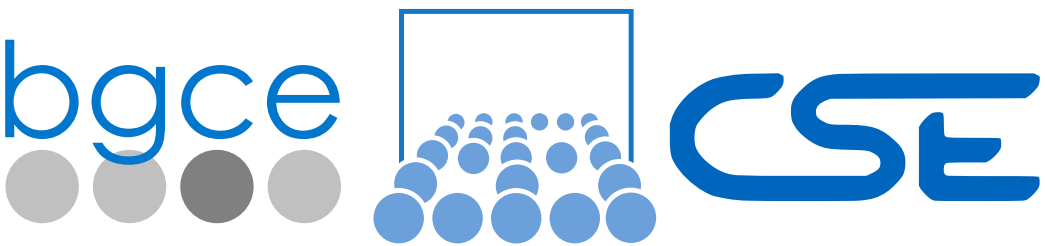
Technische Universität München

BGCE Project: CAD – Integrated Topology Optimization

BGCE Final Milestone Meeting

S. Joshi, J.C. Medina, F. Menhorn,
S. Reiz, B. Rüth, E. Wannerberg, A. Yurova

February 29, 2016



Contents

CAD issues

Problem:

- The Engineer designer pendulum

Desired:

$\Rightarrow$ One click optimization

CAD issues

Problem:

- The Engineer designer pendulum

Desired:

⇒ One click optimization

- Top-Opt algorithms are a one way street

⇒ A full circle optimization process

CAD issues

Problem:	Desired:
• The Engineer designer pendulum	⇒ One click optimization
• Top-Opt algorithms are a one way street	⇒ A full circle optimization process
• Exotic input file types	⇒ Standardized input files

What they get

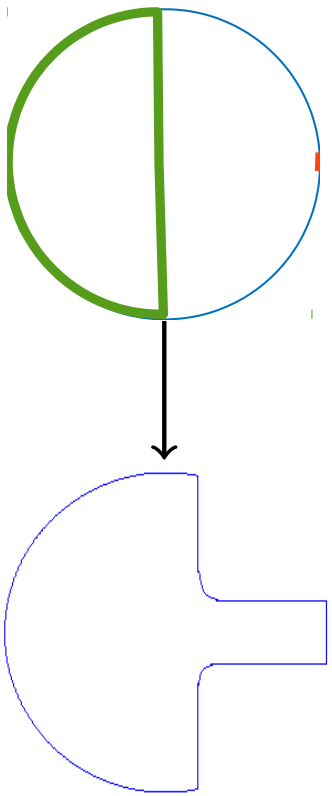
- One-step solution process
- Full 3-D optimization via Finite Elements
- Production-ready output geometry

DEMO

Scalability and Performance

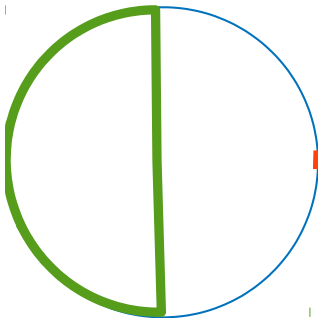
Overview: Workflow

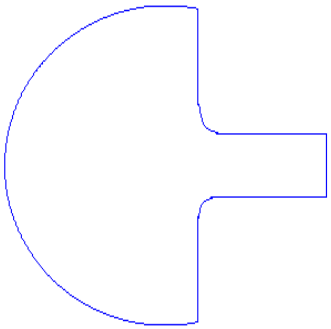
What the user sees



Overview: Workflow

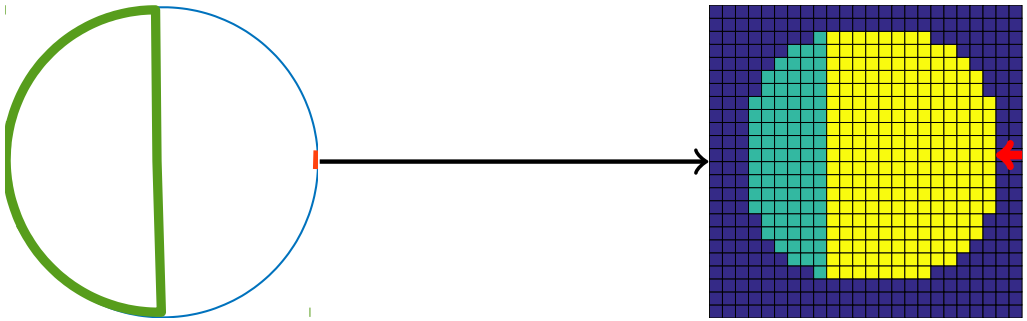
CAD design including specification of loads and fixtures

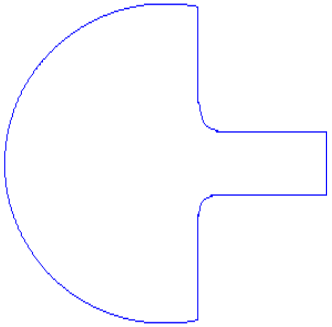




Overview: Workflow

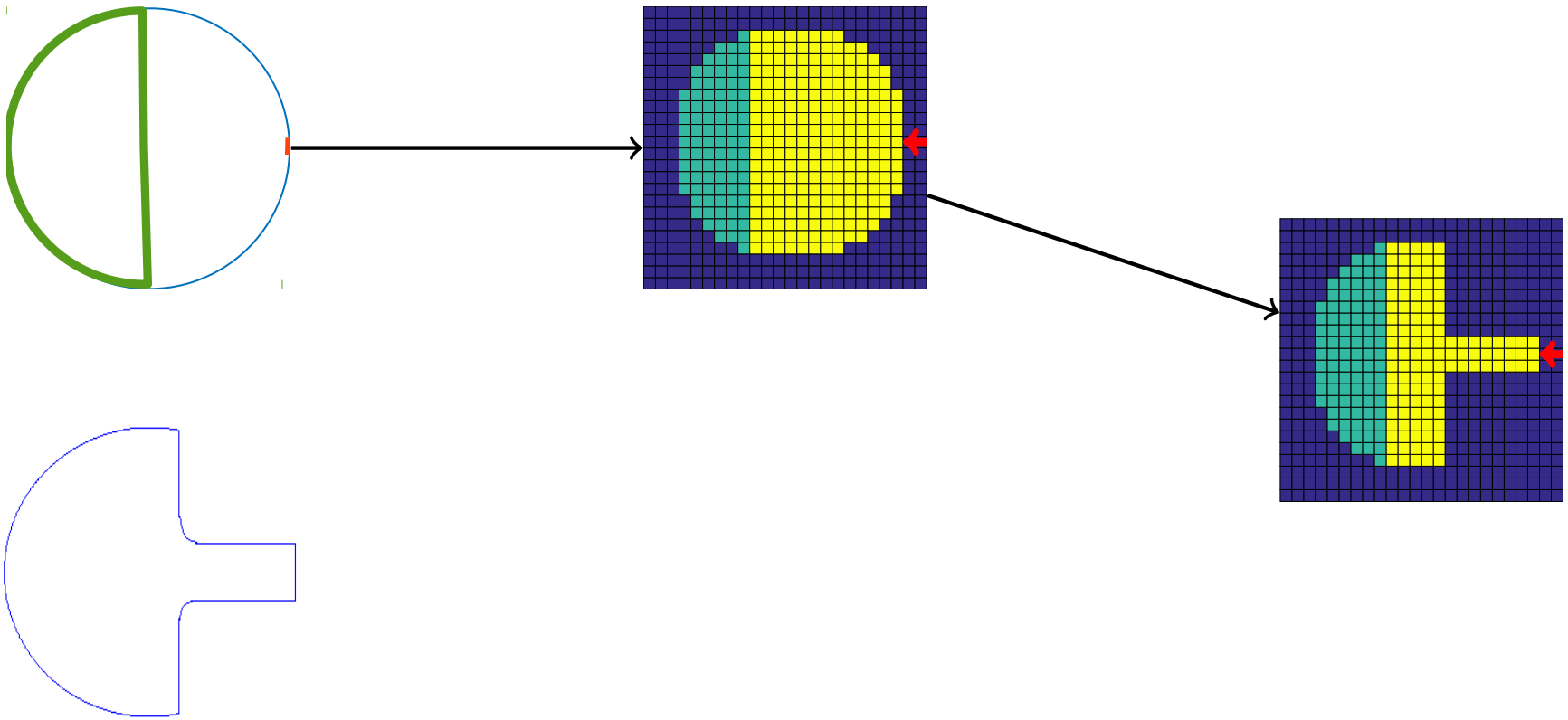
Voxelized topology





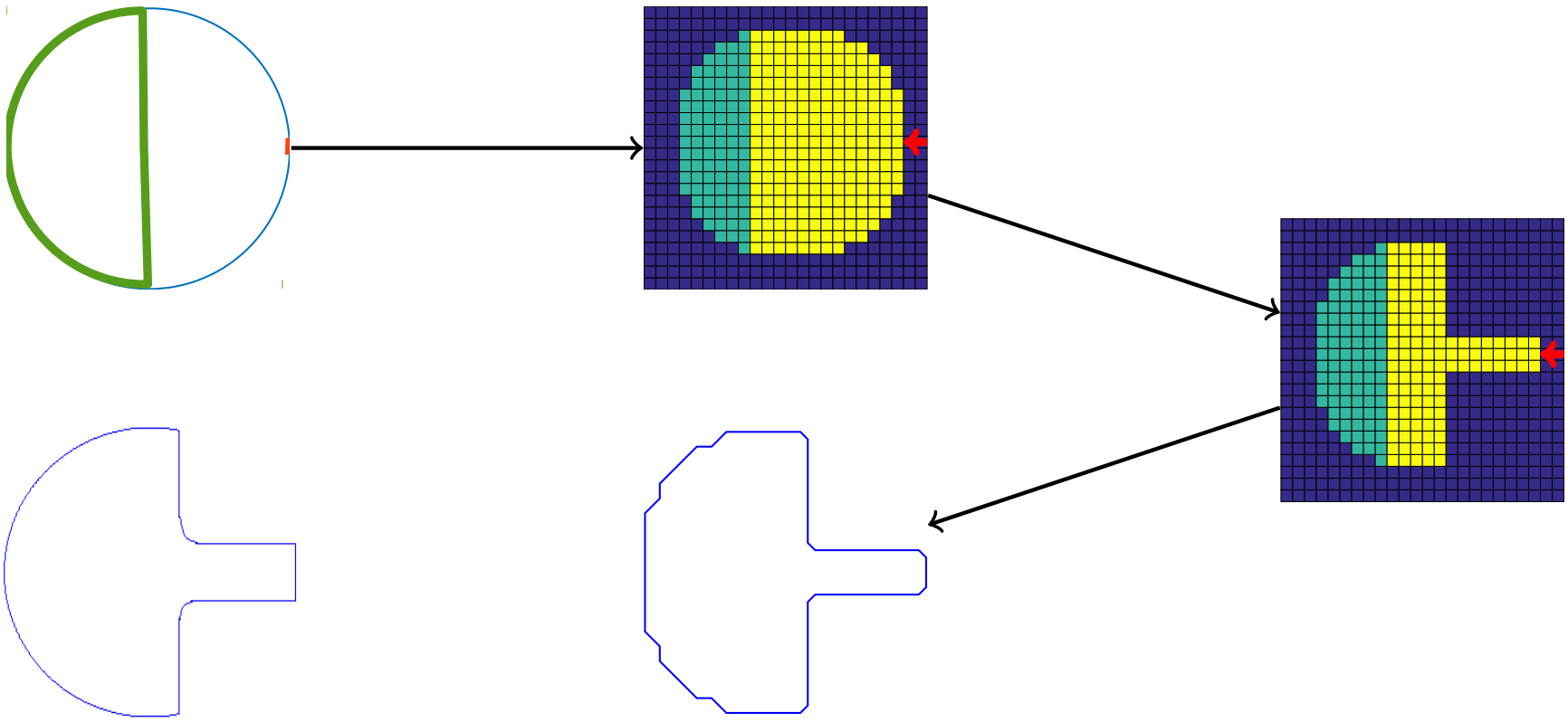
Overview: Workflow

Optimized topology



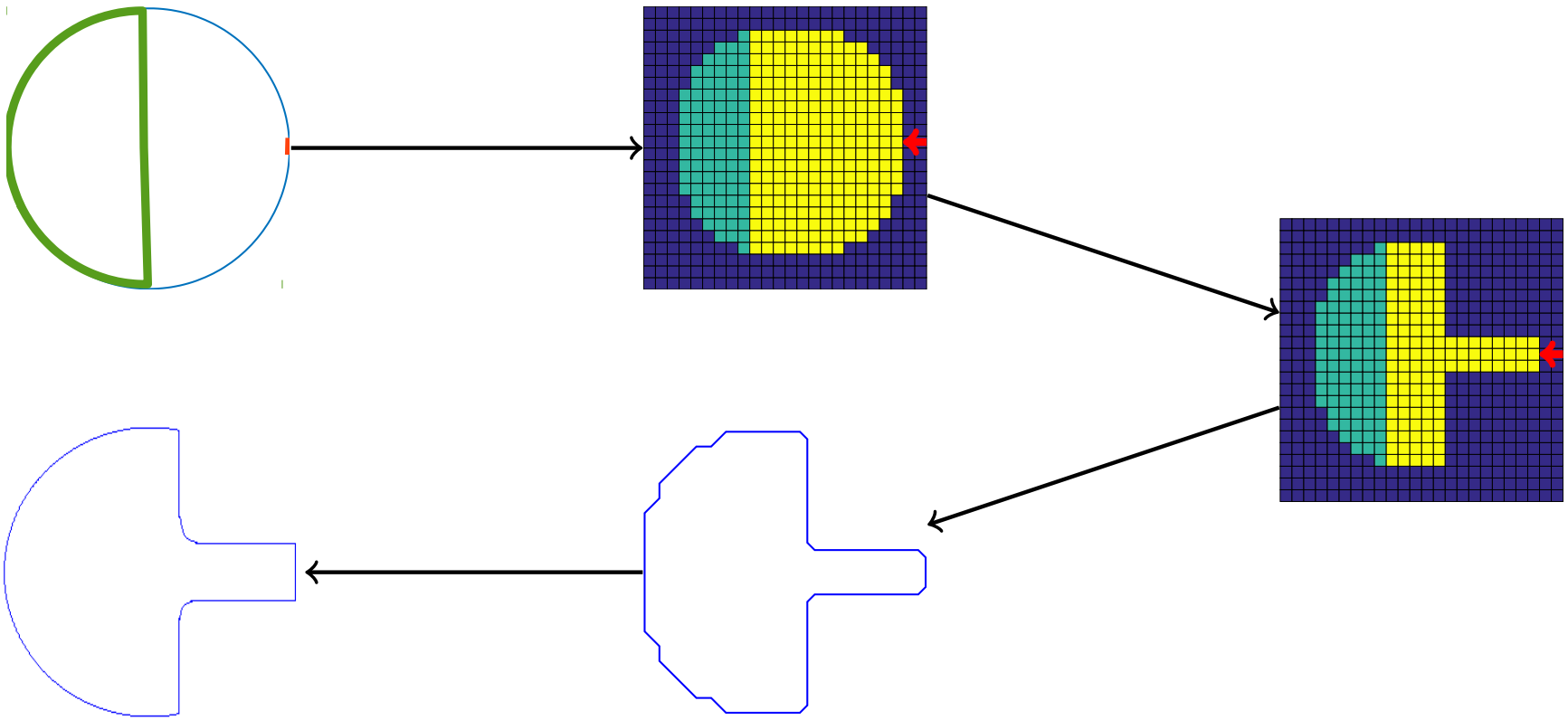
Overview: Workflow

Surface extraction



Overview: Workflow

Fit B-Spline surface



Contents

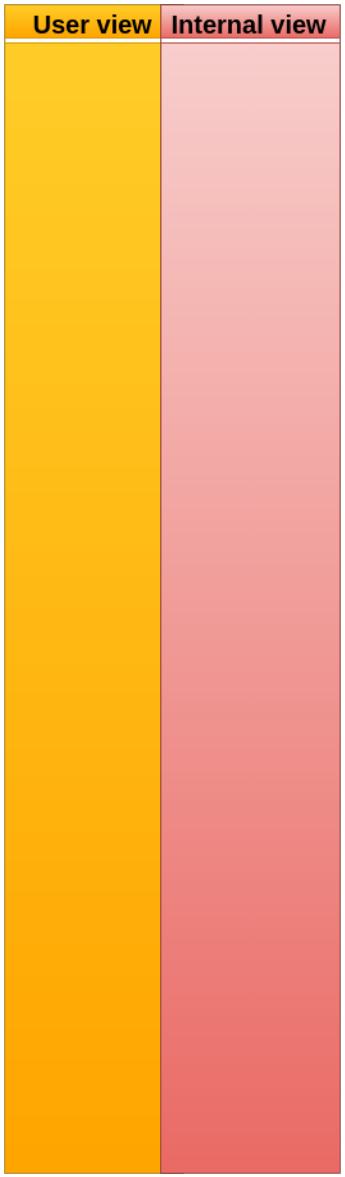
Status

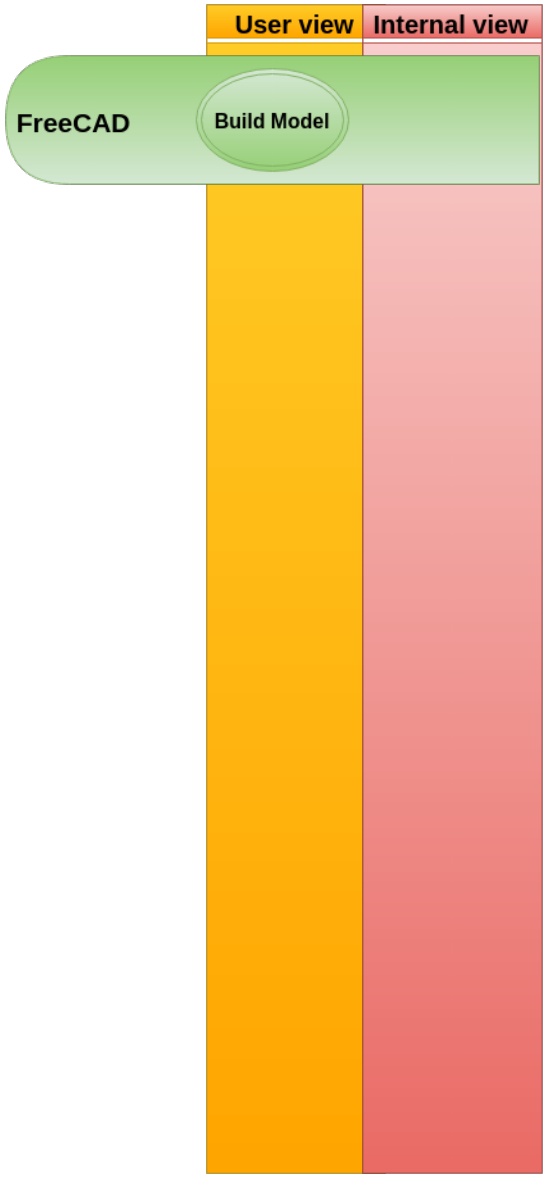
Last milestone

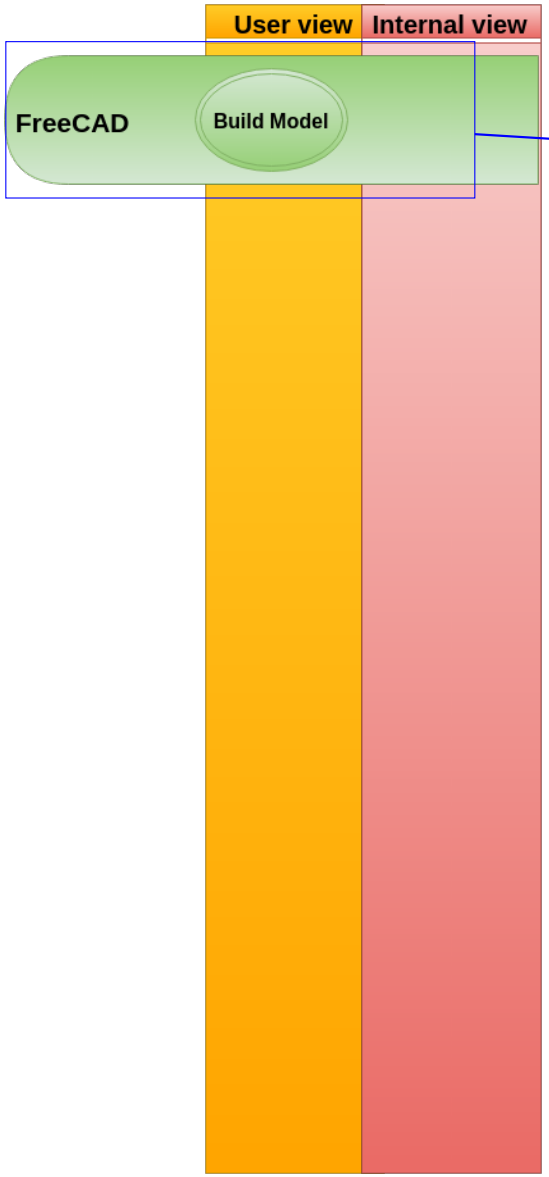
- ✓ Manual voxelization using CVMLCPP
- ✓ ”Hard coded” script for ToPy input
- ✓ Topology optimized geometry using ToPy
- ✗ Recognition of boundary conditions

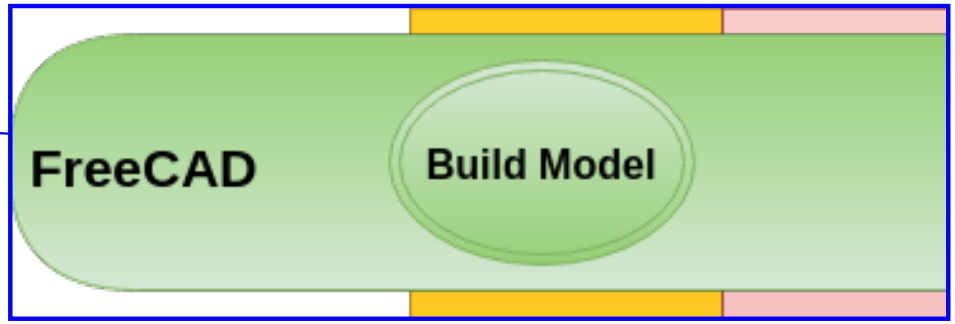
Today

- ✓ Voxelization with OpenCascade
- ✓ Extraction of loads, fixtures and active elements through colouring
- ✓ Automatic ”one click” pipeline to surface reconstruction


User view
Internal view


User view
Internal view
FreeCAD
Build Model



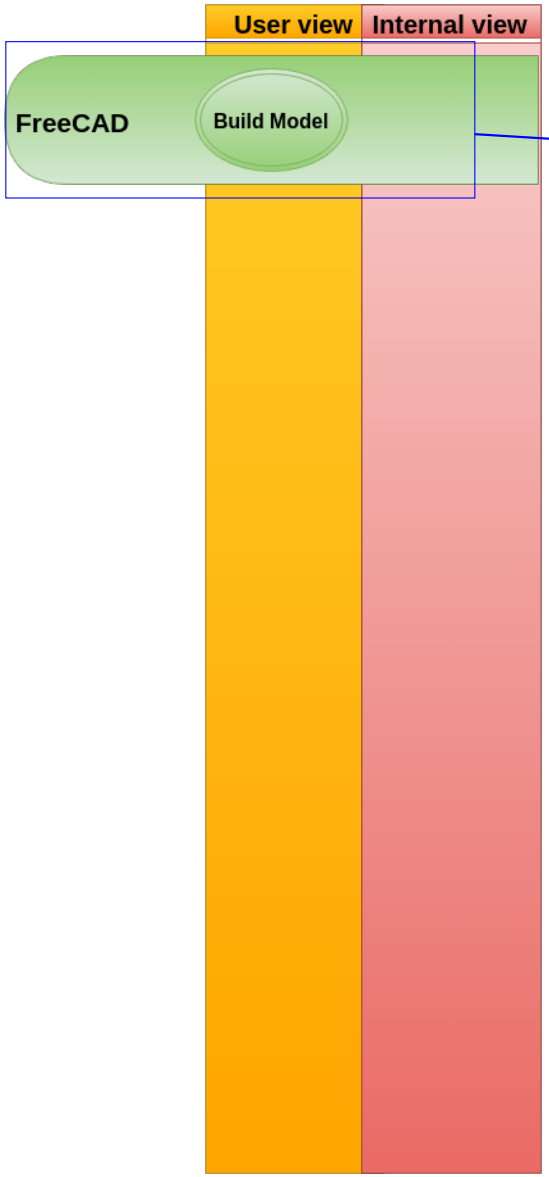


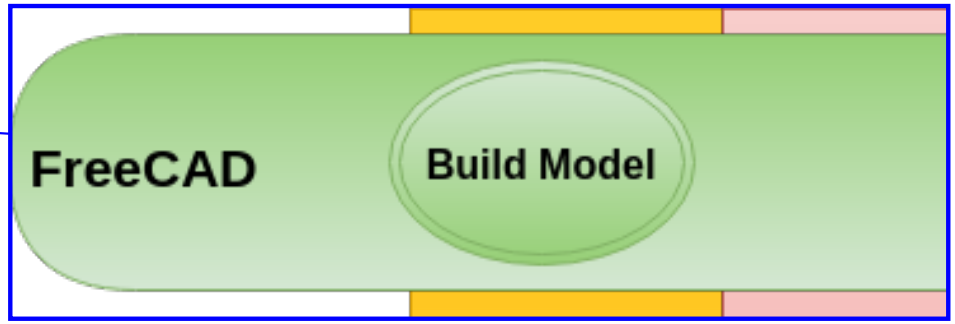
- Model geometry in your favorite CAD tool
- Colour faces for boundary conditions

  Red Fixture

  Green Active

  RGB RGB value in $[0 \leq R < 255, 0 \leq G < 255, 0 \leq B < 255]$ for load vector
- Save model as `STEP with Colours` and `IGES with Colours`





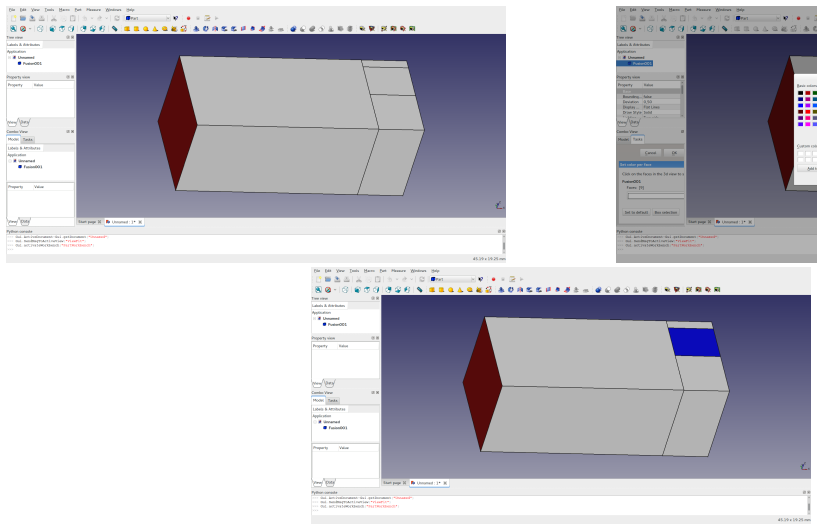
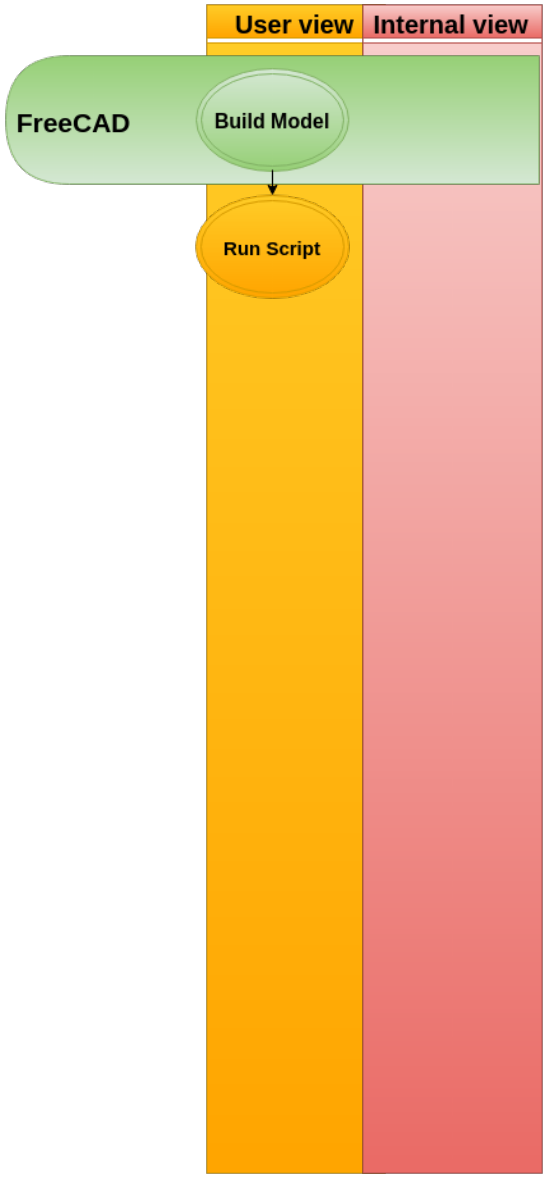


Figure : Color faces in FreeCAD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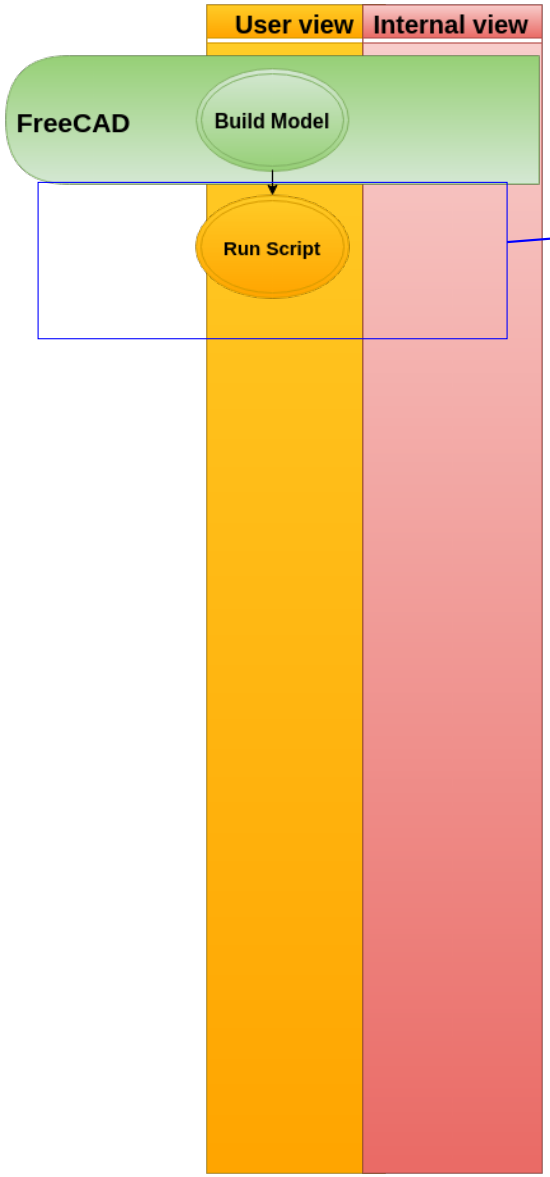
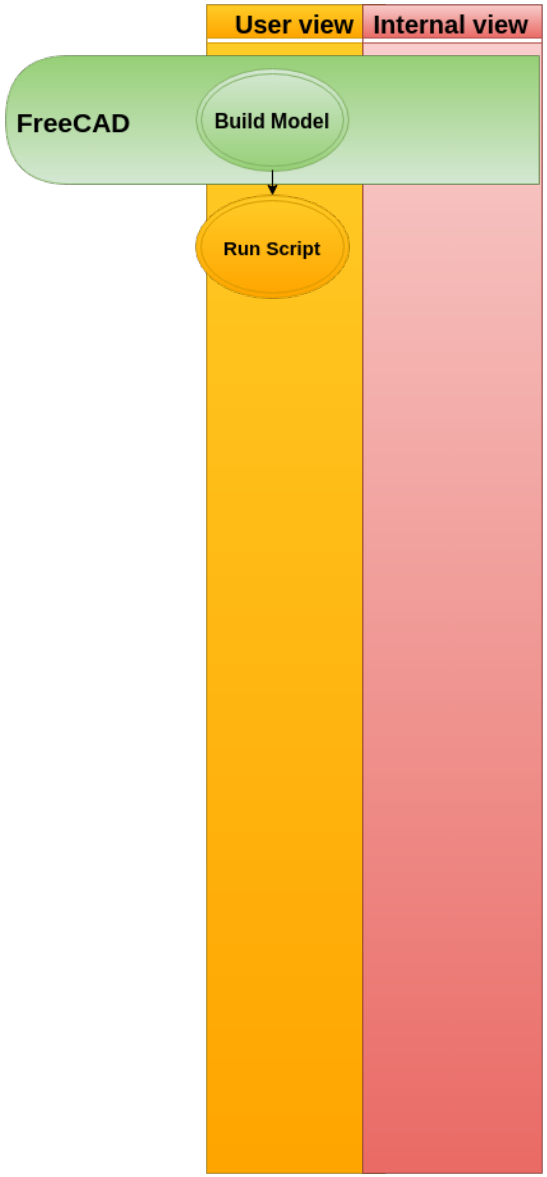


→ Run

```
CADTopOpt filedir filename force_scaling
refinement
```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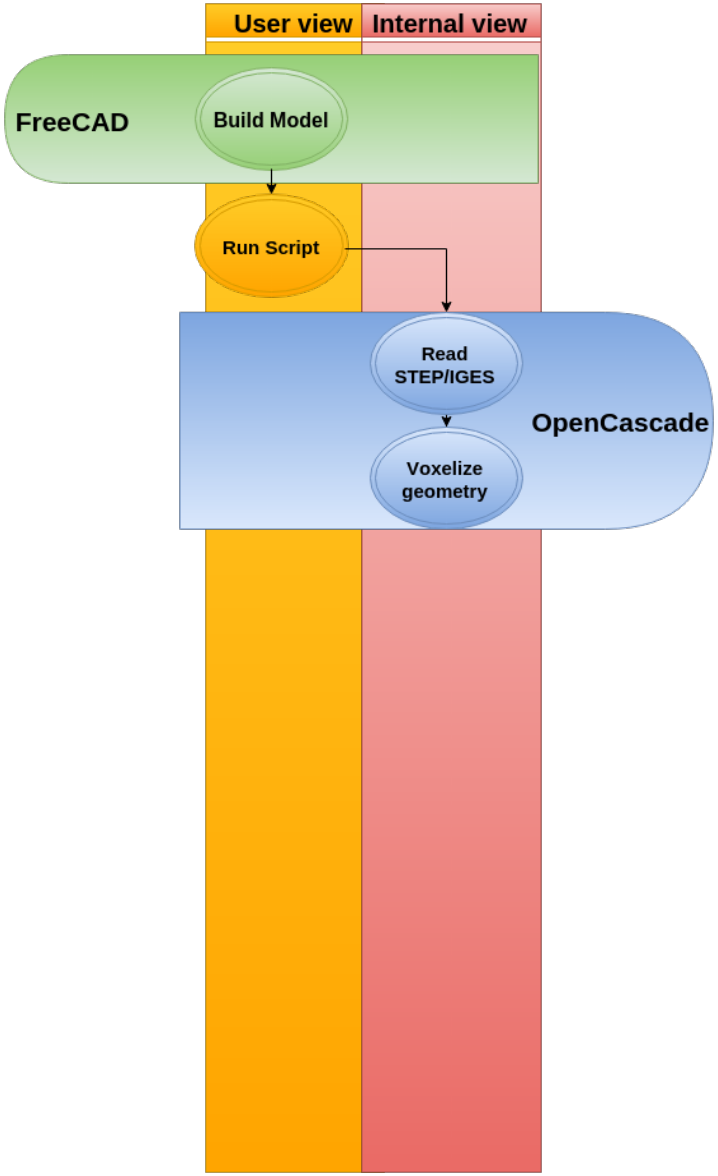
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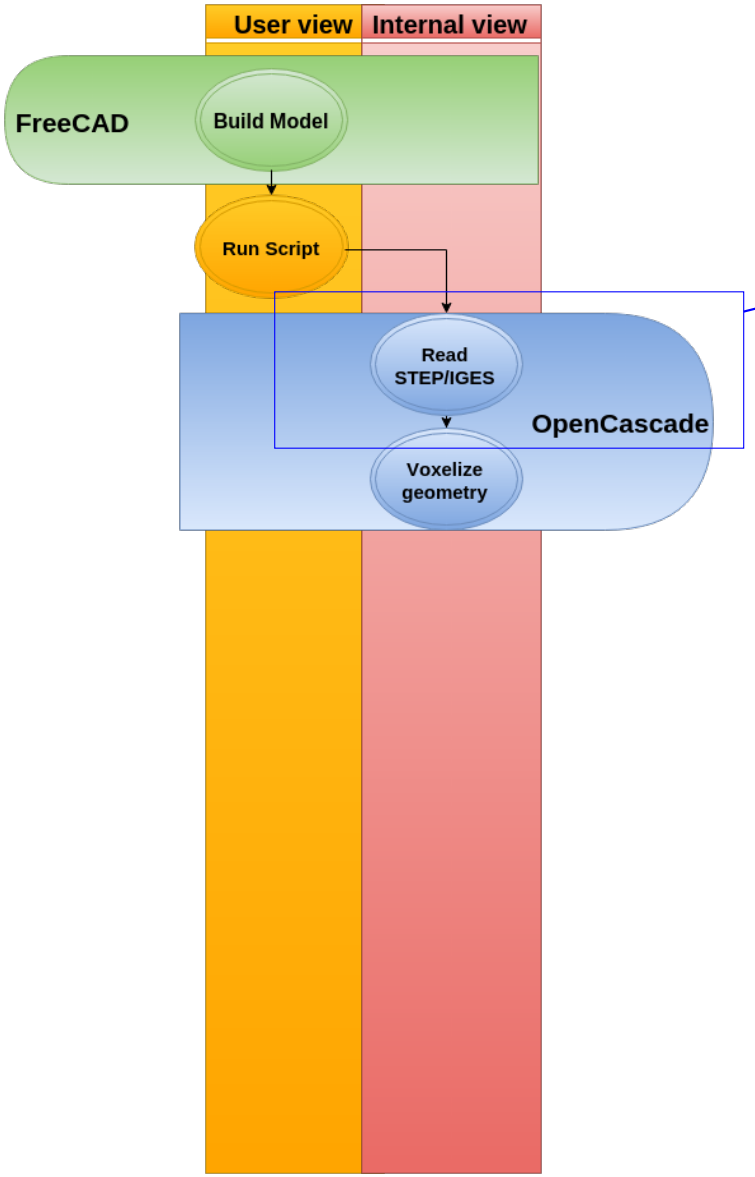
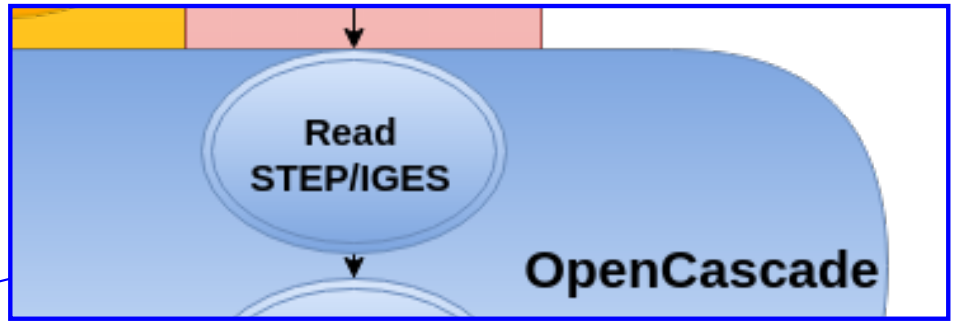
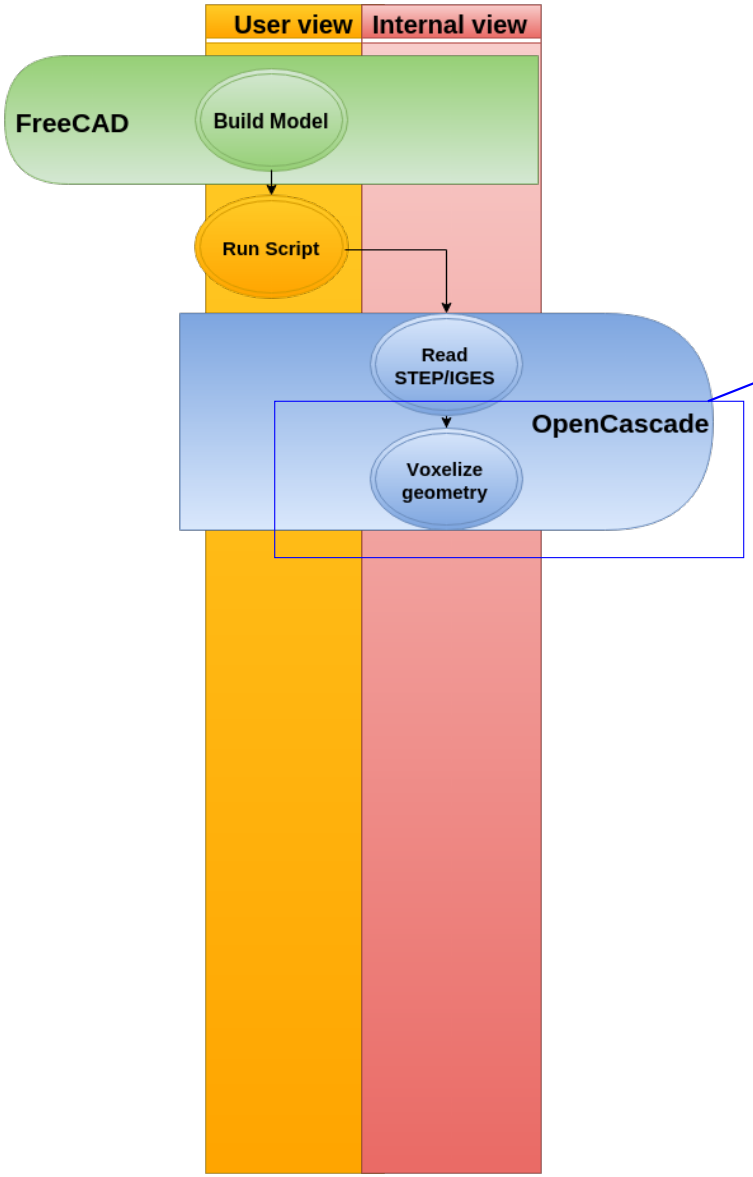
Read STEP/IGES
Voxelize geometry
OpenCascade

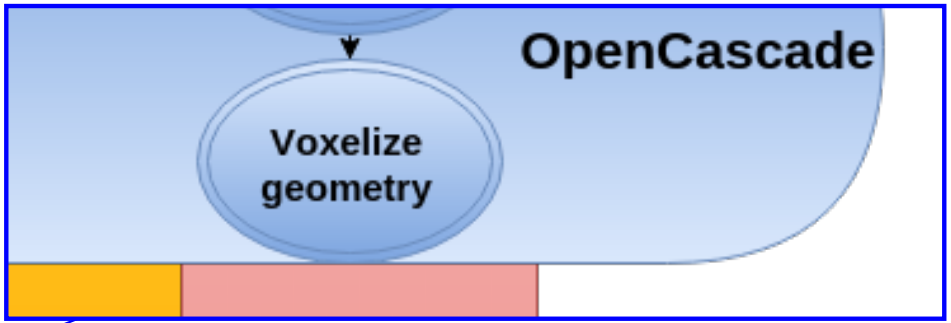




Read STEP and IGES file, extract colours and faces

- STEP holds the colours
- IGES holds the structure





Voxelize faces using OpenCascade

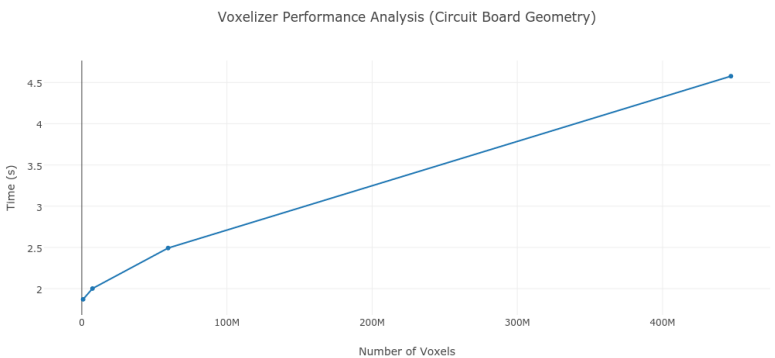
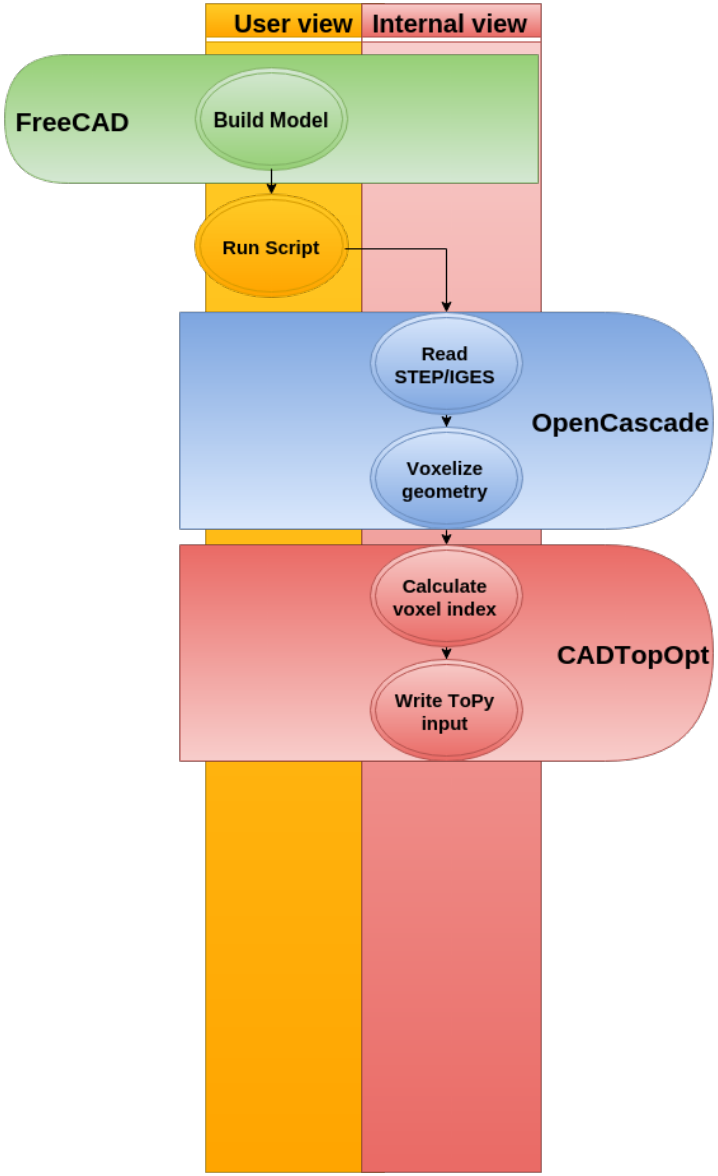


Figure : Scaling of voxelizer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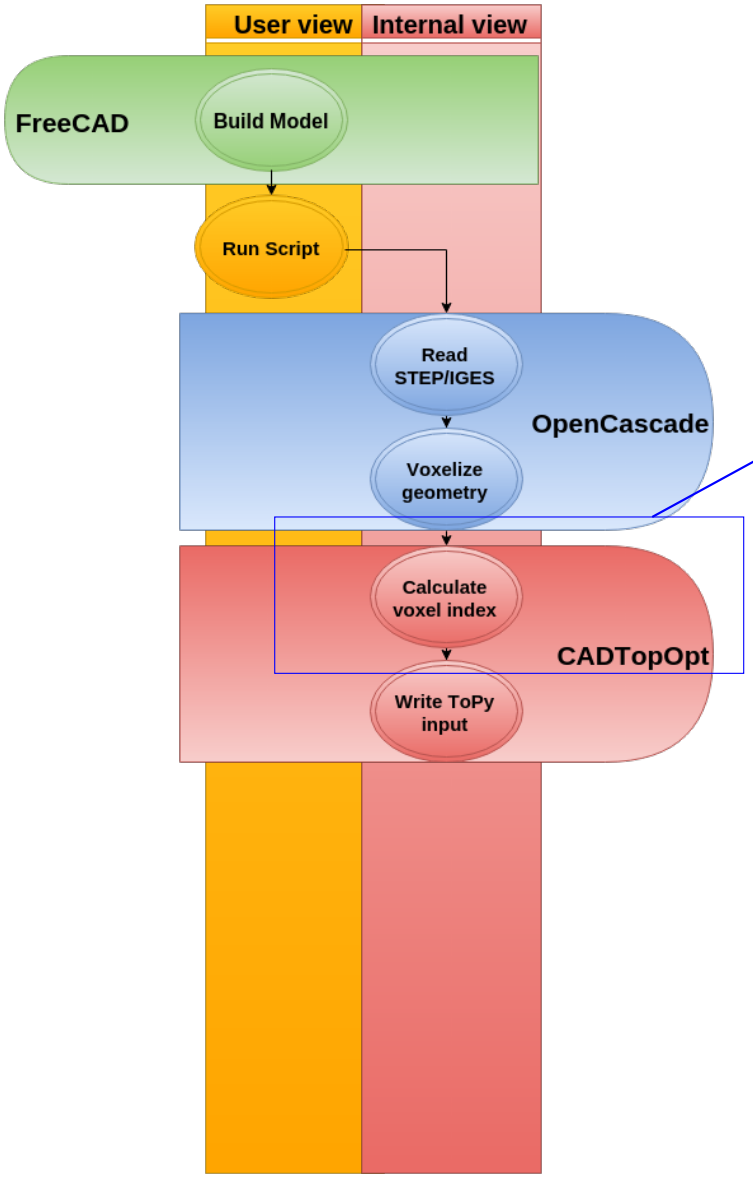
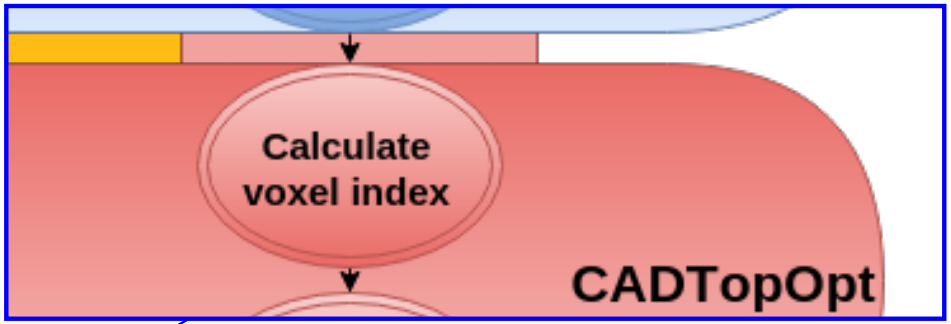
Calculate voxel index
CADTopOpt
Write ToPy input

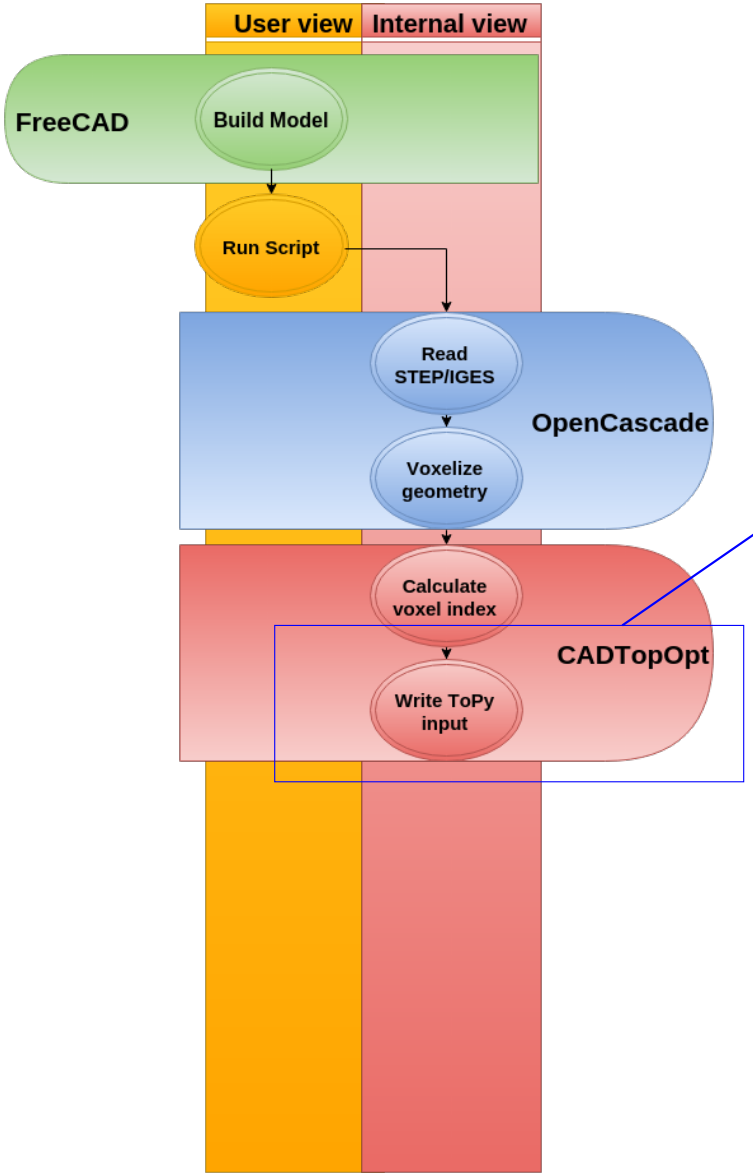


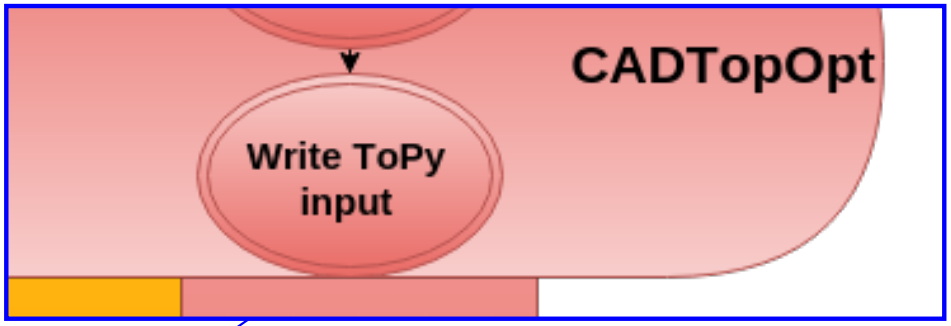


Different indexing for elements and nodes in ToPy

```
# ========================================
# === Discretisation of the design domain ===
# ========================================
# 2D: Y              3D: Y
#     |                  |
#     +---X              +---X
#                       /
#                      Z
#
# 1---5---9
# | 1 | 5 |
# 2---6---10
# | 2 | 6 |
# 3---7---11
# | 3 | 7 |
# 4---8---12
#
```

Figure : Indexing in ToPy [1]





Each voxel index is specifically written

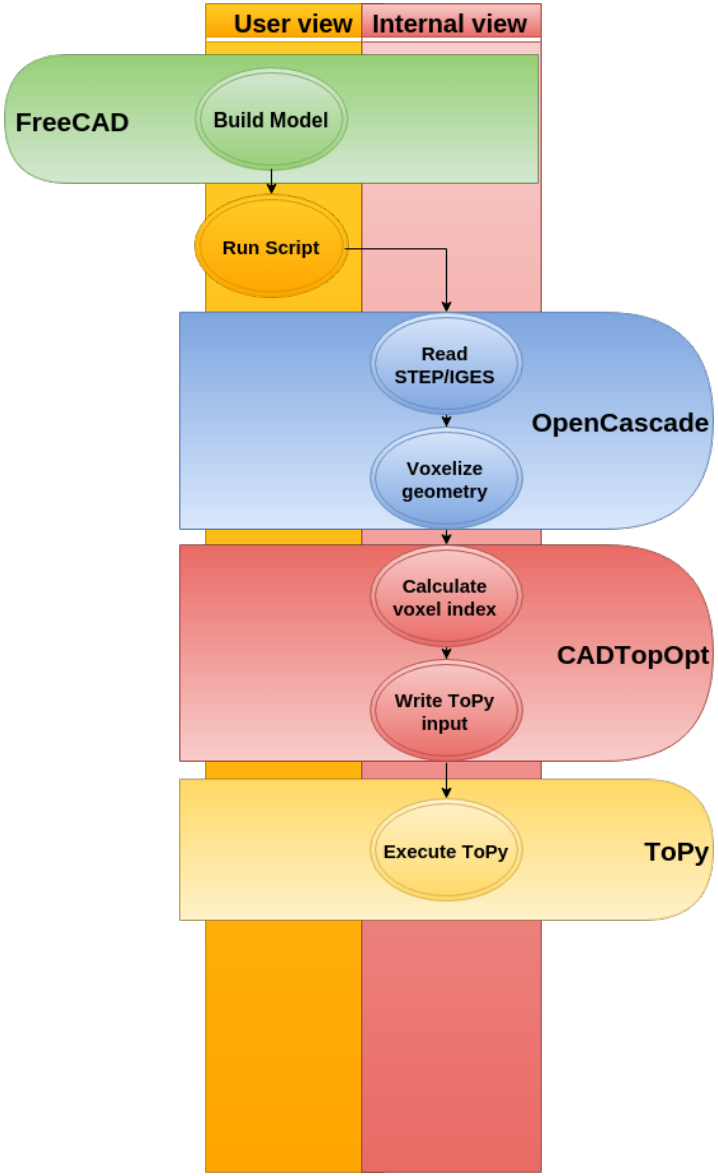
```
[ToPy Problem Definition File v2007]

PROB_TYPE:    comp
PROB_NAME:    topy_CantiLeverWithLoadAtEndSmallerMovedLoad
ETA:          0.4
DOF_PN:       3
VOL_FRAC:     0.15
FILT_RAD:     1.5
ELEM_K:       H8
NUM_ITER:     100
NUM_ELEM_X:   50
NUM_ELEM_Y:   20
NUM_ELEM_Z:   20

# Grey-scale filter (GSF)
P_FAC       : 1
P_HOLD      : 15
P_INCR      : 0.2
P_CON       : 1
P_MAX       : 3

Q_FAC       : 1
Q_HOLD      : 15
Q_INCR      : 0.05
Q_CON       : 1
Q_MAX       : 5
ACTV_ELEM: 18810; 18809; 18808; 18807; 18806; 18805; 18804; 18803; 18830; 18829; 18828; 18827; 18826; 18825; 18824; 18823; 18
18866; 18865; 18864; 18863; 18890; 18889; 18888; 18887; 18886; 18885; 18884; 18883; 18910; 18909; 18908; 18907; 18906; 18905;
18948; 18947; 18946; 18945; 18944; 18943; 18970; 18969; 18968; 18967; 18966; 18965; 18964; 18963; 18990; 18989; 18988; 18987;
19830; 19829; 19828; 19827; 19826; 19825; 19824; 19823; 19850; 19849; 19848; 19847; 19846; 19845; 19844; 19843; 19870; 19869;
19884; 19883; 19910; 19909; 19908; 19907; 19906; 19905; 19904; 19903; 19930; 19929; 19928; 19927; 19926; 19925; 19924; 19923;
19966; 19965; 19964; 19963; 19990; 19989; 19988; 19987; 19986; 19985; 19984; 19983
PASV_ELEM:
FXTR_NODE_X: 21; 20; 19; 18; 17; 16; 15; 14; 13; 12; 11; 10; 9; 8; 7; 6; 5; 4; 3; 2; 42; 41; 40; 39; 38; 37; 36; 35; 34; 33;
```

Figure : Script for ToPy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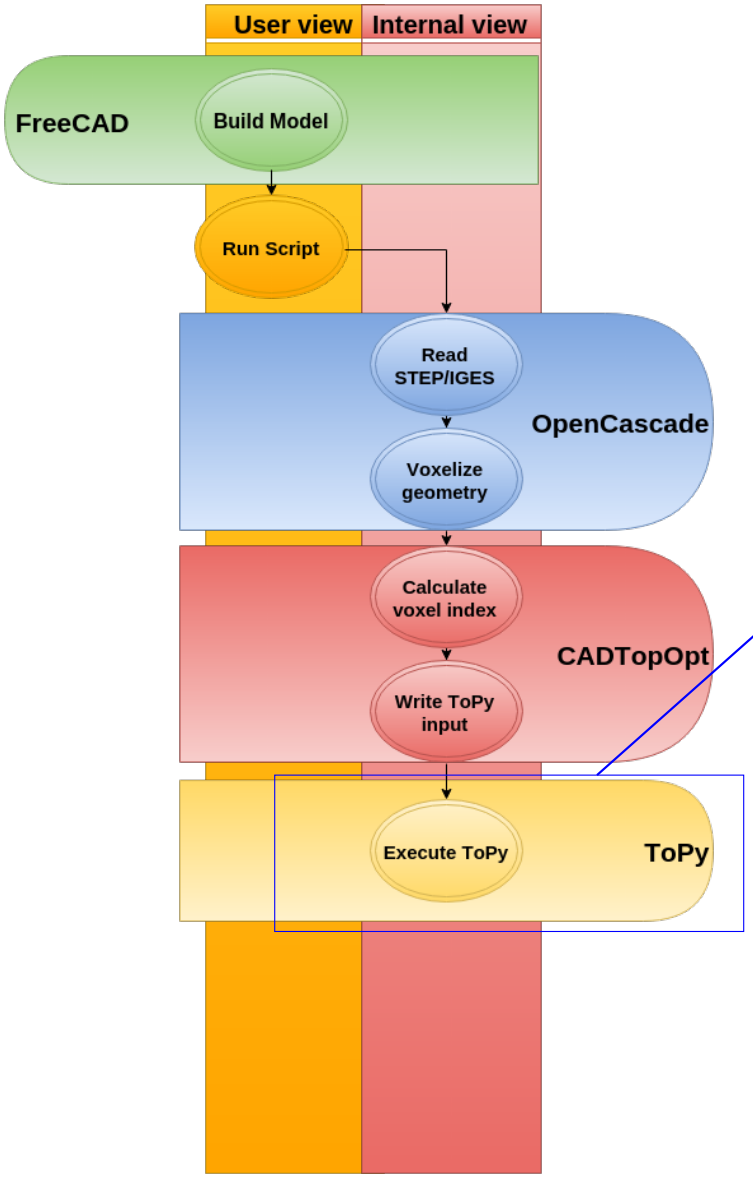
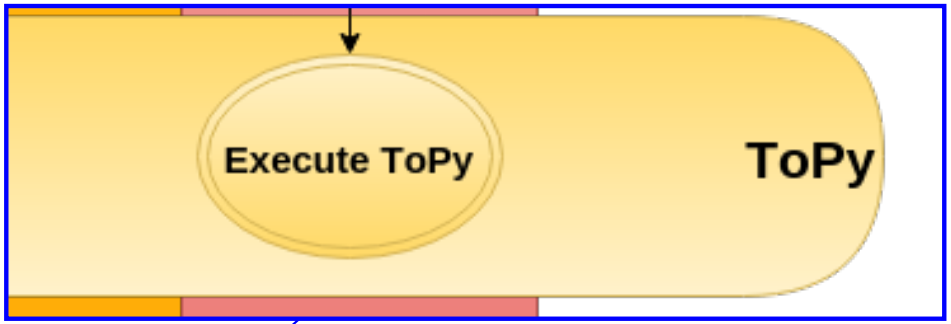
Write ToPy input
Execute ToPy
ToPy





Execute ToPy on the input file

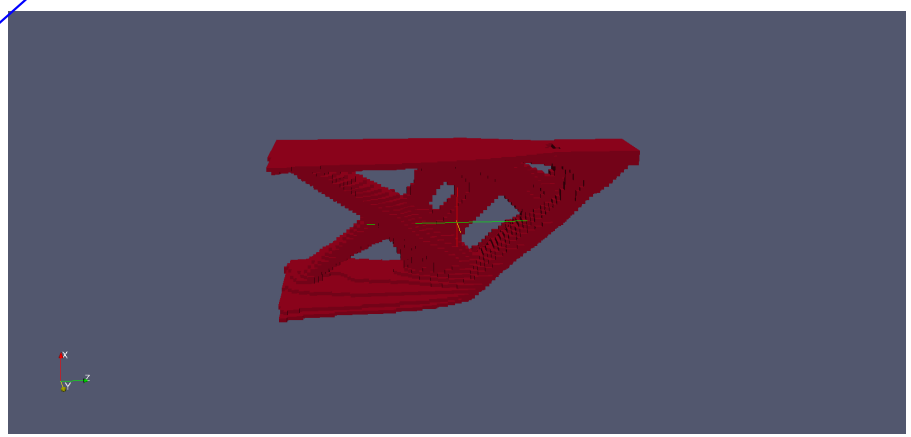
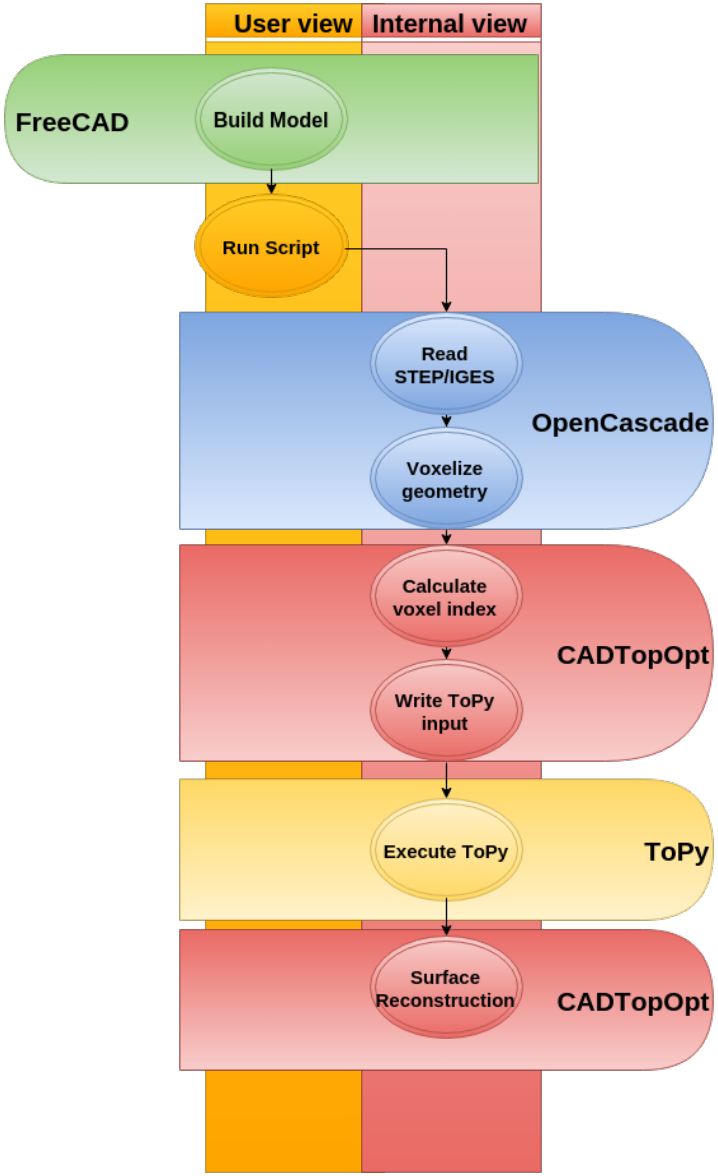


Figure : ToPy Output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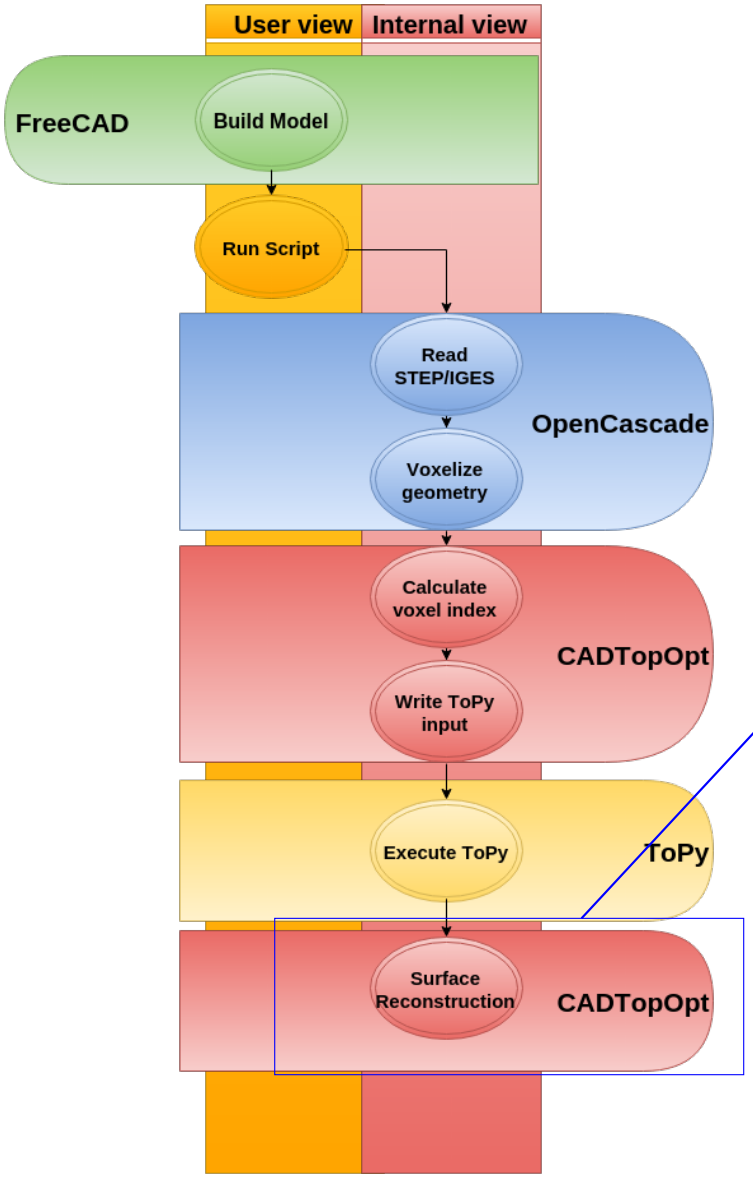
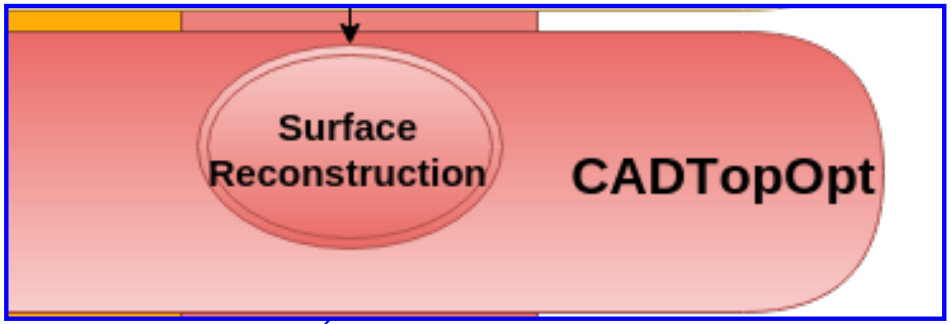




Run dual contouring algorithm

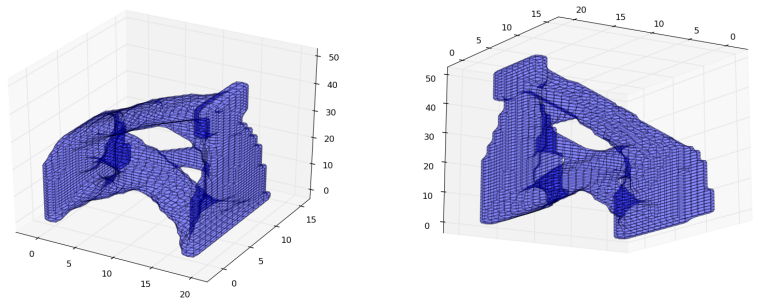
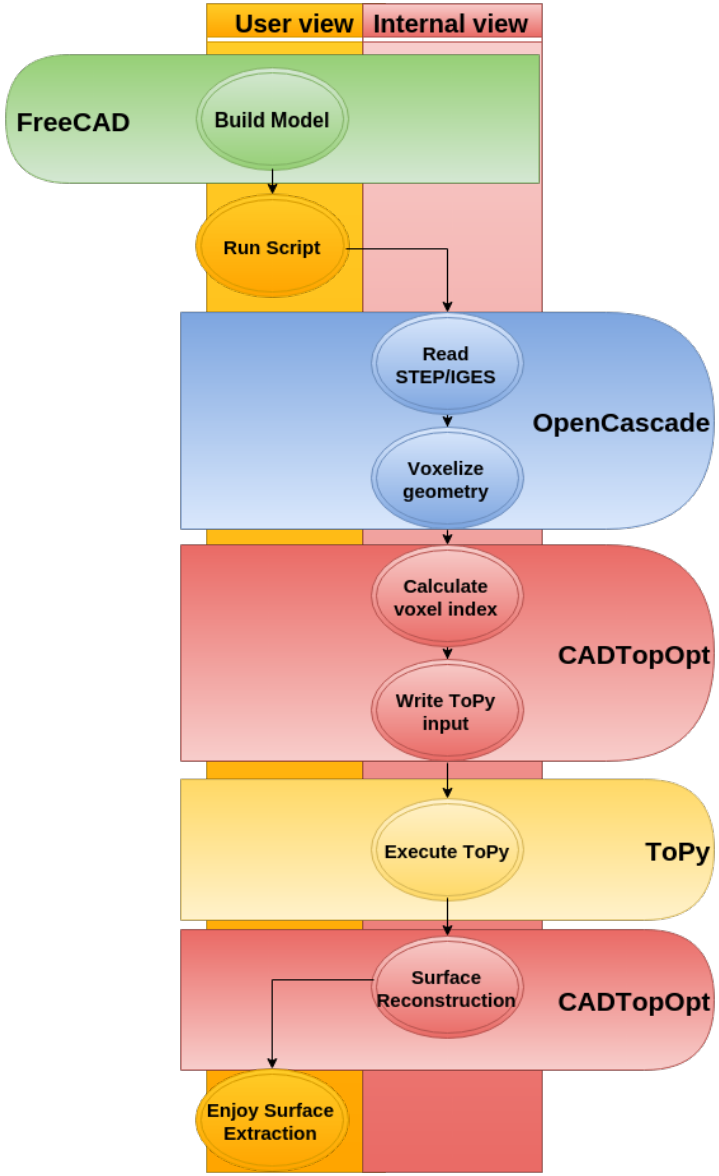


Figure : Surface extraction for Cantilever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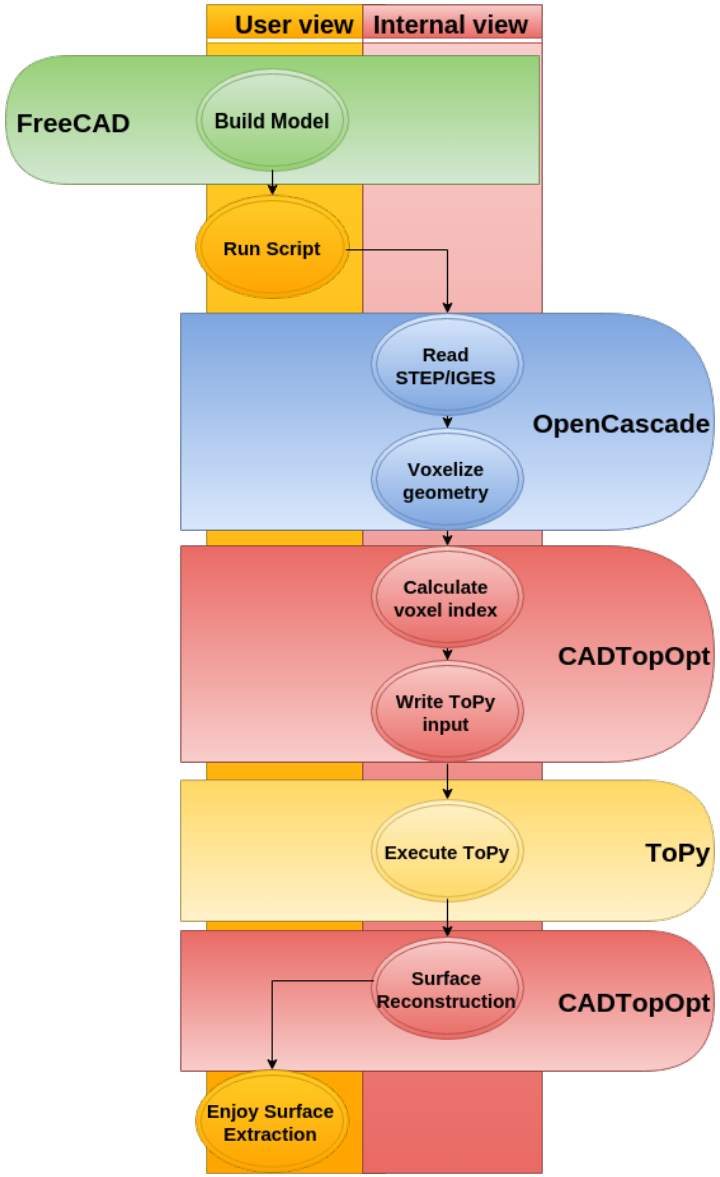
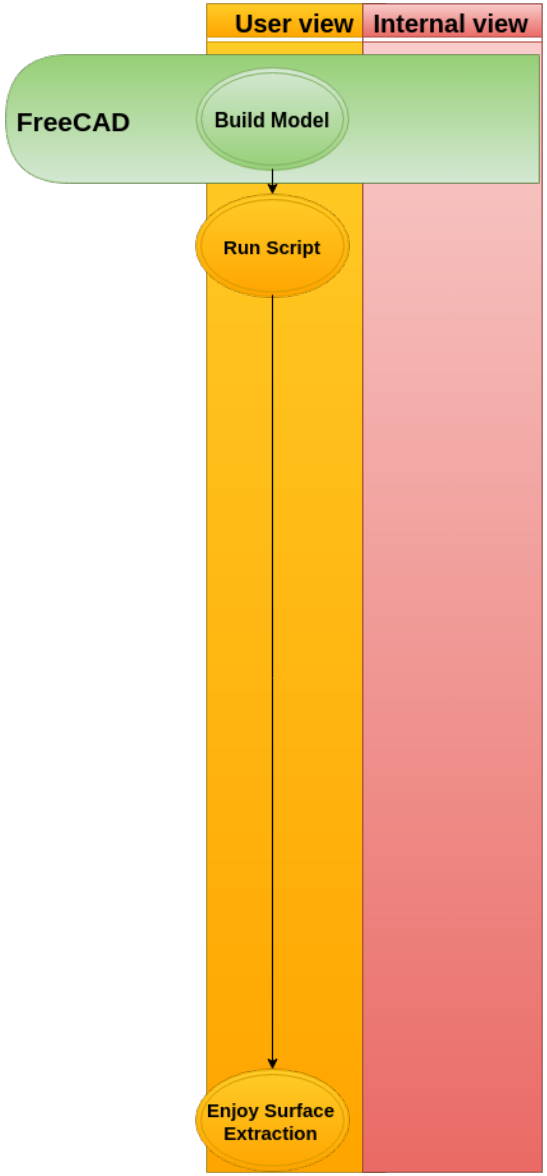
Execute ToPy
ToPy
Surface Reconstruction
CADTopOpt
Enjoy Surface Extraction



But what does the user see?



But what does the user see?

Contents

Status

Last milestone

- 🕐 Surface reconstruction with the VTK Toolbox

Today

- ✓ Extraction of voxel data from Topy
- ✓ 3D Dual Contouring implementation
- ✓ Coarsening and non-manifold edge treatment
- ✓ Projection of datapoints onto quads and respective parametrization
- 🕐 Interface to NURBS

From Voxel to Mesh Geometry

- Extract isosurface from voxel information
- Algorithms: Marching Cubes, Dual Contouring, Extended Models
- Problems with VTK's Marching Cube implementation

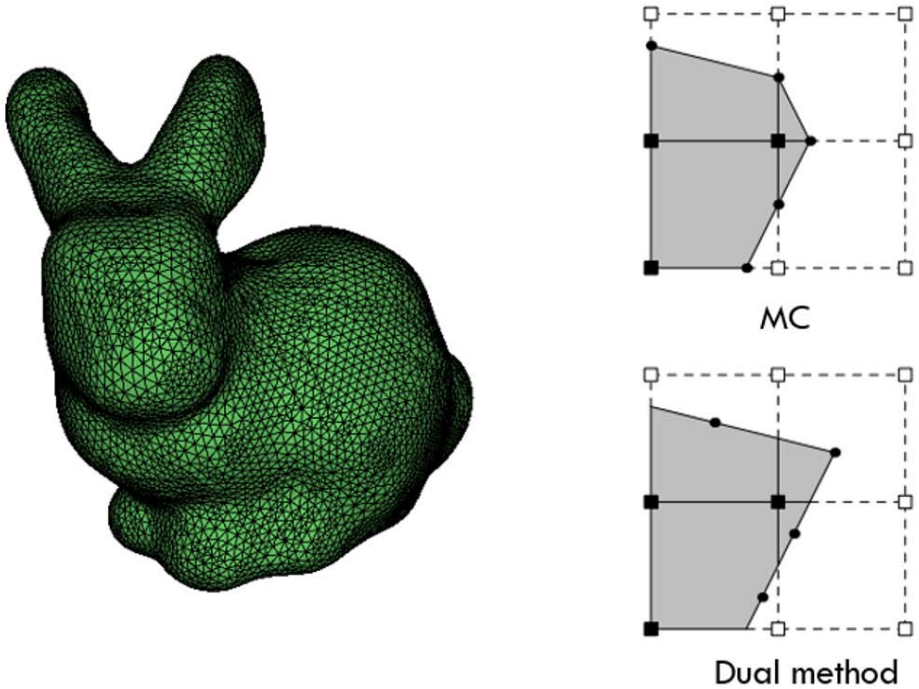
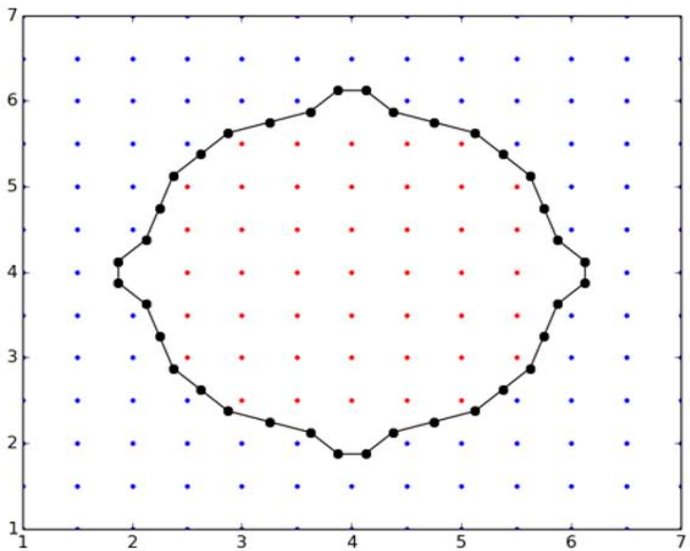
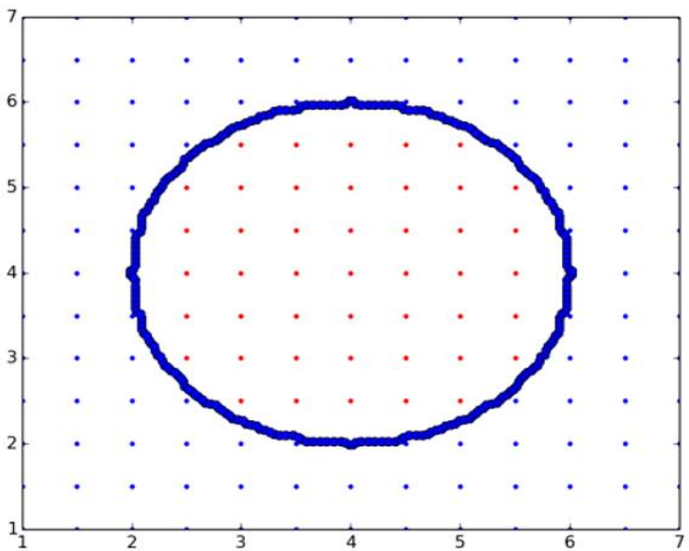


Figure : From [4],[5]

Dual Contouring

- Python implementation — Use of powerful libraries, including VTK
- Output: Closed surface made out of *quads*
- Coarsening is needed for surface fitting algorithms





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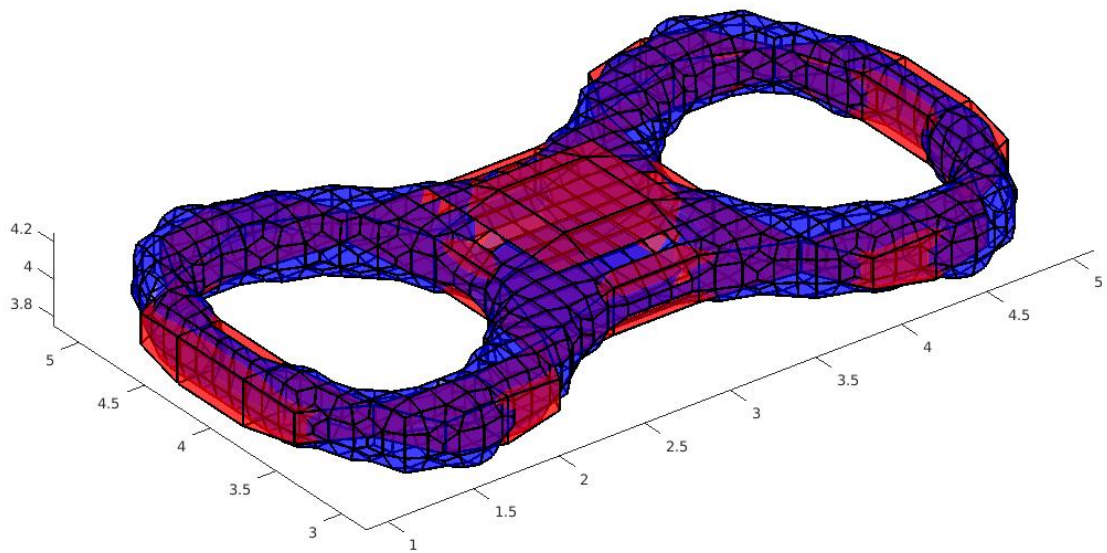
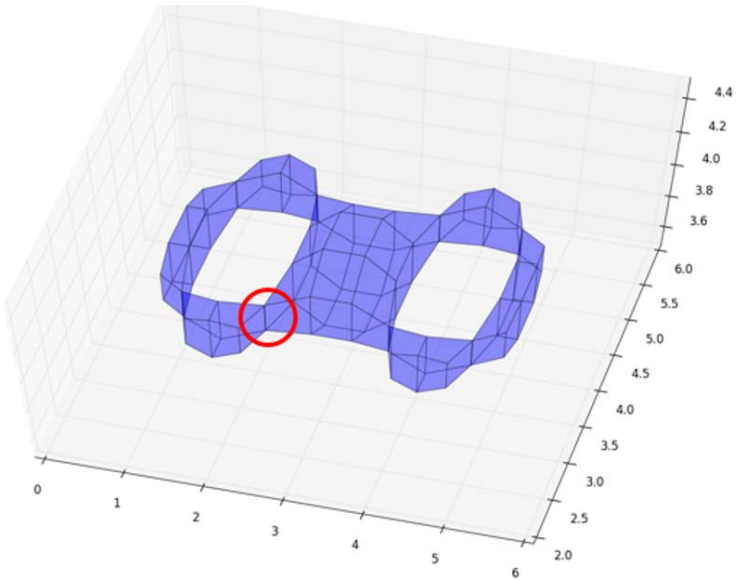


Dual Contouring — Problems

- **Non–manifold edges** appear
- One edge can only belong to two quads for the surface to be closed
- Special treatments in the implementation to avoid them



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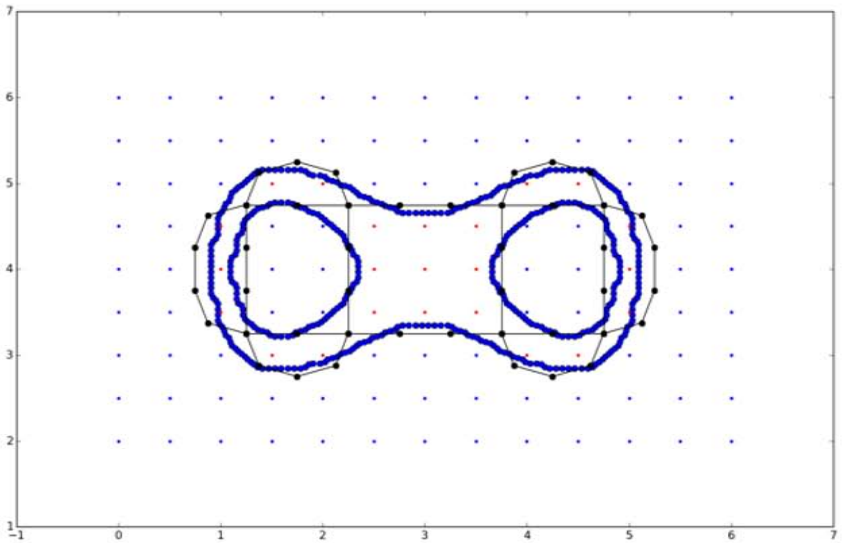
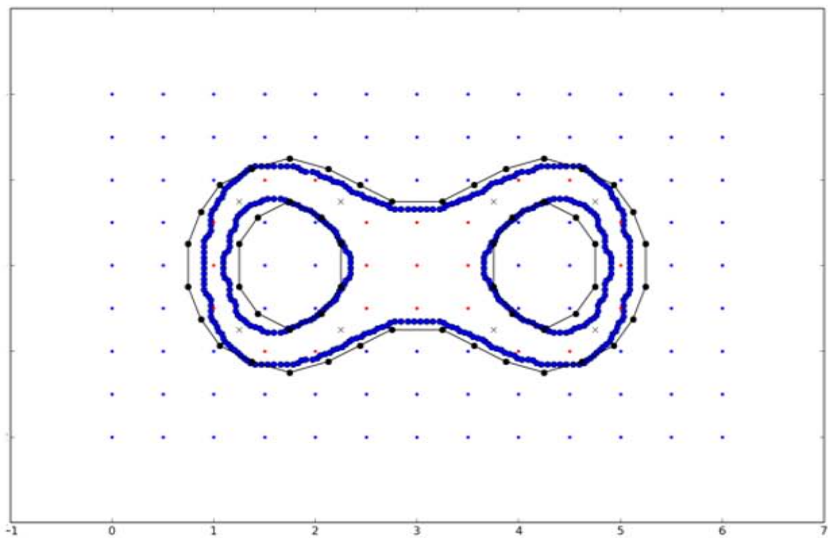
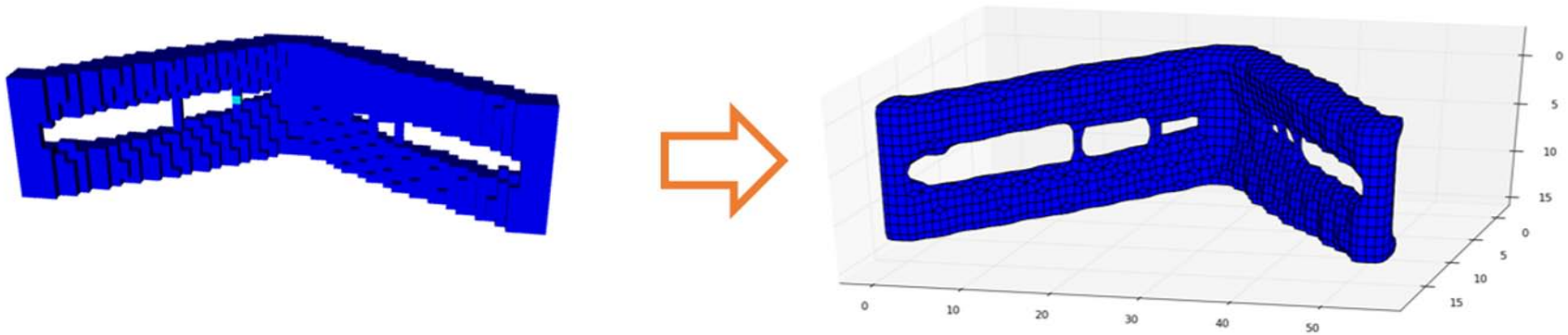
- One edge can only belong to two quads for the surface to be closed
- Special treatments in the implementation to avoid them





Dual Contouring — Input

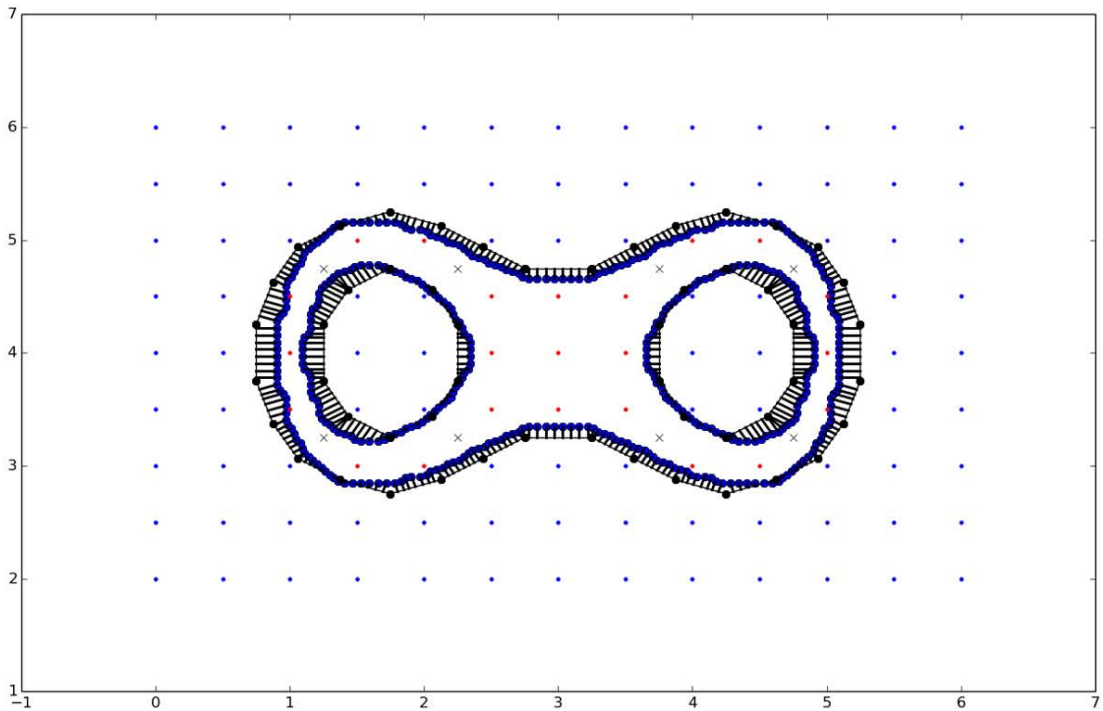
- Interface between Topology Optimization and Surface Extraction
- Special implementation to use voxel data from ToPy as input



Demo

Projection and Parametrization

- Points from finer grid are projected to quads of the coarser grid
- Parameters *u* and *v* are found for each quad
- This information is needed for the algorithms in the last part of the pipeline



Contents

B–Spline

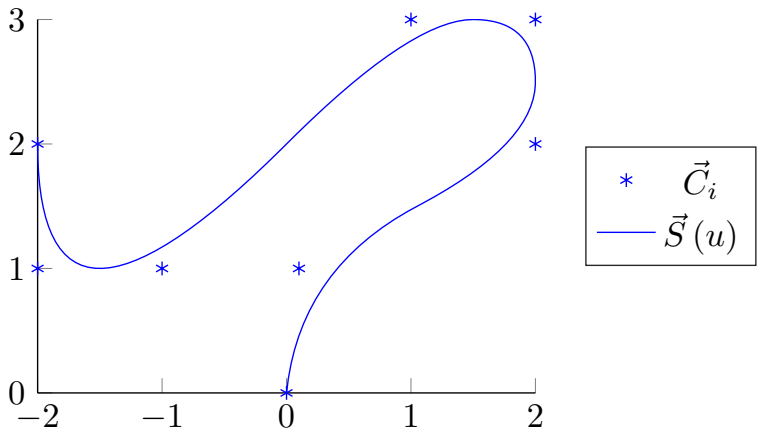
$$\vec{S}(u,v) = \sum_{i,j=1}^{n,m} \vec{C}_{i,j} N_i^p(u) N_j^p(v),$$

where p – degree of the B–Spline surface and n, m – number of control points in each direction.

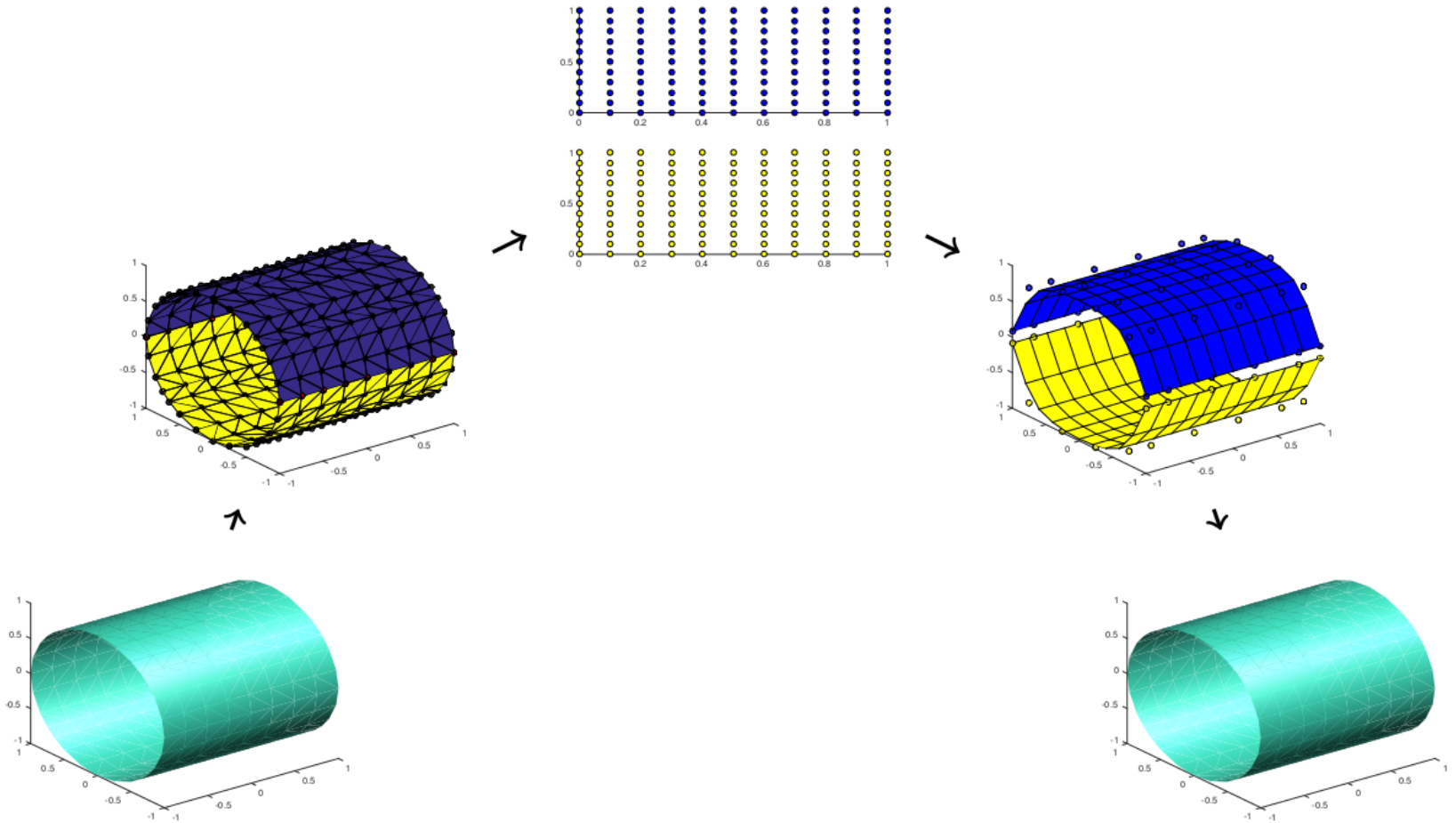
B–Splines

- offer great flexibility for handling arbitrary shapes
- are CAD–standard

Engineers are working with CAD



B–Spline Fitting Pipeline [2]



Status

Last milestone

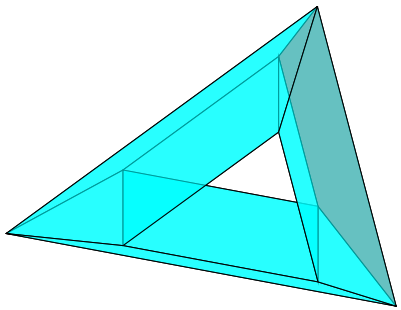
- ✗ Automatic patch selection
- ✗ Parametrization of obtained patches
- ✓ B–spline fitting using least squares
- 🕐 Smooth connection of patches
- ✗ Conversion back to CAD

Today

- ✓ Automatic patch selection – moved to the surface extraction part
- ✓ Parametrization of obtained patches – moved to the surface extraction part
- ✓ B–spline fitting using least squares – modified
- ✓ Smooth connection of patches
- ✗ Conversion back to CAD

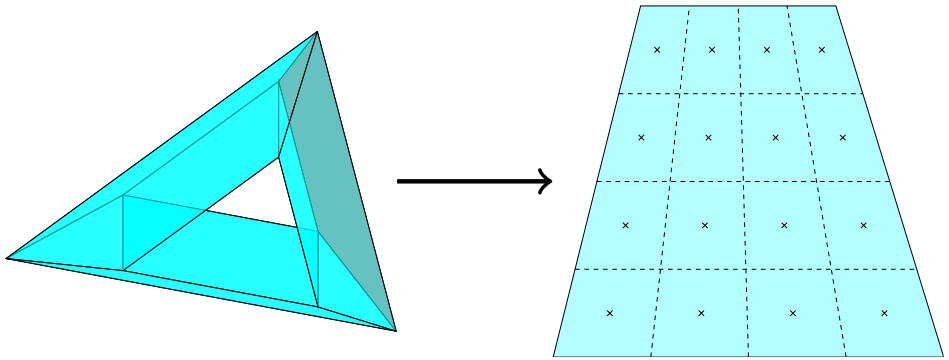
Long way to smoothness – Peter's scheme

Control mesh



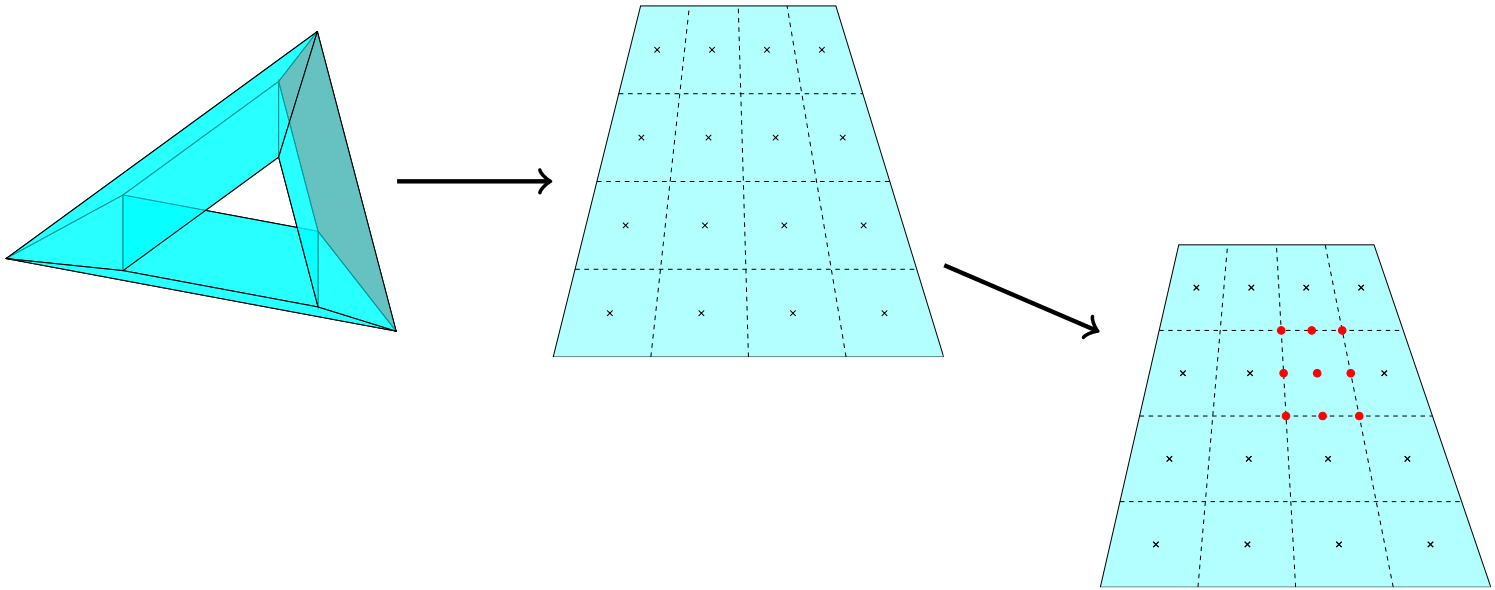
Long way to smoothness – Peter's scheme

Refined control mesh



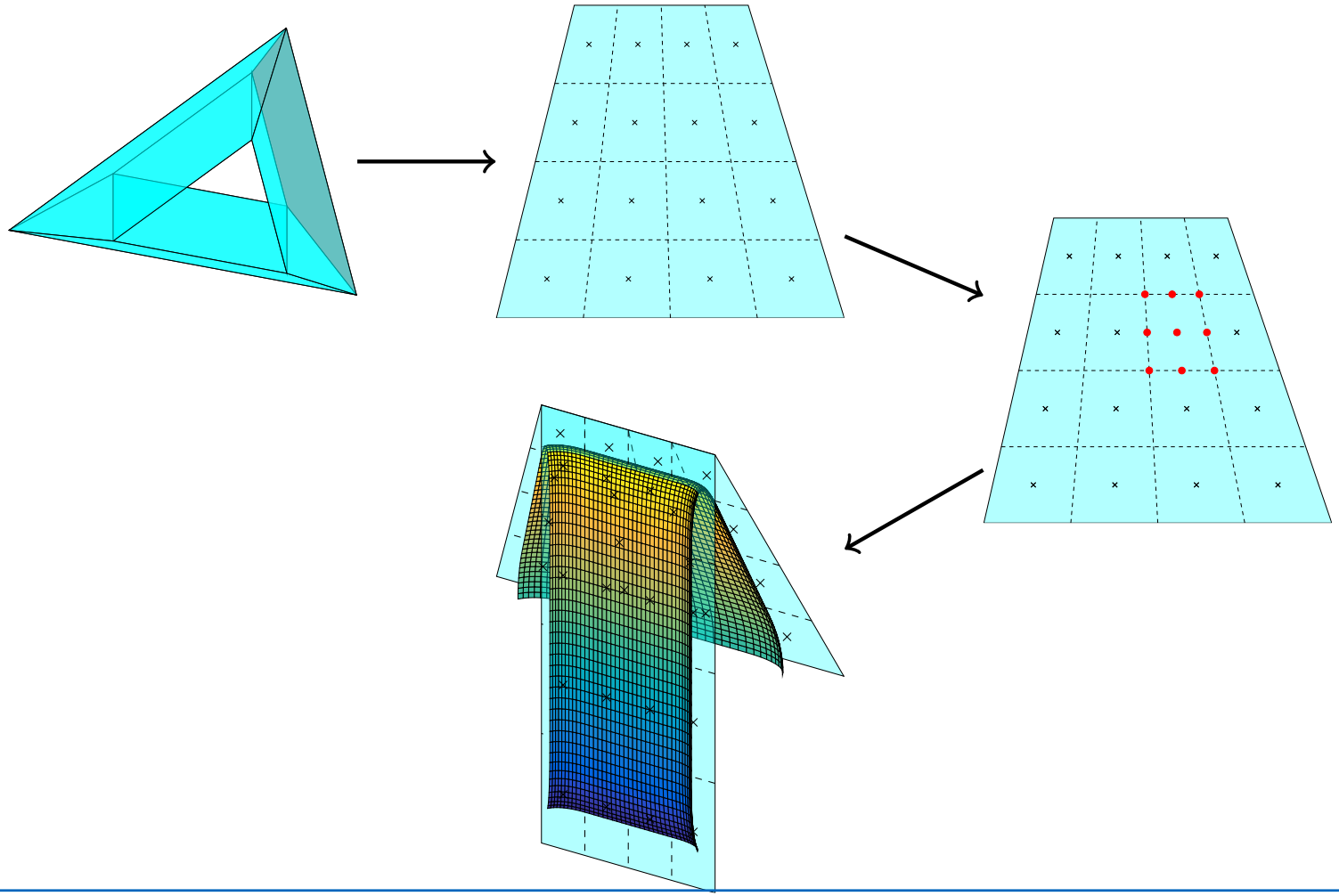
Long way to smoothness – Peter's scheme

Bezier control points



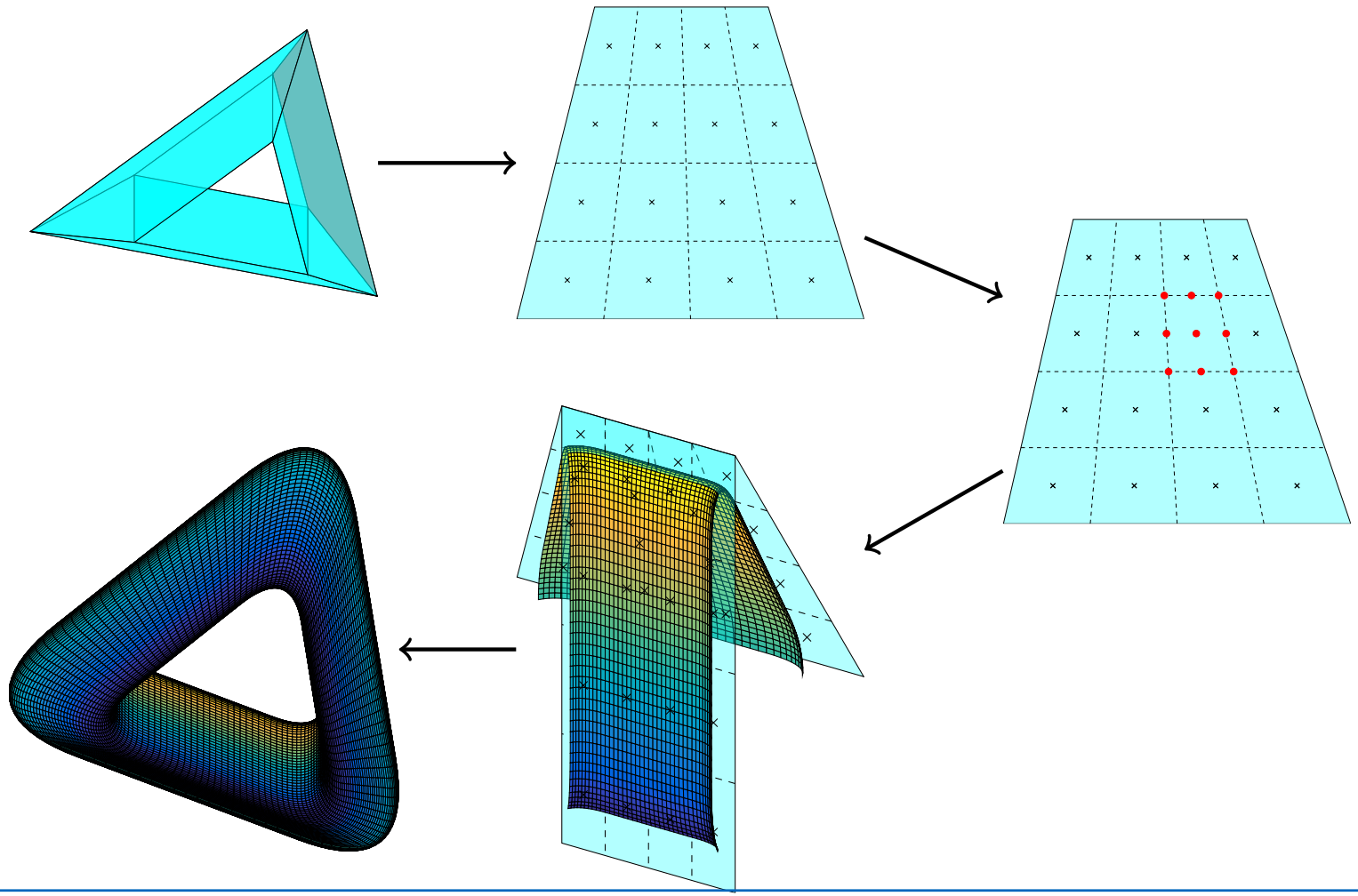
Long way to smoothness – Peter's scheme

B-Spline patch



Long way to smoothness – Peter's scheme

Peters' surface



Long way to smoothness

Main ideas

- Use the mesh obtained from Dual Contouring as a *control mesh*
- Modify the fitting step to take advantage of the **Peters' scheme**

$$\downarrow$$

$$E_{dist}(V_x) = \sum_{i=1}^{N} \| P_i - y_i V_x \|_2^2 \rightarrow min,$$

y_i - coefficients obtained from the Peters' scheme theory.

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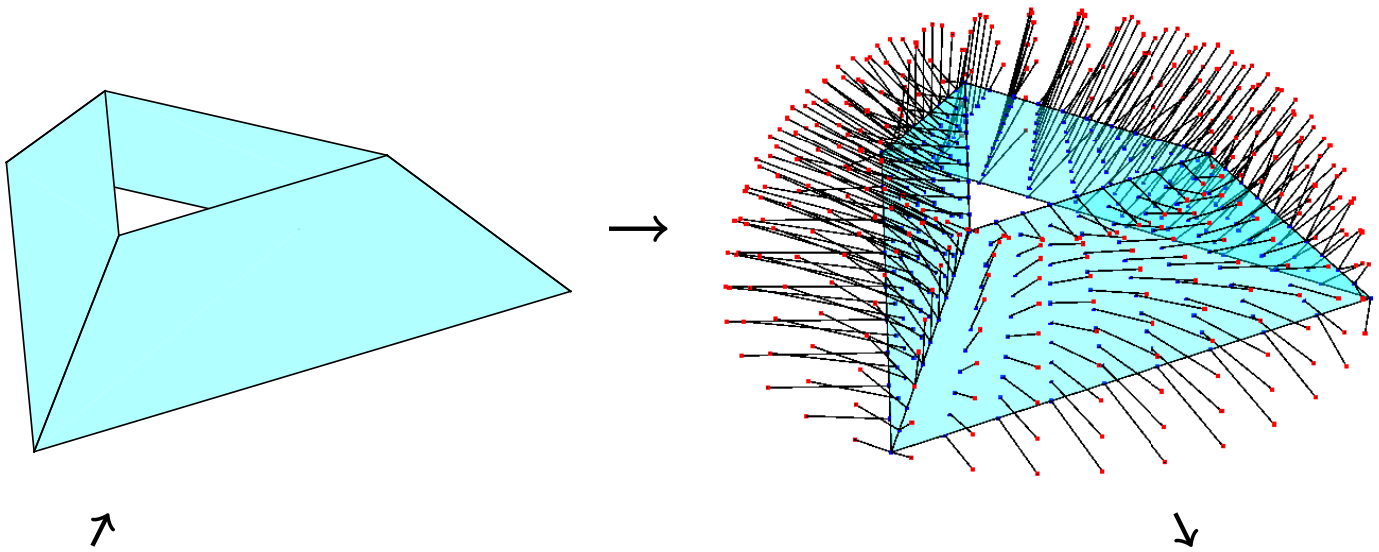
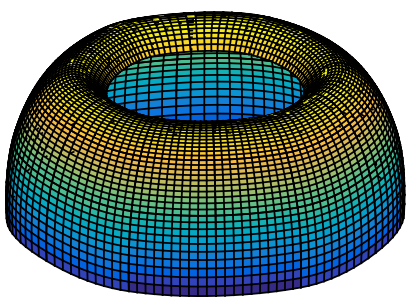
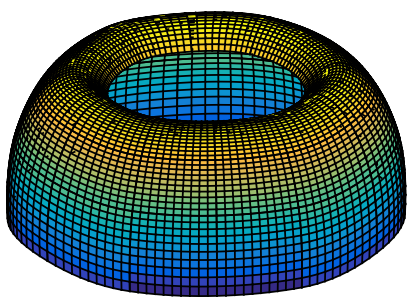
What is achieved?

- Smoothness of the fitted surface is now guaranteed by construction
- Fitting of more complex shapes achieved

Improved pipeline[3]

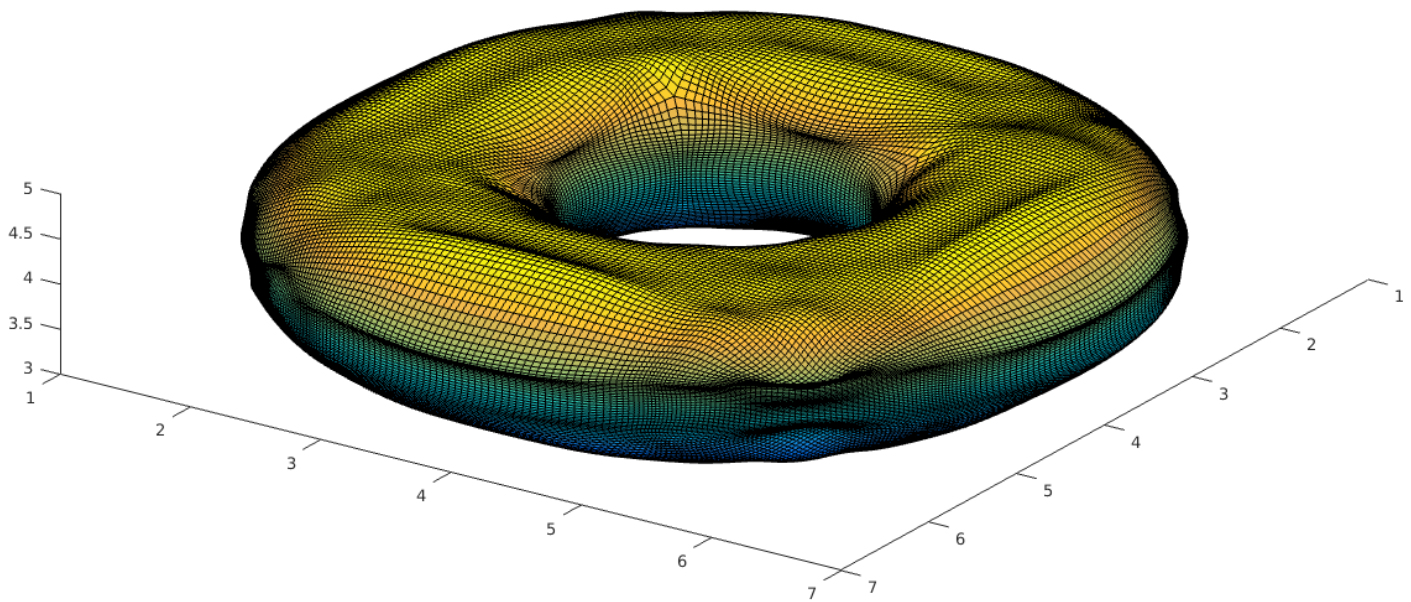






Possible optimizations

- Introduction of the *fairness functional* in order to deal with more complex shapes
- Implementation of the *adaptive refinement* in order to control a maximum error tolerance
- Implementation of the *parameter correction* for the improved pipeline



Contents

What is done? What is next?

- Topology Optimization
  - ✓ Pipeline from CAD model to optimized voxel model
  - ✓ User input of boundary conditions
  - 🕒 Support for complex geometries
  - ✗ GUI for user interaction

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Remaining questions

Python

- ⊖ First part of the pipeline is in C++
- ⊕ Second part of the pipeline is now in Python
- ⊕ Easy to port from the original MATLAB prototypes

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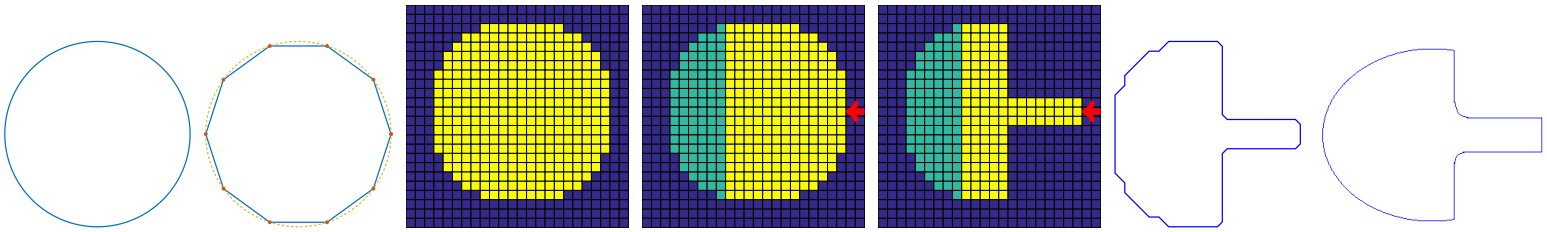
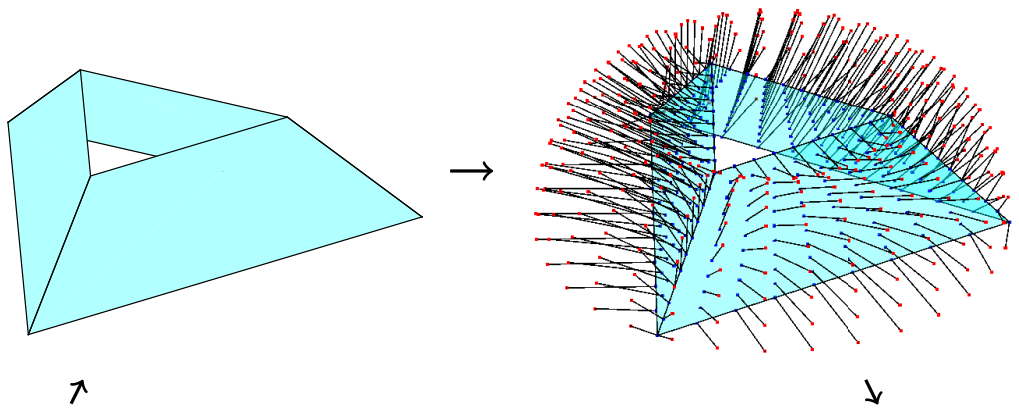
ToPy Problem

- ⊕ Current implementation is using ToPy
- ⊖ ToPy is not available any more!

Thank you for your attention!





Literature

1. **William Hunter.** ”Predominantly solid-void three-dimensional topology optimisation using open source software”
2. **Gerrit Becker, Michael Schäfer, Antony Jameson.** ”An advanced NURBS fitting procedure for post-processing of grid-based shape optimizations”
3. **Matthias Eck, Hugues Hoppe.** ”Automatic Reconstruction of B-Spline Surfaces of Arbitrary Topological Type”
4. **Greg Turk, Marc Levoy** ”Stanford Bunny”
5. **Tao Ju, Frank Losasso, Scott Schaefer, Joe Warren.** ”Dual contouring of hermite data”

Projection and Parametrization on arbitrary quads

1. find least squares plane approximating quad

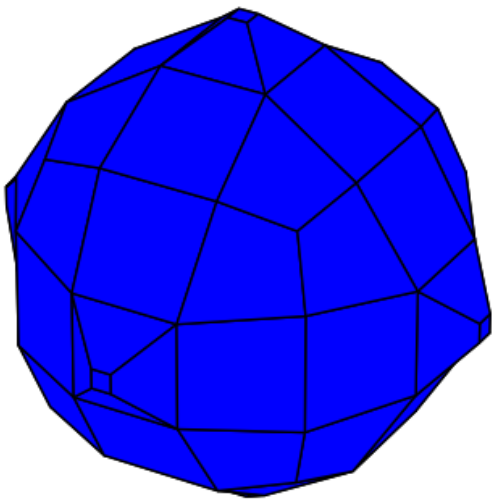


Figure : DC sphere

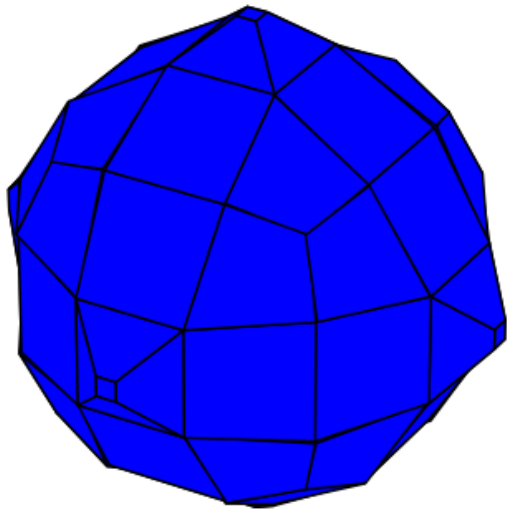
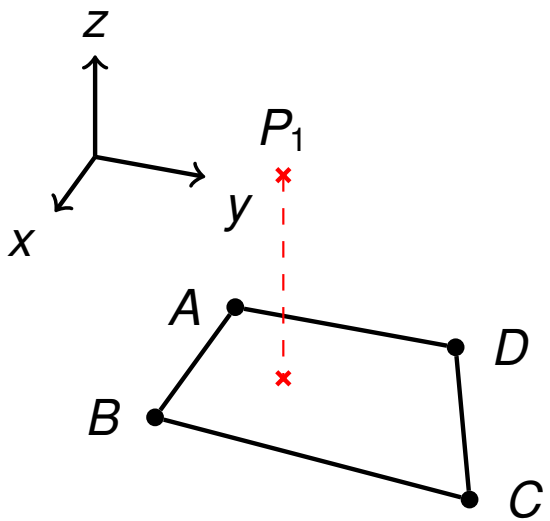


Figure : with plane quads

Projection and Parametrization on arbitrary quads

1. find least squares plane approximating quad
2. projection of datapoint onto plane



Coordinate transformation

system with basis

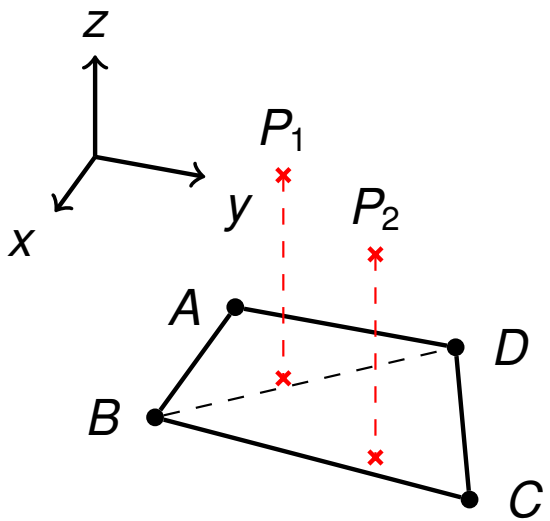
$$B_{BAD} = \begin{pmatrix} \vec{n} & \vec{AB} & \vec{AD} \end{pmatrix}$$

yields

$$(B_{BAD})^{-1} P_1 = \begin{pmatrix} d & u & v \end{pmatrix}^T$$

Projection and Parametrization on arbitrary quads

1. find least squares plane approximating quad
2. projection of datapoint onto plane
3. find corresponding parameters $[u, v] \in [0, 1]^2$



Problem:

- ✓ for P_1: $(u, v) = (0.5, 0.4)$
- ✗ for P_2: $(u, v) = (1, 1)$

Solution:

1. if we get $u + v > 1$
2. use B_{BCD} instead of B_{BAD}
3. set $u = 1 - u$, $v = 1 - v$