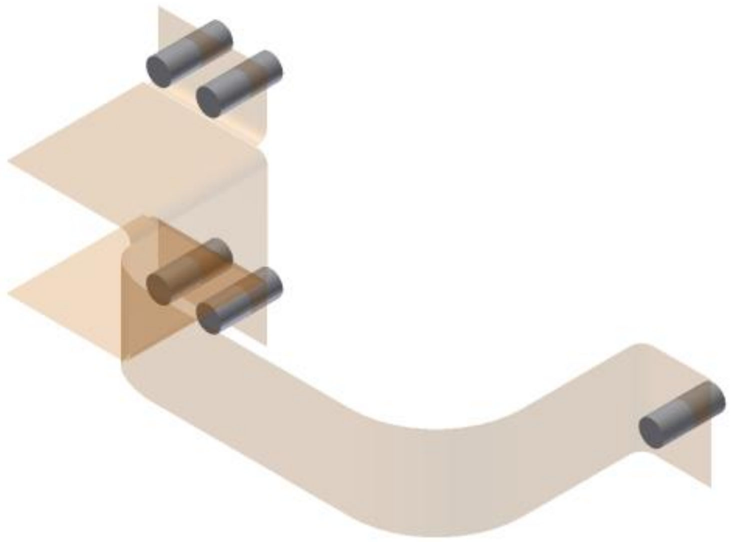


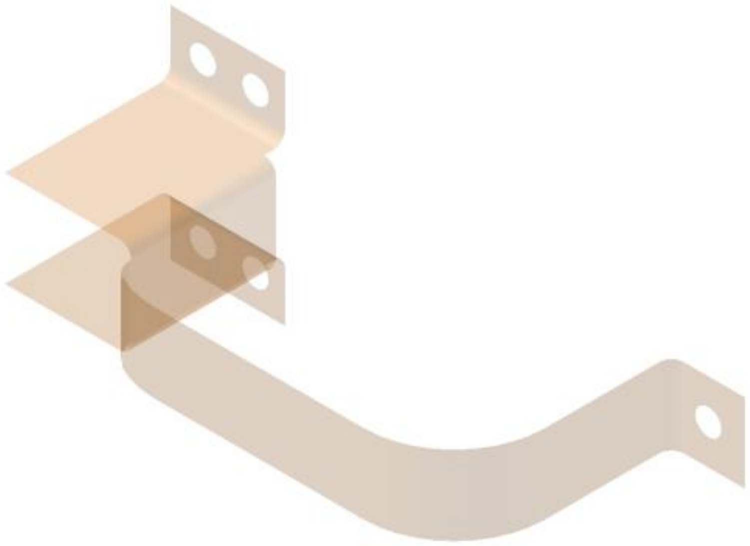
(a) Model (b) Decomposition (c) 4 *sCells*, 1 *iCell* (d) Midsurface

Summary: Midsurface Generation

- Limitations of existing approaches:
  - Post processing in formal approaches
  - Face pair detection and Patch Joining problems
  - Manual corrections
- Contributions:
  - Feature based Cellular Decomposition
  - Cellular Graph for connectivity and delegation of computation
  - Midcurve generation using enhanced polygon decomposition and cellular midcurve computation
  - Midsurface by generic rules

Re-application of Dormant Features



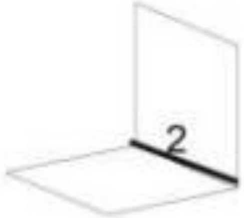
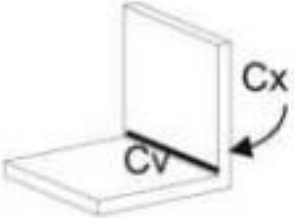
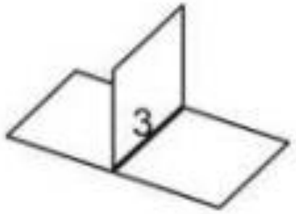
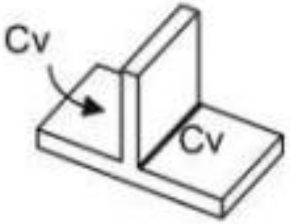
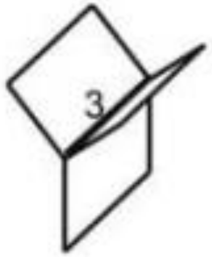
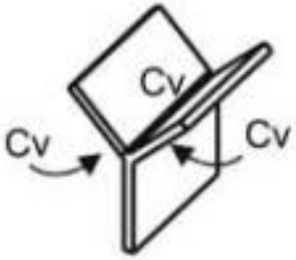


Topological Validation

Validation Types

- Manual Inspection for gaps, errors
- Tools based inspection: Hausdorff distance.
- Recent: Topological Validation: Measures topological entities of the midsurface match with the ones predicted.

Topological Validation by Lockett

L-Junction			2	1	90	0	2
3-way (T)			2	2	180	1	3
3-way (Y)			3	3	360	0	3

Approaches for Topological validation

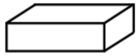
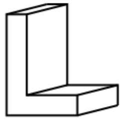
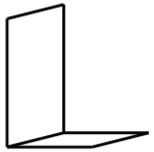
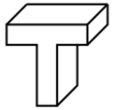
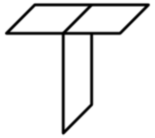
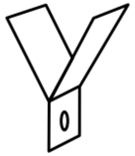
Solid-to-Surface

- Find relationship between topological entities of a thin-solid and its corresponding Midsurface.
- See if the predicated Midsurface entities validate the non-manifold equation

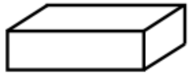
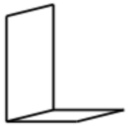
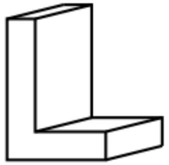
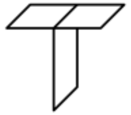
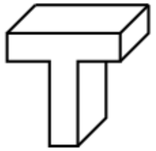
Surface-to-Solid

- Predict the topological entities of possible thin-wall solid that would be source of the given Midsurface.
- These predicted entities can be validated against entities of the original thin-solid as well as with the manifold equation

Solid to Surface

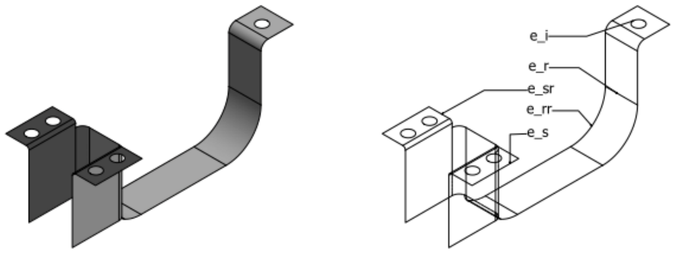
Solid	Midsurface	Solid Cells	Midsurface Cells	Predicted Topological Entities
		$sCell_0^3$	$mCell_0^2$	$1f+(4-0)e+(4-2\times 0)v = 1f+4e+4v$
		$2\times sCell_1^3 + iCell_2^3$	$2\times mCell_1^2 + mCell_2^1$	$2\times(1f+(4-1)e+(4-2\times 1)v) + (1e+2v) = 2f+7e+6v$
		$3\times sCell_1^3 + iCell_3^3$	$3\times mCell_1^2 + mCell_3^1$	$3\times(1f+(4-1)e+(4-2\times 1)v)+(1e+2v) = 3f+10e+8v$
		$3\times sCell_1^3 + iCell_3^3 + sCell_h^3$	$3\times mCell_1^2 + mCell_3^1 + mCell_h^2$	$3\times(1f+(4-1)e+(4-2\times 1)v)+(1e+2v)+(1e+1v) = 3f+11e+9v$
		$2\times sCell_1^3 + 2\times iCell_2^3 + sCell_2^3$	$2\times mCell_1^2 + 2\times mCell_2^1 + mCell_2^2$	$2\times(1f+(4-1)e+(4-2\times 1)v)+2\times(1e+2v)+(1f+(4-2)e+(4-2\times 2)v) = 3f+10e+8v$

Surface to Solid

M	f	l_p	e_s	e_{sr}	e_r	e_{rr}	e_i	v_s	v_r	v_i	f_m	e_m	v_m	χ_{m*}	**Solid**
	1	0	4	0	0	0	0	4	0	0	6	12	8	2	
	2	2	2	4	1	0	0	4	2	0	8	18	12	2	
	3	2	3	6	1	0	0	6	2	0	11	27	18	2	
	3	2	3	6	1	0	1	6	2	1	12	30	20	2	
	3	2	2	4	2	2	0	4	4	0	10	24	16	2	

Results

- Solid-Surface: Predict Midsurface entities
- Surface-Solid: Predict Solid entities
- Contribution:
  - New Topological Validation Formulation



(a) Input Midsurface (b) Topological Entities Classification

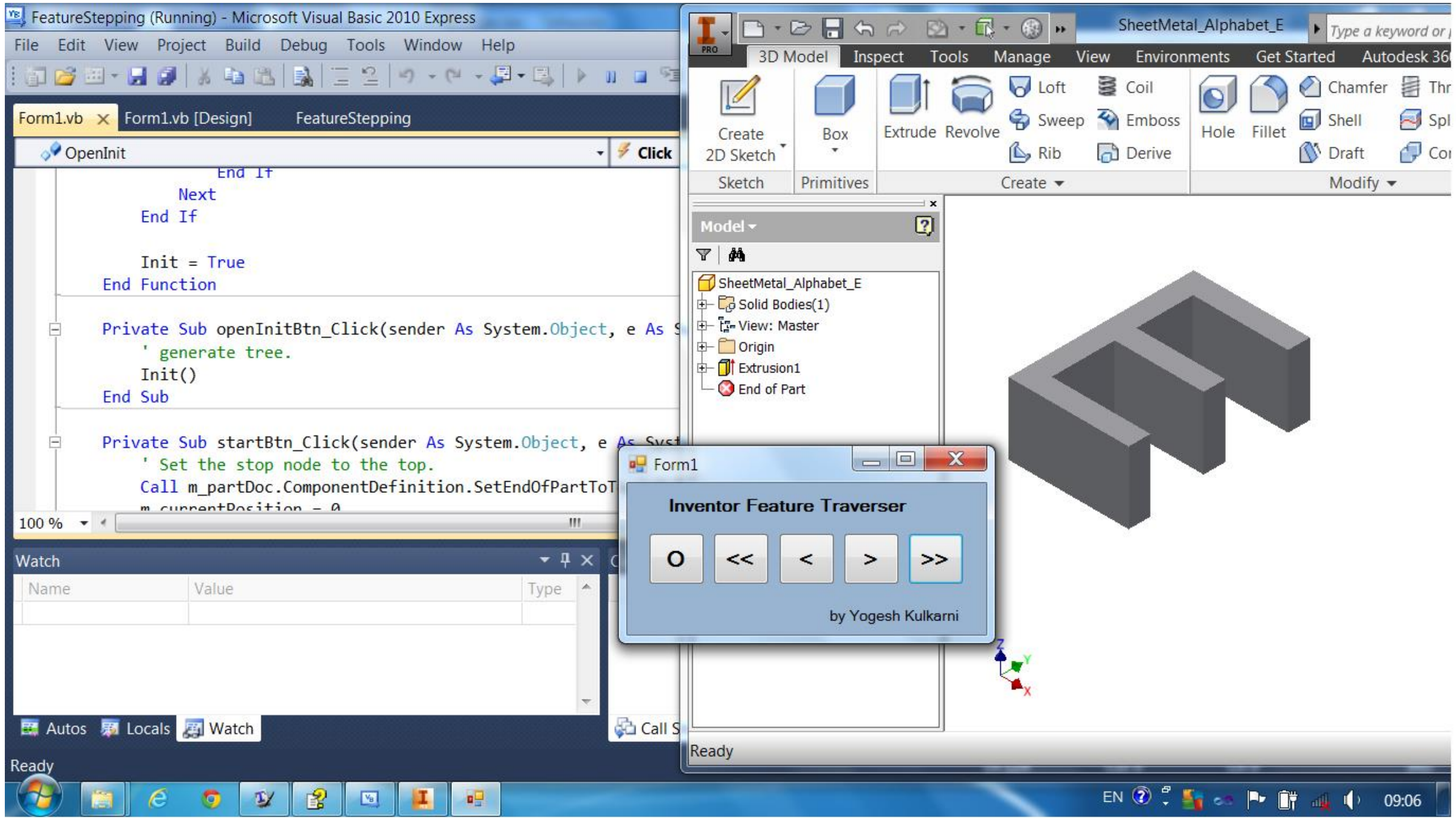
Figure 7.11: Solid to Surface Transformation Approach for Bracket

- **Predicted number of manifold-faces**:
  $f_m = 2f + e_s + l_p + e_i$
  $= 2 \times 15 + 3 + 9 + 5 = 47$
- **Predicted number of manifold-edges**:
  $e_m = 2(e_s + e_{sr} + e_{rr} + e_i) + \sum n_r e_r + v_s + v_i$
  $= 2(3 + 10 + 19 + 5) + (2 \times 12 + 4 \times 2) + 8 + 5 = 119$
- **Predicted number of manifold-vertices**:
  $v_m = 2(v_s + v_i) + \sum n_r v_r$
  $= 2 \times (8 + 5) + 2 \times 24 = 74$
- **Predicted number of manifold-shells-holes**:
  $s_m = s = 1, h_m = r_i = 5, r_m = 2r_i = 10$
- **Input midsurface's non-manifold equation's left side**: χ_{nml}
  $= v - e + f$
  $= 32 - 46 + 15 = 1$
- **Input midsurface's non-manifold equation's right side**: χ_{nmr}
  $= s - h + r$
  $= 1 - 5 + 5 = 1$
- **Solid's manifold equation's left side**: χ_{ml}
  $= v_m - e_m + f_m$
  $= 74 - 119 + 47 = 2$
- **Solid's manifold equation's right side**: χ_{mr}
  $= 2(s_m - h_m) + r_m$
  $= 2(1 - 5) + 10 = 2$

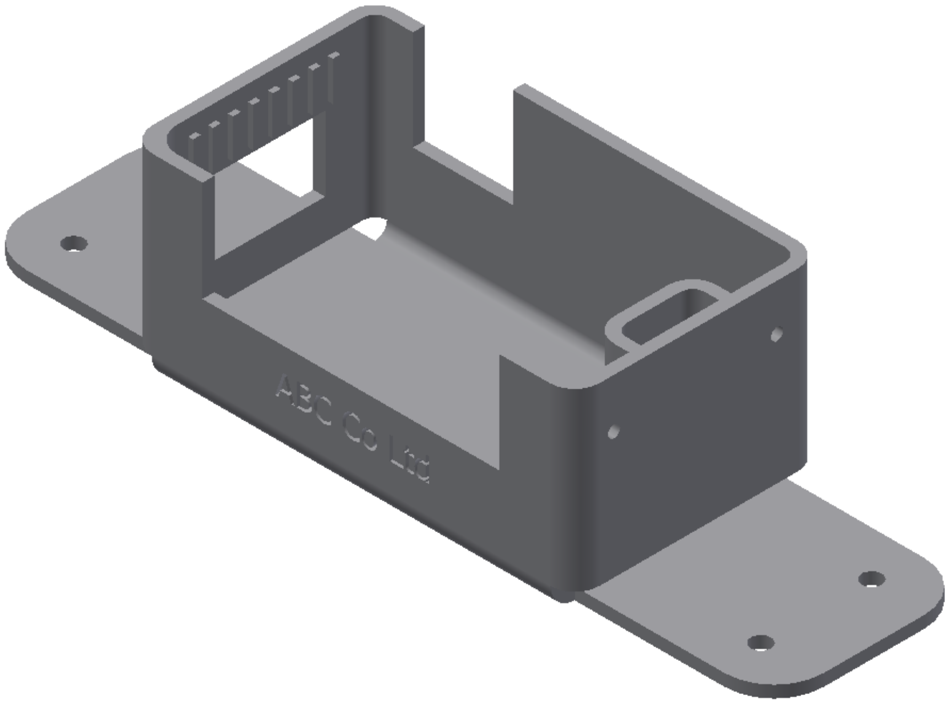
Case studies

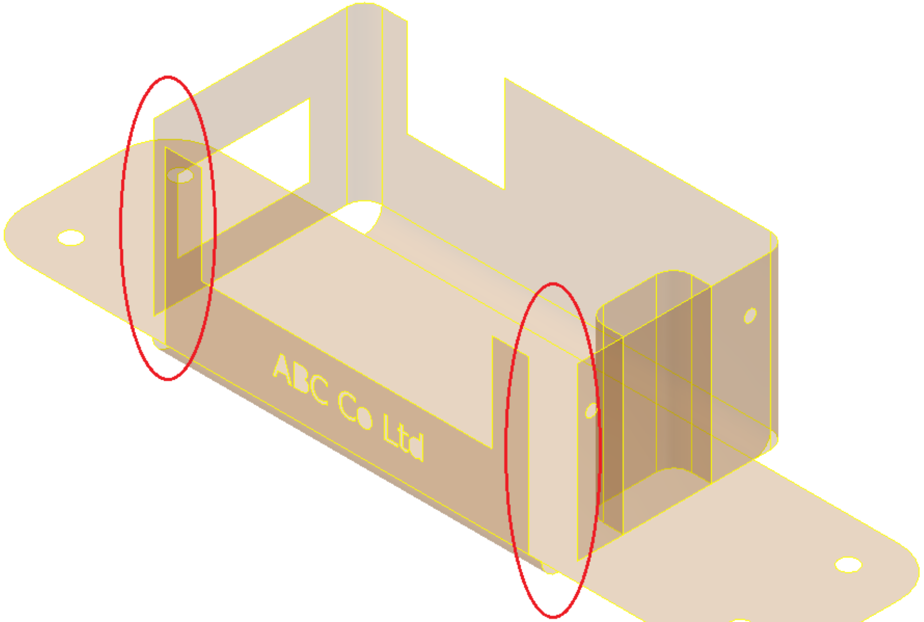
MidAS Implementation

- Inventor Professional 2014 – Student edition
- Feature based 3D modeller based on ACIS kernel
- API support via VB.net

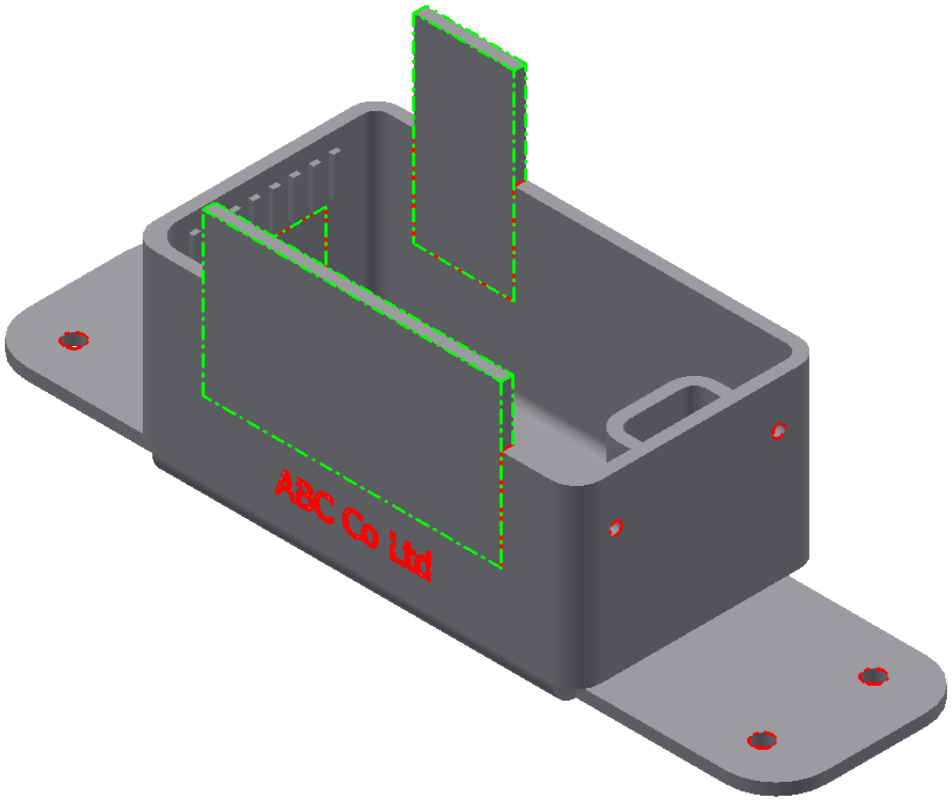


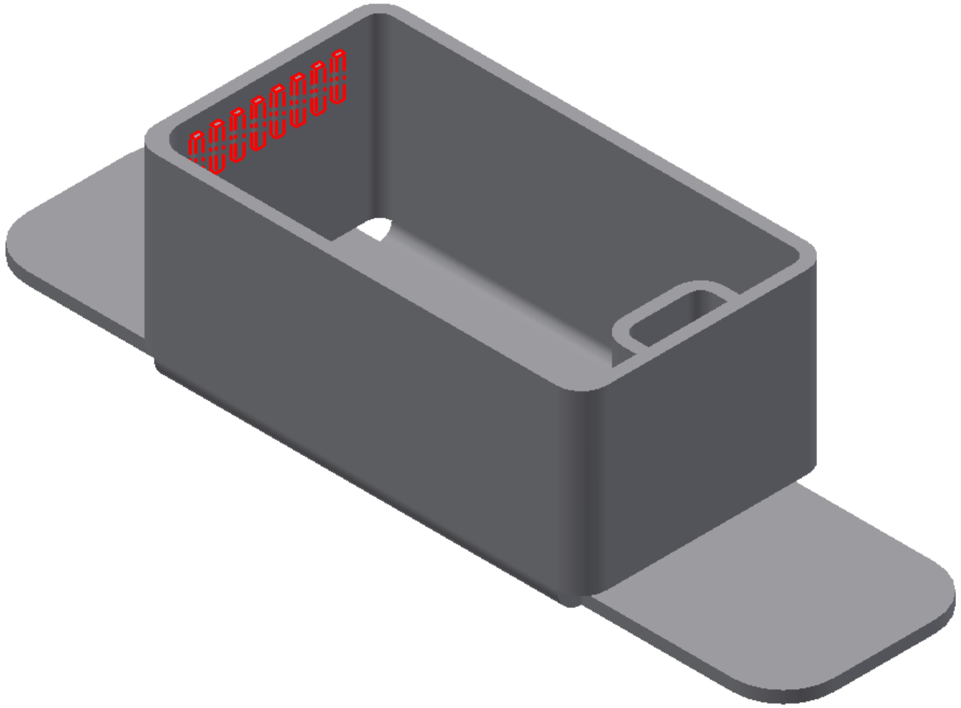
Benchmarking



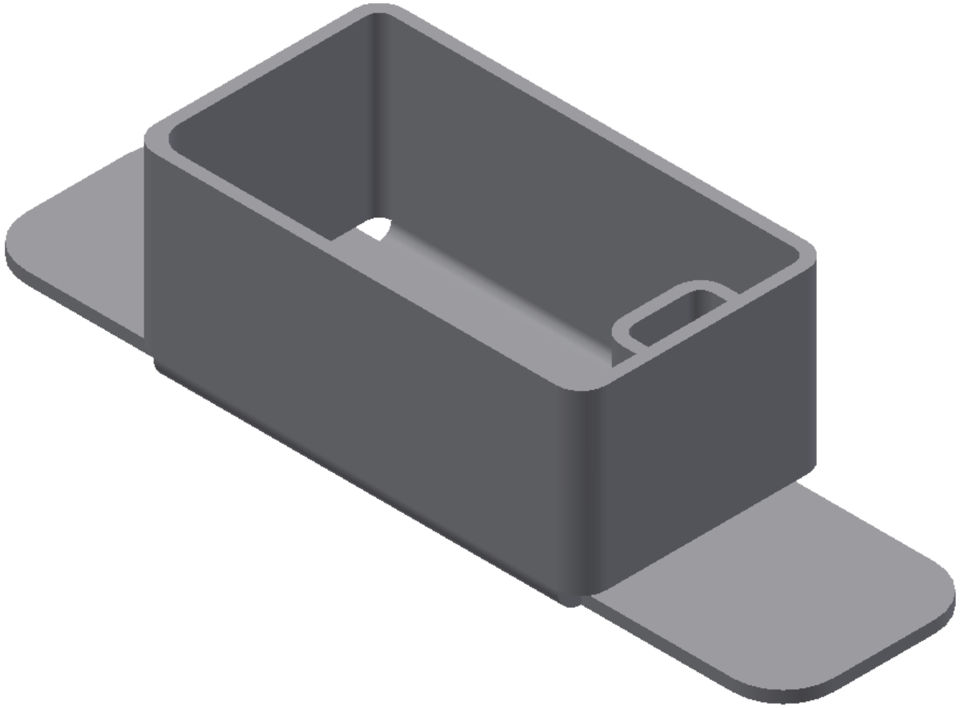


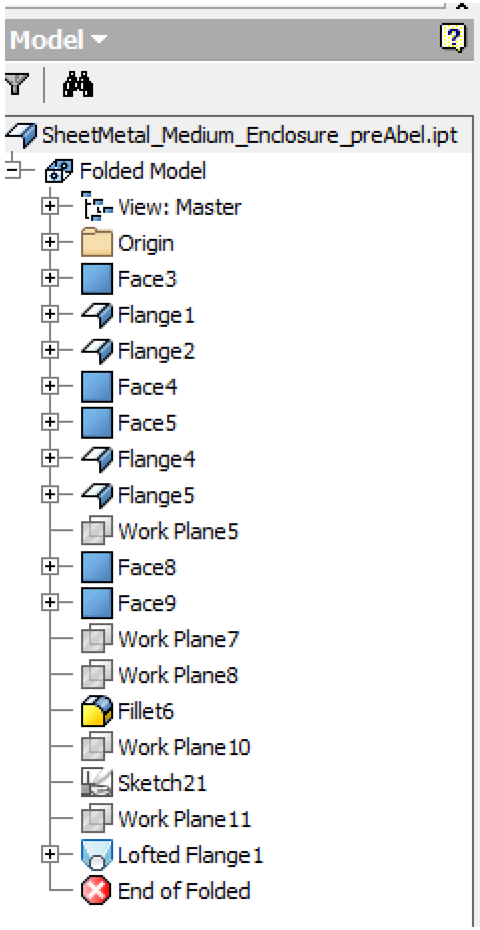
Model Defeaturing

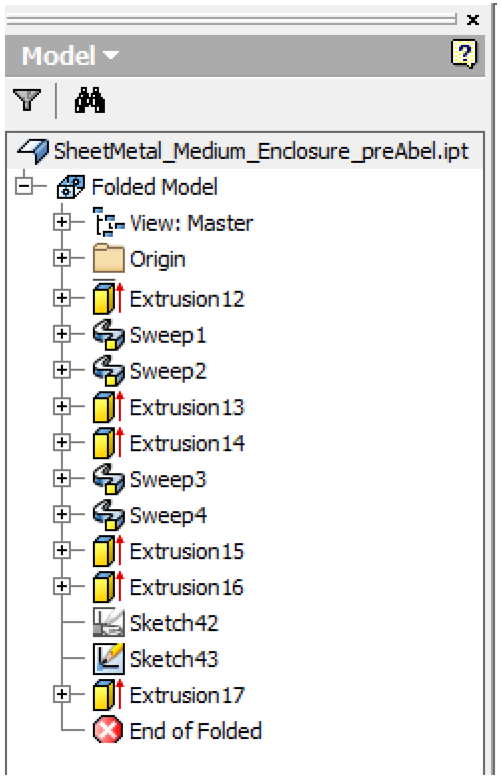




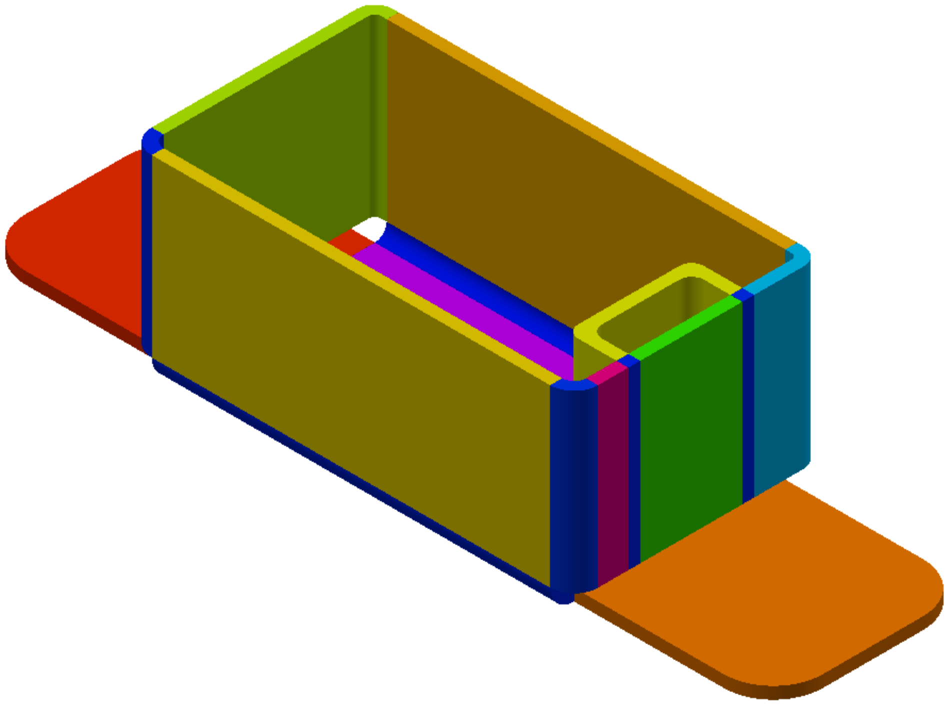
Feature Generalization

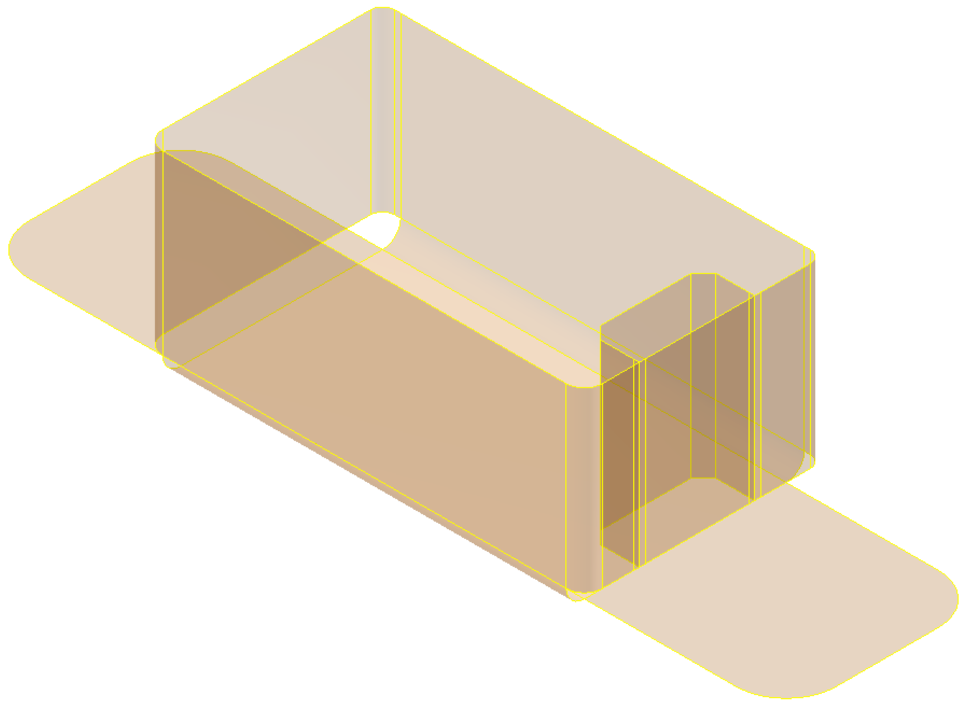




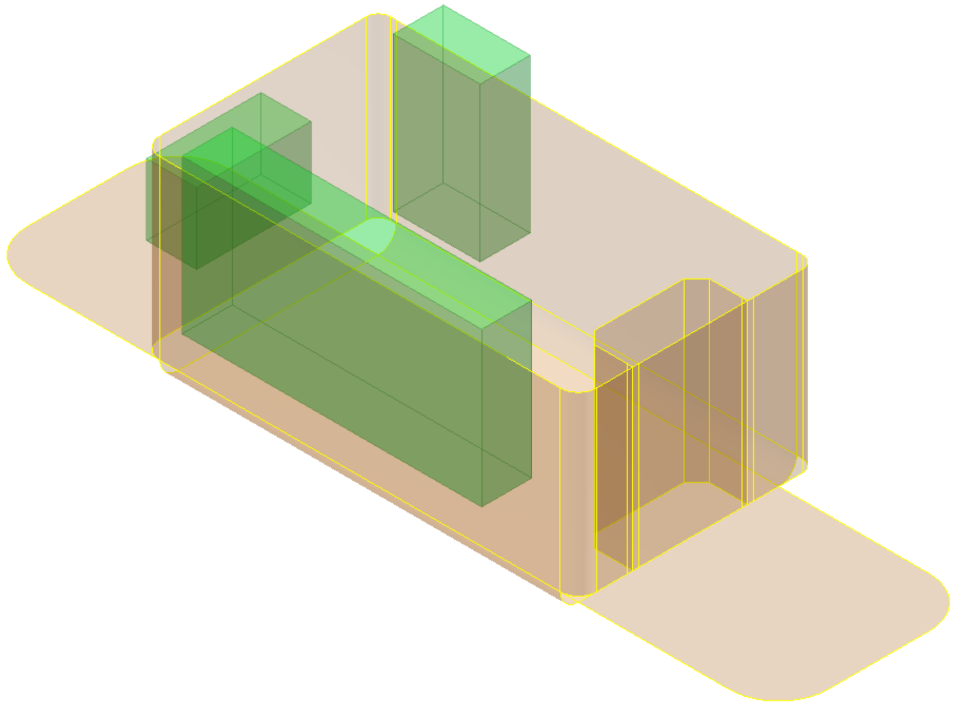


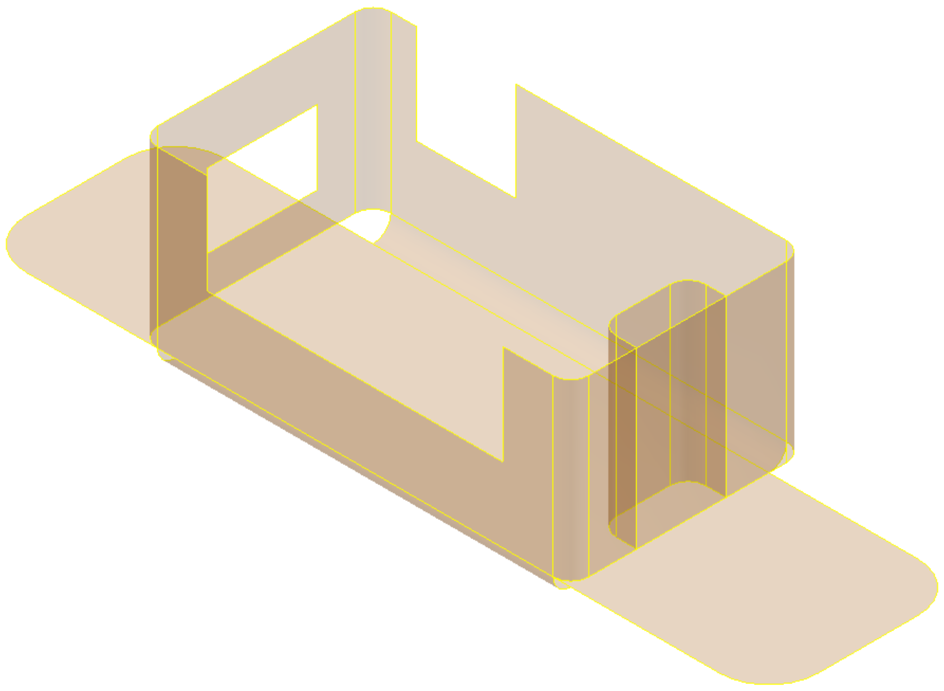
Cellular Decomposition - Midsurface



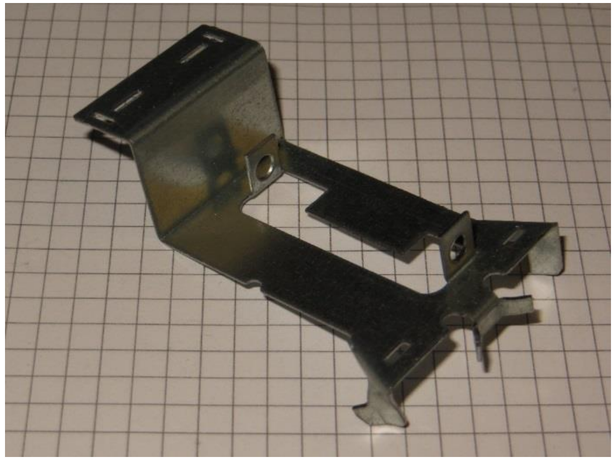


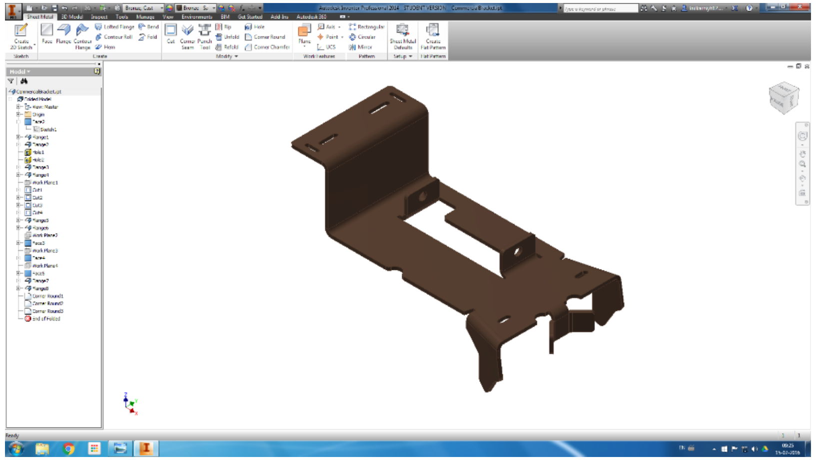
Final Midsurface by Dormant re-application

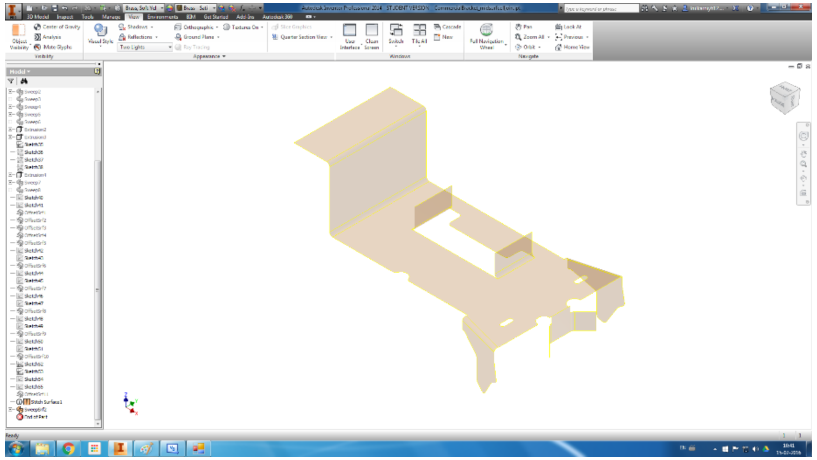




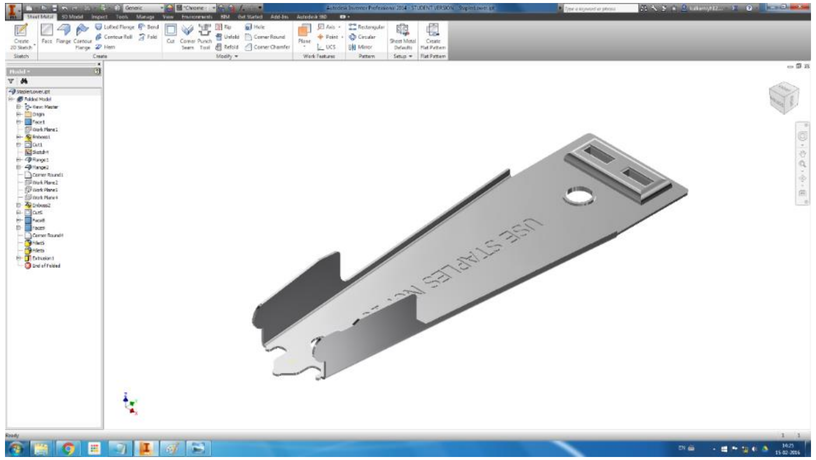
Test-case I : Bracket

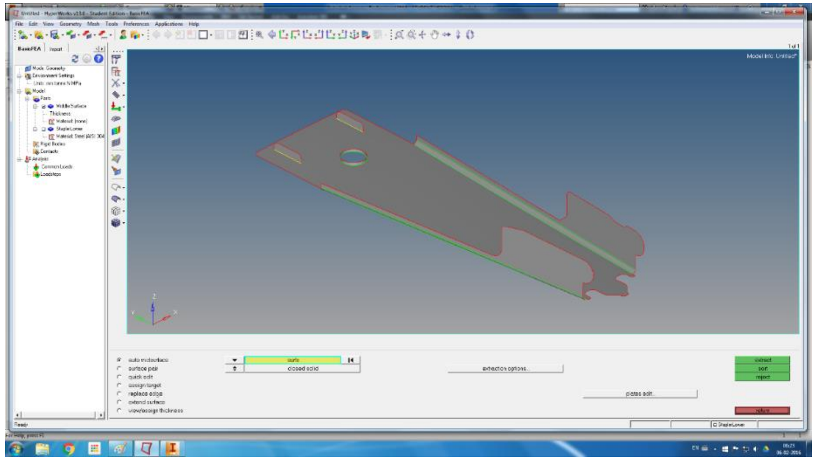


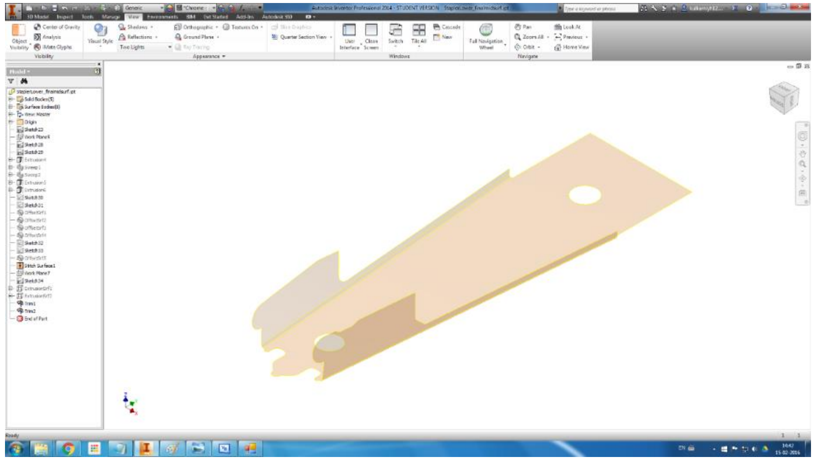




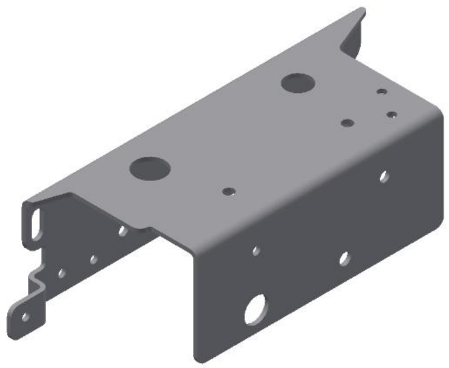
Test-case II: Stapler lower bottom

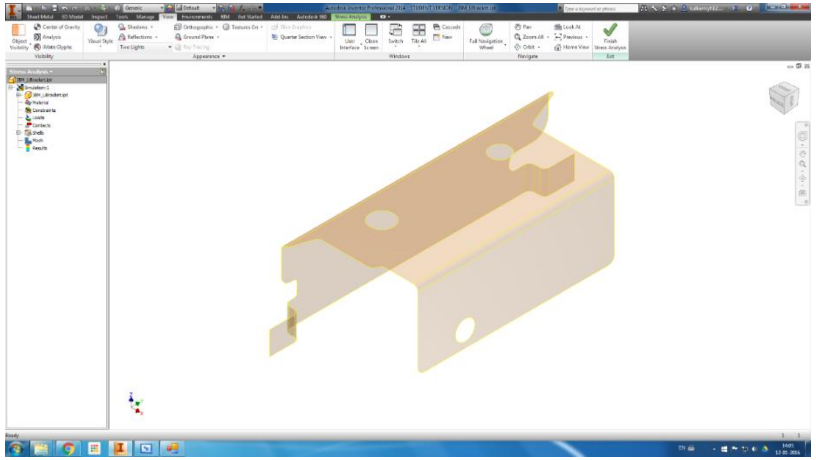






Test-case III





Conclusions

Conclusions

- Development of Feature based Midsurface Computation approach
- Feature based Defeaturing: Taxonomy, Remnant, Dormant
- Feature generalization: Loft as a generic feature
- Leveraging Cellular Decomposition for 2D (midcurve), 3D (midsurface) computation
- Bi-directional Topological Validation of midsurface
- Demonstration of efficacy of the approach in the system implemented, called MidAS

Research Contributions

- Feature-based CAD Algorithm paradigm: Simplification – Generalization – Decomposition – Cellular Graph
- Automatic defeaturing of sheet metal feature-based CAD model
  - Based on newly developed sheet metal features taxonomy
  - Based on newly developed, more accurate criteria of Remnant feature sizes
  - Based on newly developed approach of Dormant features
- Automatic transformation of sheet metal features to generalized features
  - Newly developed generalized CAD model representation, called ABLE
  - Transformation mapping of Sheet Metal features to Loft equivalents
- Automatic computation of Midsurface
  - Midcurve Computation: Enhanced Polygon Decomposition and newly developed cellular midcurve computation
  - Midsurface Computation: Cellular graph based, generic logic for connections.
- New Topological Validation formulation framework

Future work

- Implementation:
  - Internal Development instead of using-API.
  - Adopting to different CAD modellers
- Domain:
  - More sheet metal features
  - Catering to Injection moulding domain
- Geometric Modelling:
  - Development of Feature based Cellular Kernel
  - Expansion of ABLE transformations to other fields such as Meshing

Research Publications

- International Journals
  1. July 2016, Leveraging feature generalization and decomposition to compute a well-connected midsurface, Yogesh Kulkarni, Anil Sahasrabudhe, Mukund Kale, Engineering with Computers, **Springer**
  2. July 2016, Computation of Midsurface by Feature-based Simplification-Abstraction-Decomposition, Yogesh Kulkarni, Anil Sahasrabudhe, Mukund Kale, Jrnl of Comp and Info Sc in Eng, **ASME**
  3. May 2015, Topological Validation of Midsurface Computed from Sheet Metal Part, Yogesh Kulkarni, Anil Sahasrabudhe, Mukund Kale, Computer-Aided Design and Applications, **Taylor & Francis**
  4. June2016, Defeaturing Sheet Metal Part Model based on Feature Information, Yogesh Kulkarni, Ravi Kumar Gupta, Anil Sahasrabudhe, Mukund Kale, Alain Bernard, Computer-Aided Design and Appl, **Taylor & Francis**
  5. January 2017, Dimension-Reduction Technique for Polygons, Yogesh Kulkarni, Anil Sahasrabudhe, Mukund Kale, Intl. Journal of Computer Aided Engineering and Technology}, **Inderscience**

- International Conferences
  1. June 2015, Defeaturing Sheet Metal Part Model based on Feature Information, Yogesh Kulkarni, Ravi Kumar Gupta, Anil Sahasrabudhe, Mukund Kale, Alain Bernard, Proceedings of CAD 15, **London**
  2. December 2014, Formulating Midsurface using Shape Transformations of Form Features, Yogesh Kulkarni, Anil Sahasrabudhe, Mukund Kale, 5th Intl. and 26th AIMTDR, **IIT Guwahati**
  3. December 2013, Strategies for using feature information in model simplification, Yogesh Kulkarni, Anil Sahasrabudhe, Mukund Kale, Intl. Conf. on CAE, **IIT Madras**
  4. May 2013, Using Features for generation of Midsurface, Yogesh Kulkarni, Anil Sahasrabudhe, Mukund Kale, Intl. Conf. on Advances in Mech Eng, **COEP, India**

- National Conferences
  1. January 2014, Midcurves Generation Algorithm for Thin Polygons, Yogesh Kulkarni, Anil Sahasrabudhe, Mukund Kale, Natl. Conf. on Emerging Trends in Eng and Science, **Asansol, India**.

Thank you