Resource-Driven Product Family Design in Additive Manufacturing

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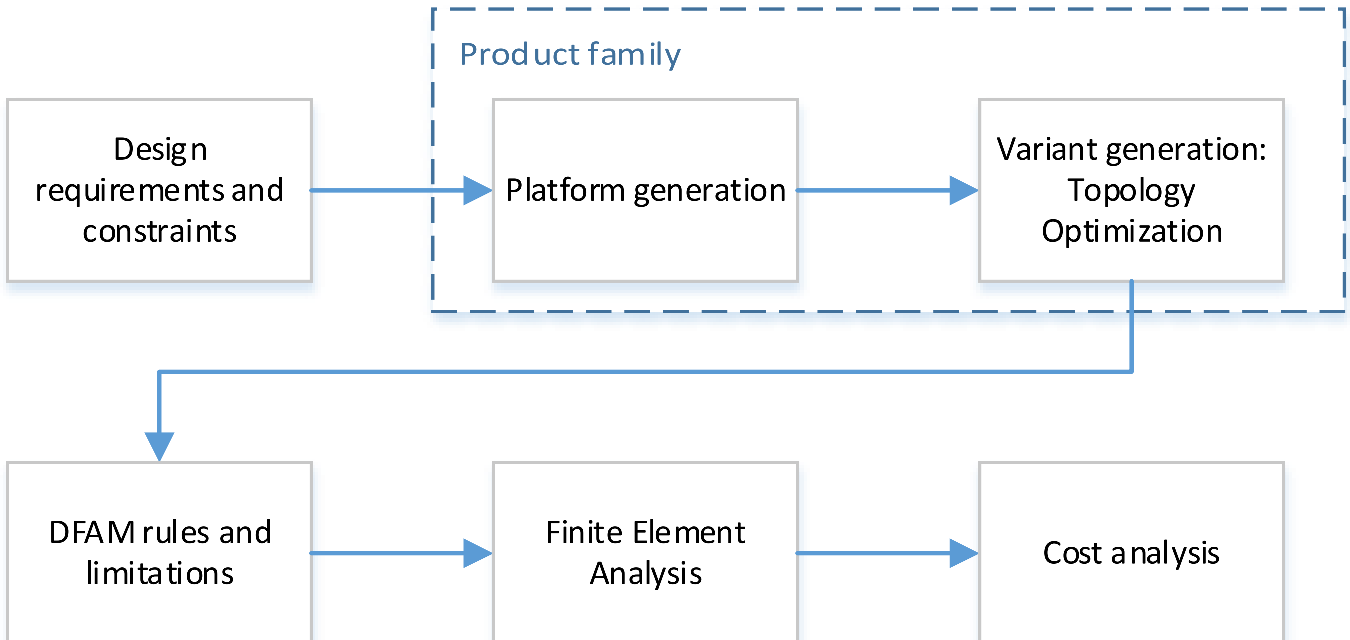
Introduction

- Product family
  - A group of related products (variants) derived from a set of common elements (platform) [1]
- Additive manufacturing (AM)
  - Manufacture products with complex geometry, ideal for customized product design [2]
- Resource-driven product family design in AM
  - Resource (material, manufacturing time, cost) as a key design consideration in product family design in AM

[1] T. Simpson, Z. Siddique, and J. Jiao, "Platform-Based Product Family Development," in *Product Platform and Product Family Design*, T. Simpson, Z. Siddique, and J. Jiao, Eds., ed: Springer US, 2006, pp. 1-15.
[2] R. Ponche, J. Hascoet, O. Kerbrat, and P. Mognol, "A new global approach to design for additive manufacturing," Virtual and Physical Prototyping, vol. 7, no. 2, pp. 93–105, 2012.

Methodology

- Overview of the proposed design framework



Methodology

- Topology Optimization (TO)
  - TO algorithms distribute finite elements of material within a predefined space [3]
  - Solid Isotropic Material with Penalization (SIMP) approach [4]:
    - Power law of material properties
    - Objective: minimize structure compliance under loading
    - Constraint: total amount of material (volume fraction)

[3] M. P. Bendsøe and O. Sigmund, Topology optimization: theory, methods and applications / M. P. Bendsøe, O. Sigmund., ser. Engineering online library. Berlin; New York : Springer, 2003., 2003.
[4] M. Bendsøe, "Optimal shape design as a material distribution problem," Structural optimization, vol. 1, no. 4, pp. 193–202, 1989.

Methodology

- Design for additive manufacturing (DFAM) rules and limitations
  - Process/machine-dependent
  - Minimum wall thickness, minimum hole diameter, maximum build envelope, etc.
  - Modify each variant design based on these rules and limitations

Methodology

- Cost analysis
  - Manufacturing time and cost are measures of resource consumption of each variant in the product family
  - Manufacturing time

$$t = t_{setup} + t_{preheat} + \sum_{i=1}^{n} t_i$$

Where:

t_{setup} = Machine setup time
$t_{preheat}$ = Preheat time
t_i = Time to build the i-th layer
n = Total number of layers of one part

Methodology

- Cost analysis
  - Total manufacturing cost of each variant in the product family

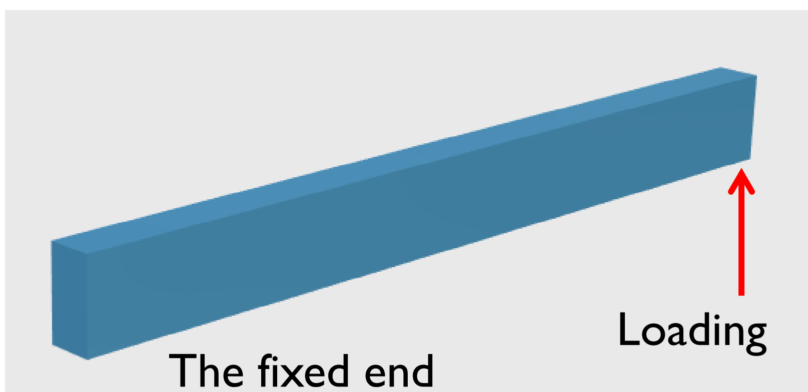
$$C = C_{material}M + C_{operation}t + C_{manpower} + C_{overhead}$$

Where:

$C_{material}$ = Unit cost of material usage per gram
M = Total mass of the material usage
$C_{operation}$ = Machine operation cost per hour
t = Total time to build a part
$C_{manpower}$ = Manpower cost in preparing the build as well as post-processing
$C_{overhead}$ = Other overhead cost

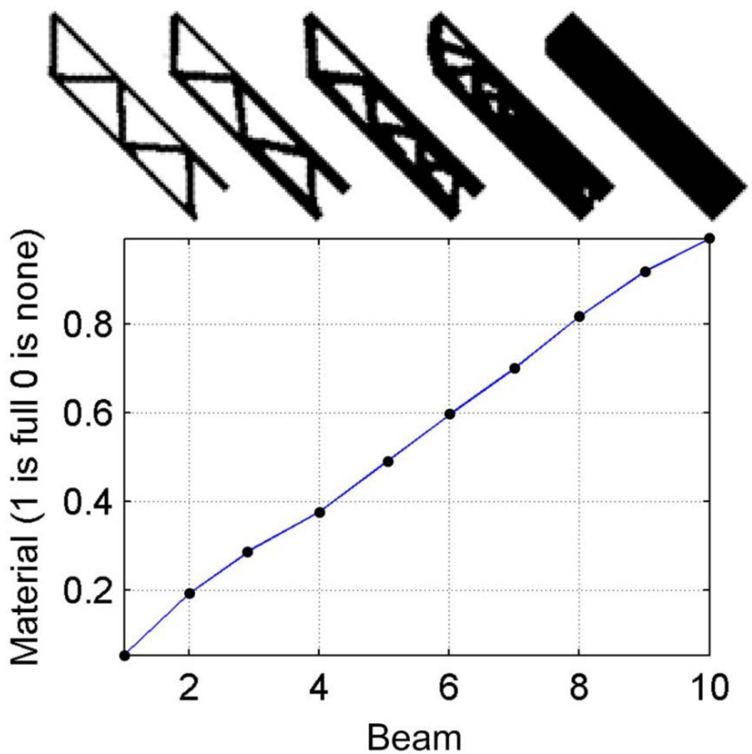
Case study

- Cantilever beam: fixed at one end, load = 10N at the free end
- Design requirements: low compliance upon loading, light-weight
- Platform
  - A solid rectangular cantilever beam
  - Length = 200mm, height = 20mm, thickness = 10mm



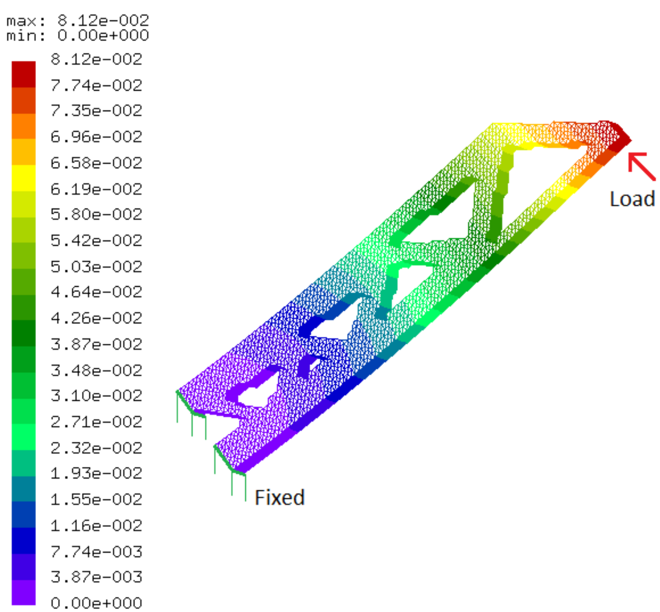
Case study

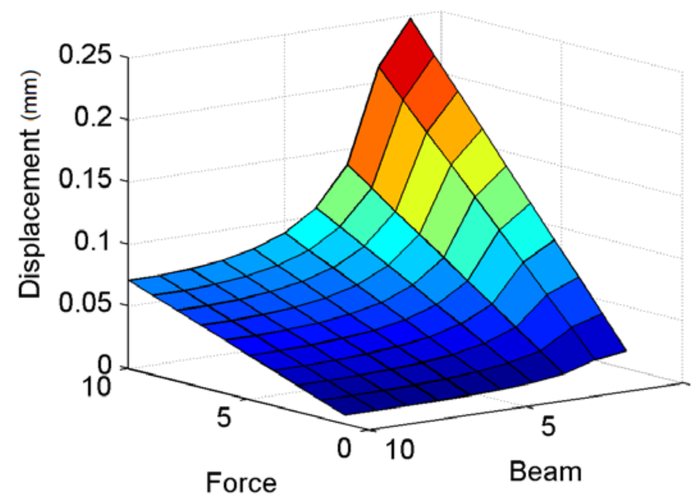
- Variant generation – Topology optimization (SIMP)
  - 10 variants, with different overall material consumption (measured in volume fraction): 10%, 20%, … 100%



Case study

- FEA, using Calculix
  - Simulate the maximum displacement at the free end
  - A tradeoff is found between material consumption and structural strength



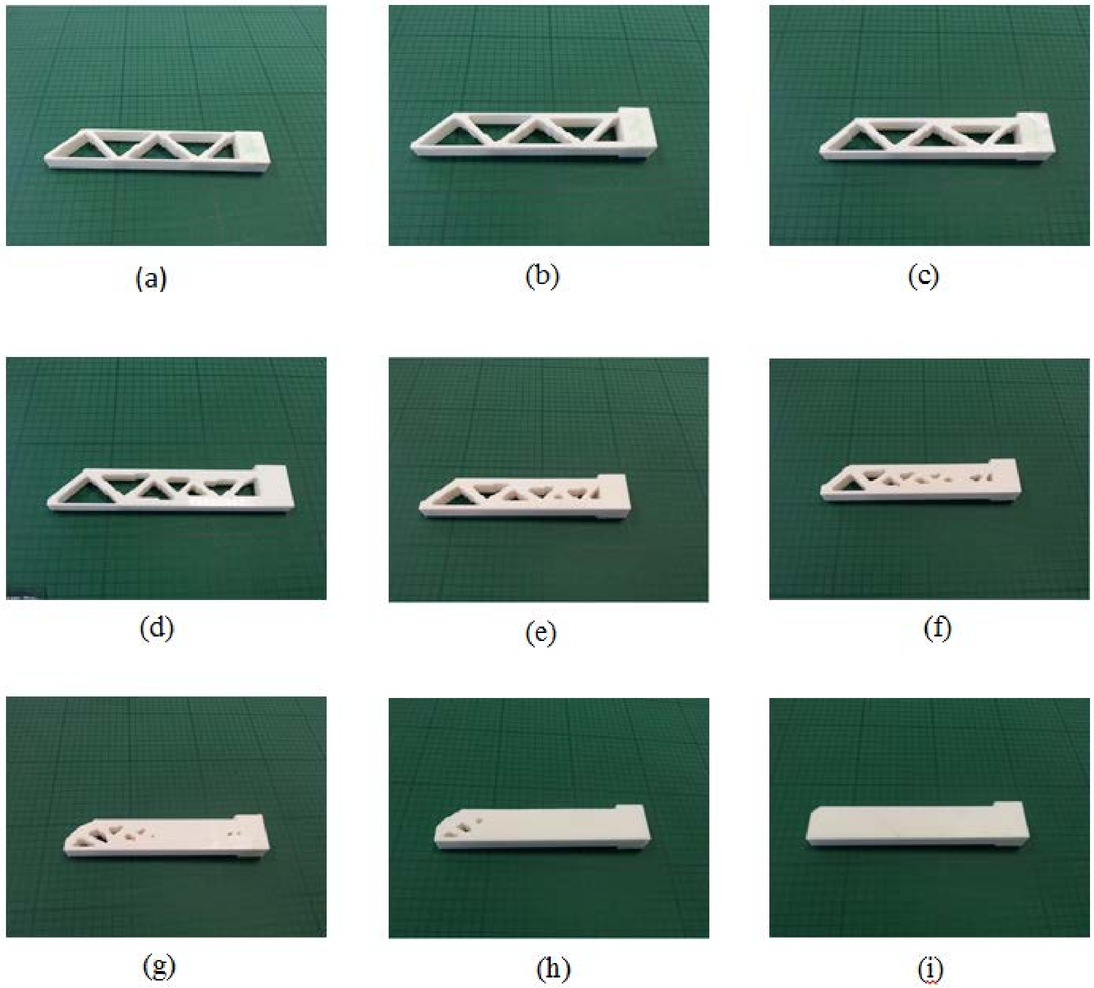


Case study

- Design for AM rules and limitations
  - Fused Deposition Modeling (FDM) process
  - Minimum allowable wall thick = 0.8mm → Beam NO. 1 (10% material) is not manufacturable
- Additive manufactured samples:
  - Beam NO.2 to NO. 10 were built by FDM
  - Material: Polylactic acid (PLA) thermoplastics

Layer thickness (mm)	Fill density (%)	Print speed (mm/s)	Track width (mm)	Nozzle temperature (°C)	Platform temperature (°C)
0.1	100	80	0.4	210	55

Case study



Nine beams of the family: (a) Sample NO. 2; (b) Sample NO. 3; (c) Sample NO. 4; (d) Sample NO. 5; (e) Sample NO. 6; (f) Sample NO. 7; (g) Sample NO. 8; (h) Sample NO. 9; (i) Sample NO. 10

Case study

- Manufacturing time and cost of each variant in the product family

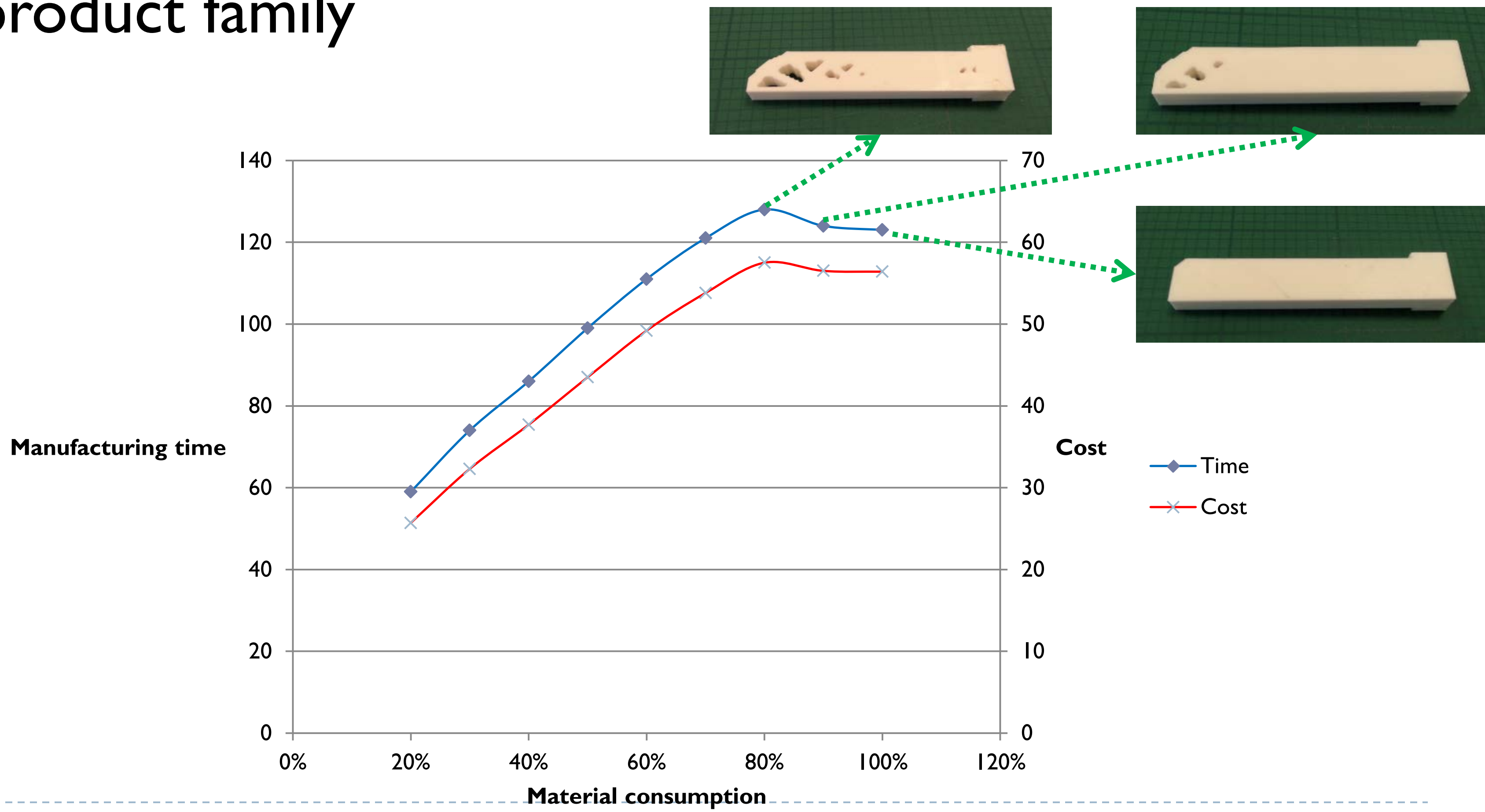
$$t = t_{setup} + t_{preheat} + \sum_{i=1}^{n} t_i$$

$$C = C_{material}M + C_{operation}t + C_{manpower} + C_{overhead}$$

Sample NO.	2	3	4	5	6	7	8	9	10
Material consumption	20%	30%	40%	50%	60%	70%	80%	90%	100%
Manufacturing time (min)	59	74	86	99	111	121	128	124	123
Cost ($)	25.7	32.3	37.7	43.5	49.2	53.8	57.5	56.5	56.4

Case study

- Manufacturing time and cost of each variant in the product family



Closing remark

- A resource-driven product family design framework in additive manufacturing
- Parts with complex geometry and material distribution can be manufactured by AM, which provides more freedom to product family design
- Tradeoff is found between product performance and resource consumption
- Resource consumption (material usage, manufacturing time, and cost) can be a consideration for selecting production plan

Future work

- Costing models for other AM processes
- More complex products, perhaps with assemblies

THANK YOU