An optimization approach for automated as-built 3D modeling

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Outline

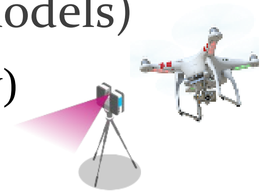
Section 1

BACKGROUND & OPPORTUNITY

1.1 As-built 3D modeling of civil infrastructures

- As-built models [1]
  - Increasingly important for AEC/FM†
    - Construction management
    - Facility management
    - Built env. conservation
    - Business with VR/AR, *etc.*
  - See as-planned, as-designed, as-demolished BIMs

- Popular technologies (surface models)
  - Photogrammetry (videogrammetry)
  - Point cloud
  - 3D Geographic information system
  - Others (statistical rules, deep learning [2], etc.)



†: Architecture, Engineering and Construction/ Facilities Management

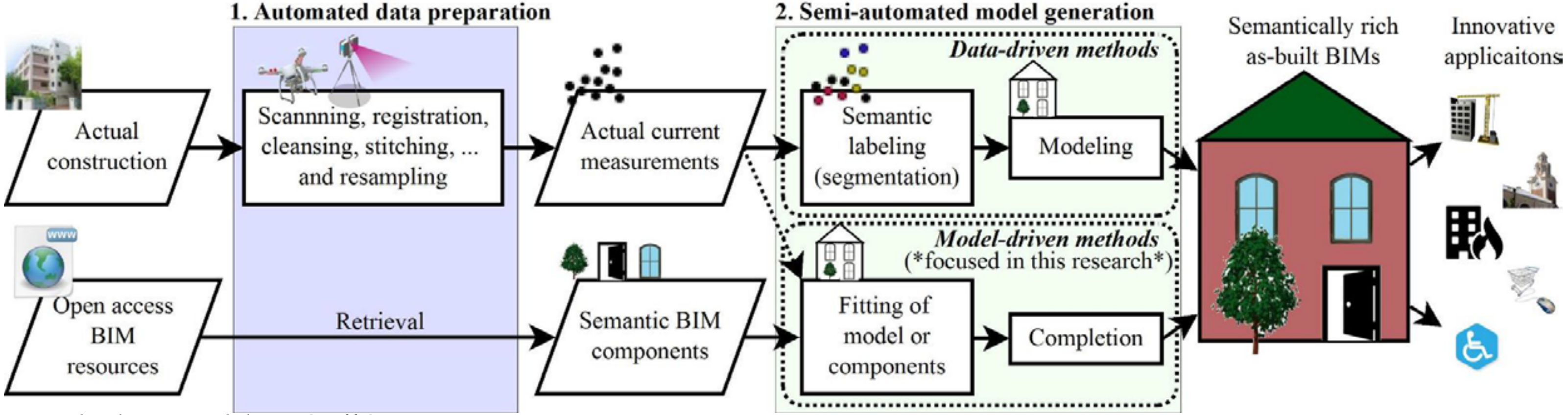
An example of photogrammetry: Kowloon Wall City (Source: patrick-@sketchfab.com)

An example of point cloud: Pompei City (Source: MAP-Gamsau lab, CNRS, France)

An example of GIS-based: 3D Berlin (Open Data, source: berlin.de)

1.1 The (semi-)automated as-built 3D modeling

- Two categories of methods
  - Data-driven v.s. Model-driven
- Some challenges remains
  - Unsatisfactory semantic/abstraction discovery
    - → huge size (data-driven), poor reusability(model-driven)
  - Others

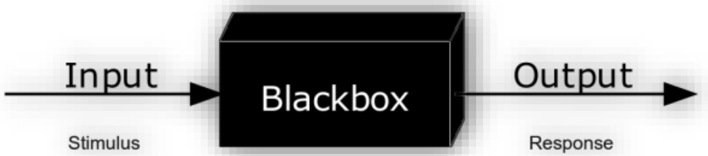


1.2 Derivative-free Optimization in OR†

- Optimization (a.k.a. Mathematical programming)
  - the selection of a *best* element (with regard to some criteria) from *some* set of available alternatives.
- Nonlinear optimization
  - When *objective function* or some *constraints* are nonlinear
- Derivative-free Optimization (DFO) [3]
  - *Objective function* or *constraints* are *unknown*
    - E.g., model selection, parameter tuning in simulations
    - Especially when function is *very expensive* or *unanalyzable*
  - Challenging (*NP*-hard), but achieved significant success
    - In applied science and engineering such as *molecular biology* and *material sciences*

$$\max f: \mathbb{R}^n \longmapsto \mathbb{R}$$

An example of optimization

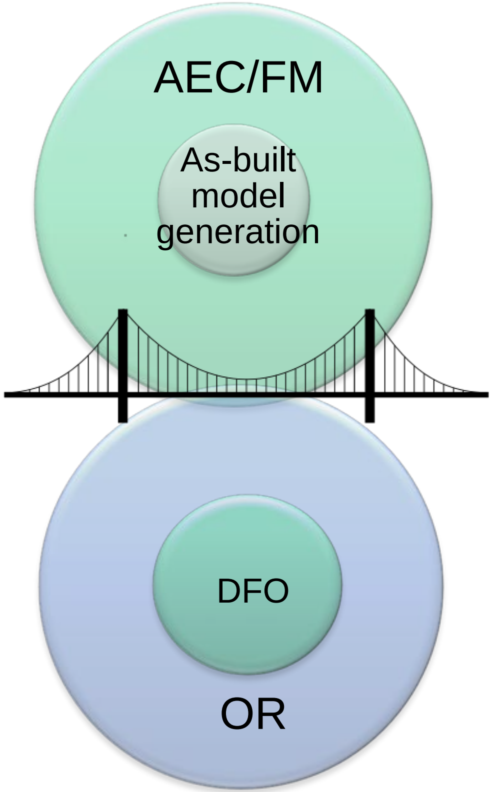


DFO: Manipulating a black-box
(Figure adapted from Wikipedia)

†: Operations Research

1.3 An opportunity

- The questions
  - *Can the model generation be generally solved by DFO methods?*
    - *If true, can semantic data be discovered at the same time?*
- If all true, we can
  - Map between a typical problem in AEC/FM and a class of powerful algorithms in OR
    - Also expose as-built model generation to many other nonlinear methodologies
  - Discover semantic (abstraction) information



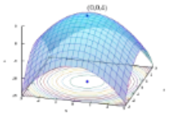
Section 2

AS-BUILT MODELING AS OPTIMIZATION

2.1 A meta-model of as-built 3D modeling

- Given a reference **measurement**, a set of parametric **components**
- A meta-model of optimization is from such a formulation:

$$\max f(X)$$
$$\text{s.t. } A(X) \le 0$$



Meta-model of constrained optimization & its solution space

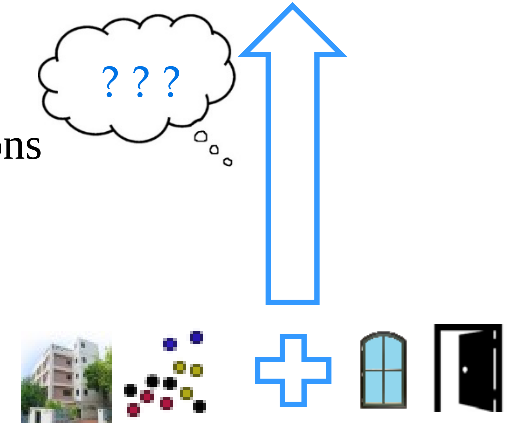
Tells computers:

What to change

What is good

Rules to follow

  - The **variables (X)** are the parameters of the components;
  - The **objective function (f)** is to maximize the similarity (or minimize dissimilarity) between the 3D model (as combinations of the parametric components) and the measurement; and
  - The **constraints (A)** over the variables are the topological relationships between components.
- Meta-: Abstraction
  - from Greek prefix *μετά*-, "beyond"

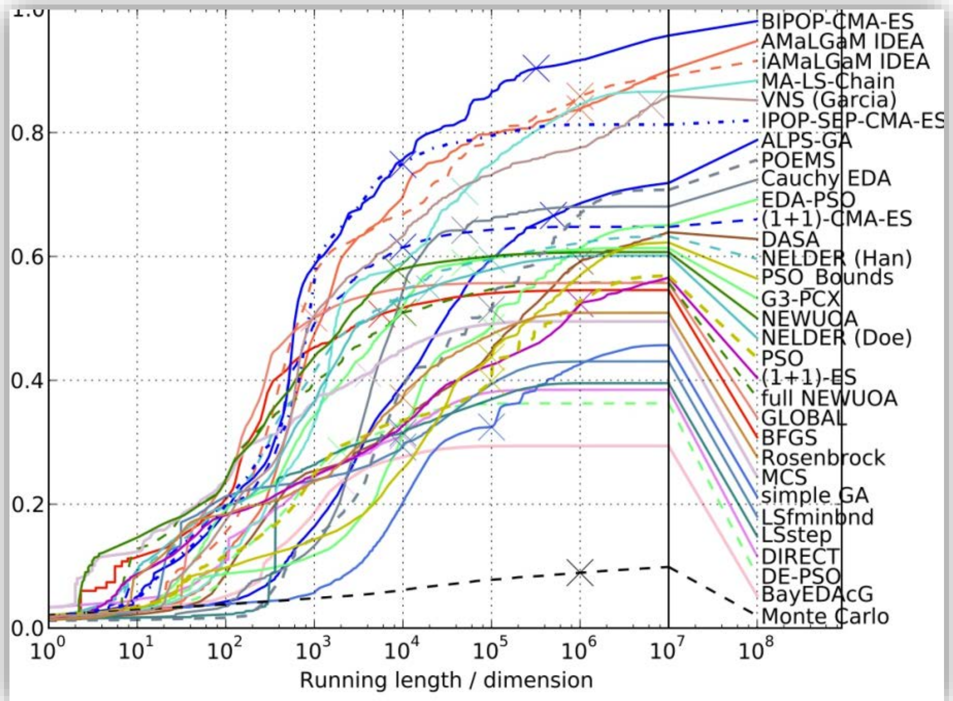


Reference measurements

Parametric (& semantic) components

2.1 Computational algorithms for the meta-model

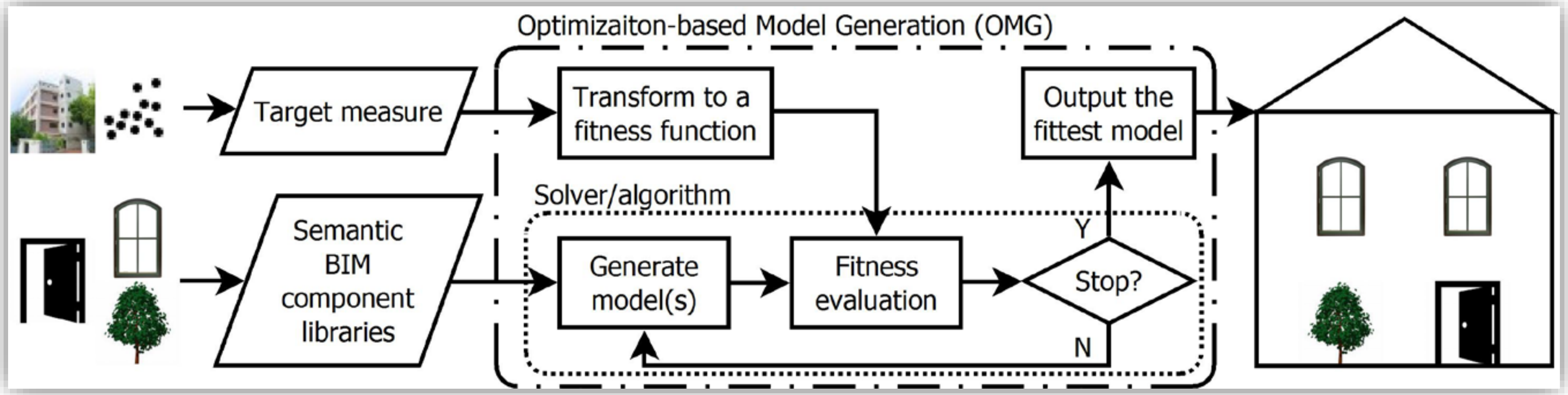
- Brutal-force search is impractical
- Fortunately, there are a long list of off-the-peg algorithms for solving such a meta-model as a black-box:
  - Surrogate methods
    - CMA-ES (Covariance matrix adaptation with evolution strategy) [5] and its variants are competitive
  - Trust-region methods
  - Metaheuristics (GA, PSO, VNS, *etc.*)
  - Hyper-heuristics, data mining
  - … and Monte Carlo



Comparison of algorithms for BBOB-2009 (Black-Box Optimization Benchmarking, higher is better) [4]

2.1 The framework: A bird's-eye view

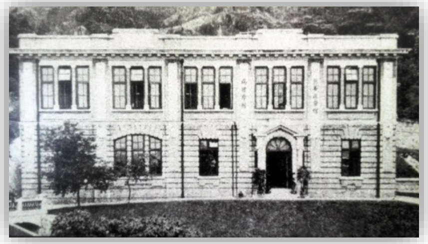
- The full framework of optimization-based model generation
  - Input 1: Reference measurements (photo, point clouds, video)
  - Input 2: Semantic and parametric components
  - Process: Systematically finding the fittest model by solving meta-model with DFO methods
  - Output: A semantic as-built model



The overall framework of optimization-based modeling

2.2 A pilot: A demolished building at campus

- The pilot case
  - A demolished baroque-style two-storey building
    - Once occupied by School of Tropical Medicine and School of Pathology, HKU
  - Input: A photo
- Preparing parametric components
  - Only apparent (>1m) components (for feasibility test)
  - 7 components were collected from *3D Warehouse* of *SketchUp*
    - With a keyword filter "*baroque*"
    - With limited (3) pairs of conflicting components
  - Adjusting components for the case
    - Removing extra parts, alignment



A historical photo (Source: MTR HKU Station, re-photographed by an Android phone)

- Door portico
- Tree × 2
- Wall × 2
- Windows × 2

(Contributors: Mohamed EL Shahed, Richard, KangaroOz 3D, Yoshi Productions, 3dolomouc, Architect, Ben @ 3D Warehouse)

2.2 The meta-model

- Meta-model of as a constrained optimization problem
  - Minimize the dissimilarity
    - Between the projected image of model and the input photo
    - E.g., Mean square error (MSE) of pixels or SSIM [6] †
  - With respect to topological constraints
  - Computational functions implemented on SketchUp (2016 Pro) Ruby API
    - Objective function interface
    - Variables as parameters (per component)

      Manifolds (0, 1) + scaling (*xyz*) + location (*xyz*) + ~~rotation ($\alpha\beta\gamma$)~~ = 4 ~ 6 variables
    - Constraints of topological relationships
  - A virtual *Ground* object is placed at first

min f = *dissimilarity*

= 1-SSIM†

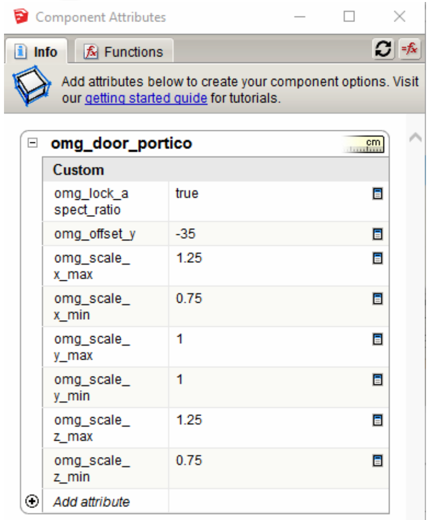
(or maybe f =MSE of pixels)

s.t. Semantic constraints of *position*, *scaling*, and *ABOVE*/ *BELOW*/ *CONTAINS_ON* for each component

†: Structural similarity

2.1 Details of the topological relationships

- Topological relationships
  - Categories
    - Adjacency: ABOVE, BELOW, NEXT_TO, …
    - Separation: SEPERATED
    - Containment: CONTAINS_ON, CONTAINS_IN
    - Intersection: INTERSECTS_WITH
    - Connectivity: CONNECTS_TO
- Semantic definition
  - Adding properties like *scaling* and *topological relationships* to their SketchUp dictionaries
    - E.g., ABOVE, BELOW, CONTAINS_ON, *etc.*



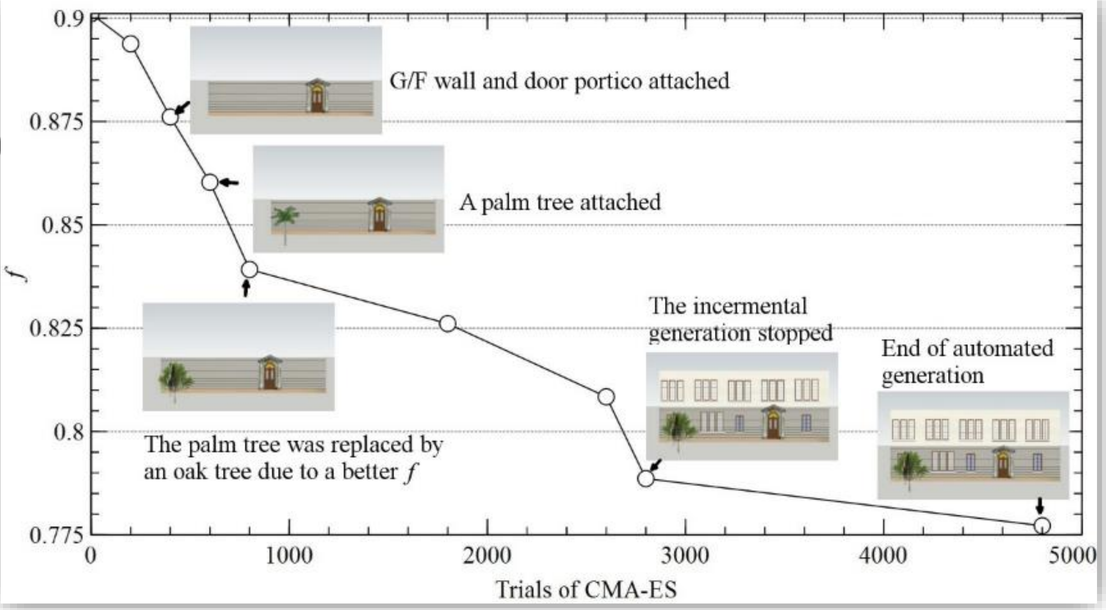
An example of the dictionary of component in SketchUp

Time of preparation of components

- Collection (~15 minutes)
- Adjustment (~30 minutes)
- Semantic def. (~15 minutes)

2.2 An earlier computational experiment in 2016

- Automated generation
  - Two phases:
    - Incremental (2,800 trials)
    - Refinement (2,000 trials)
  - The Solver: CMA-ES (C++ code [7] in a Ruby wrapper)
  - Time: 3,822.4s†
    - After so much simplification
  - Fault-tolerant (see the trees)
  - Semantic/grammar-enhanced



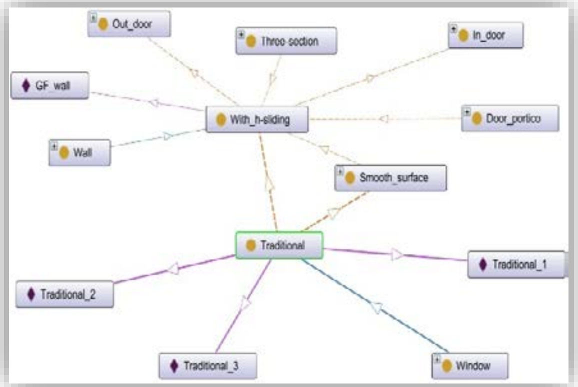
Automated generation of semantic as-built model as solving the nonlinear optimization problem, by a well-known DFO algorithm CMA-ES in 3,822.4 seconds (4,800 trials, single thread) on an Intel i5-6500 CPU (3.2 GHz)

† : Should be much faster now.

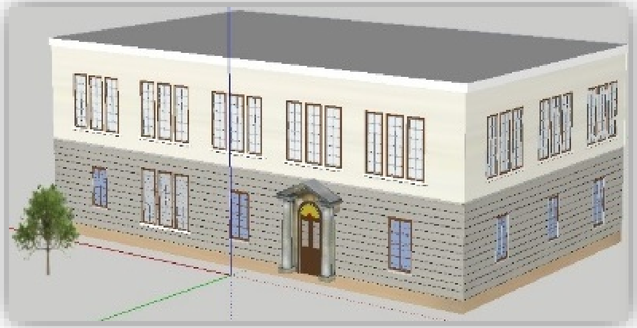
2.2 Results and post-processing

- Obtained
  - The facade in the photo
  - Semantic links
- Post-processing
  - Manual completion
    - Copy & paste
  - Georeferencing and display in 3D

(a) Direct result: The façade in the photo



(b) The semantic links illustrated in Stanford Protégé (Circle denotes a component class and a diamond stands for an instance/object)

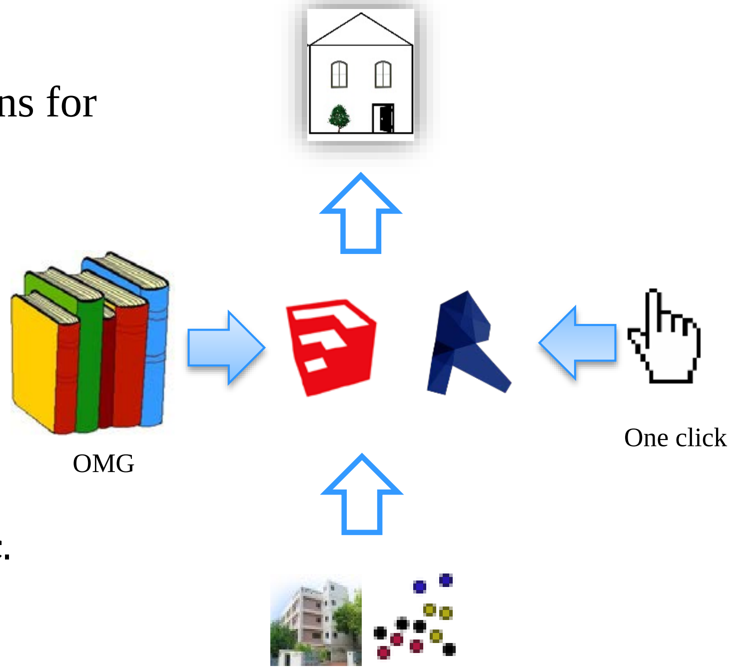


(c) Manually completed approximate model (~15 minutes)

(d) Georeferencing and illustration on Google Earth, near MTR Exit A (~5 minutes)

3.3 OMG & live demonstration

- A library OMG (optimization-based model generator) is under development
  - A shared computational library with specific plugins for
    - SketchUp, Revit, *etc*.
  - Multiple meta-models with various
    - Objective functions
    - Measurement types, and
    - Solving algorithms
  - Multiple modeling options
    - Ontology-guided, free discovery, finetuning, etc.
    - Extended the earlier pilot study
- Demo (more efficient now)



Section 3

DISCUSSION & FUTURE RESEARCH

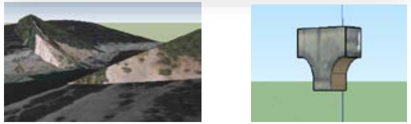
3.1 Discussion

- Meta-modeling of as-built 3D modeling as constrained optimization
  - Pros: General, simple, no explicit object recognition/segmentation (also challenging)
  - Cons: A larger search space (slower), slow full projection, limited by pixels, less accurate
- Semantic definitions of components
  - Pros: Realized 'grammar' of components, simplified optimization
  - Cons: Some manual work needed, subject to redefinition from a project to another
- The framework as a whole
  - Pros: High automation, reusing components and abstractions, less requirements on equipment, tolerant to errors, scalable to new environments, (hopefully) semantically rich
  - Cons: Less accurate in geometry, still in its *infancy*
  - Answers to the question: 1) True; 2) Applicable to some relations
    - Semantic recognition/segmentation is another pillar for semantic BIM

3.2 Future research

- Effectiveness
  - More didomains (e.g. infrastructures, *etc*.)
  - Advanced DFO methods
  - More objective functions
  - On real BIM/CIM models instead of surface models
- Efficiency
  - Efficient ways of manipulating point clouds (working…)
    - E.g., *k*d-tree, approximate *k*NN, convex hull, planar and object detection
- Extensions
  - Shared component libraries for reusability (e.g., IFC-compatible)
  - Handling other challenging AEC/FM problems

We are still on the way (Source: clipartpanda.com)



The Roman aqueduct Pont du Gard
(Source: Wikipedia/ 3Dwarehouse.com)

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- [2] Patraucean, V. (2016). Deep machine learning: key to the future of BIM? Cambridge: University of Cambridge, Mar 14 2016. Accessed July 15 2016. http://www-smartinfra structure.eng.cam.ac.uk/news/viorica-patraucean-featured-in-infrastructure-intelligence-.
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- [4] Auger, A., Finck, S., Hansen, N., and Ros, R. (2010). BBOB 2009: Comparison tables of all algorithms on all noisy functions (PhD thesis, INRIA).
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- [6] Wang, Z., Bovik, A. C., Sheikh, H. R., and Simoncelli, E. P. (2004). Image quality assessment: from error visibility to structural similarity. IEEE Transactions on Image Processing, 13 (4): 600-612.
- [7] CMA-ESpp, an open source library, see: https://github.com/AlexanderFabisch/CMA-ESpp

Thank You !

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