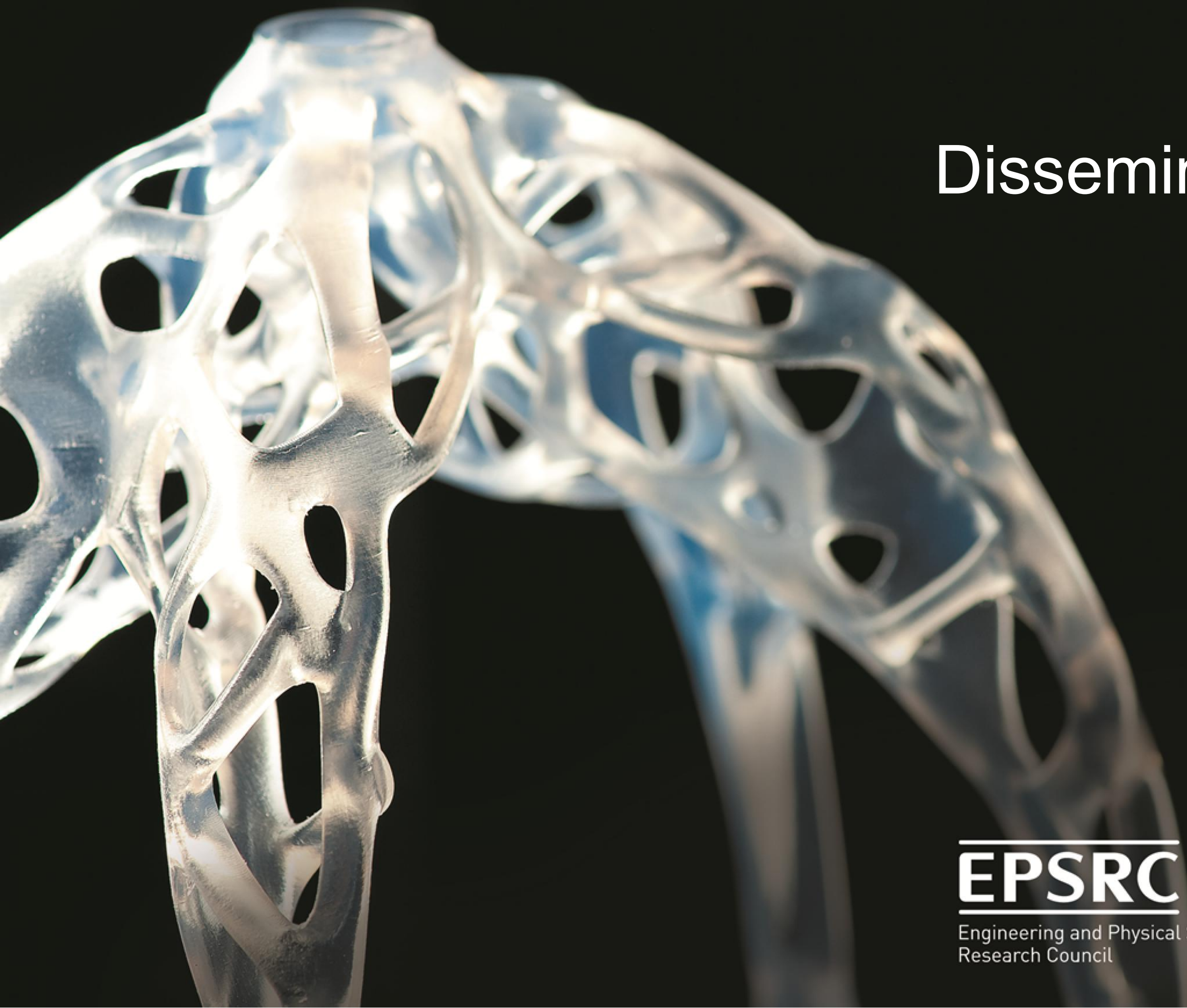
EPSRC Centre for
Innovative Manufacturing in
Additive Manufacturing

3DP-RDM:
A total cost model

Dissemination Workshop
Cambridge
13-14 Jan 2016



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Agenda

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- Project motivation and goal
- Methodology
- Model results
  - Relevance for average cost models of AM
- Evidence of learning effects
  - Impact of process repetition
- Conclusions

Project motivation and goal

Motivation

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- Started with existing unit cost models of the ‘break even’ type
  - For comparison of cut-off quantities for different processes
- Most describe a relationship between production quantity (X-axis) and average cost (per unit, Y-axis)
  - Effectively describing a cost function

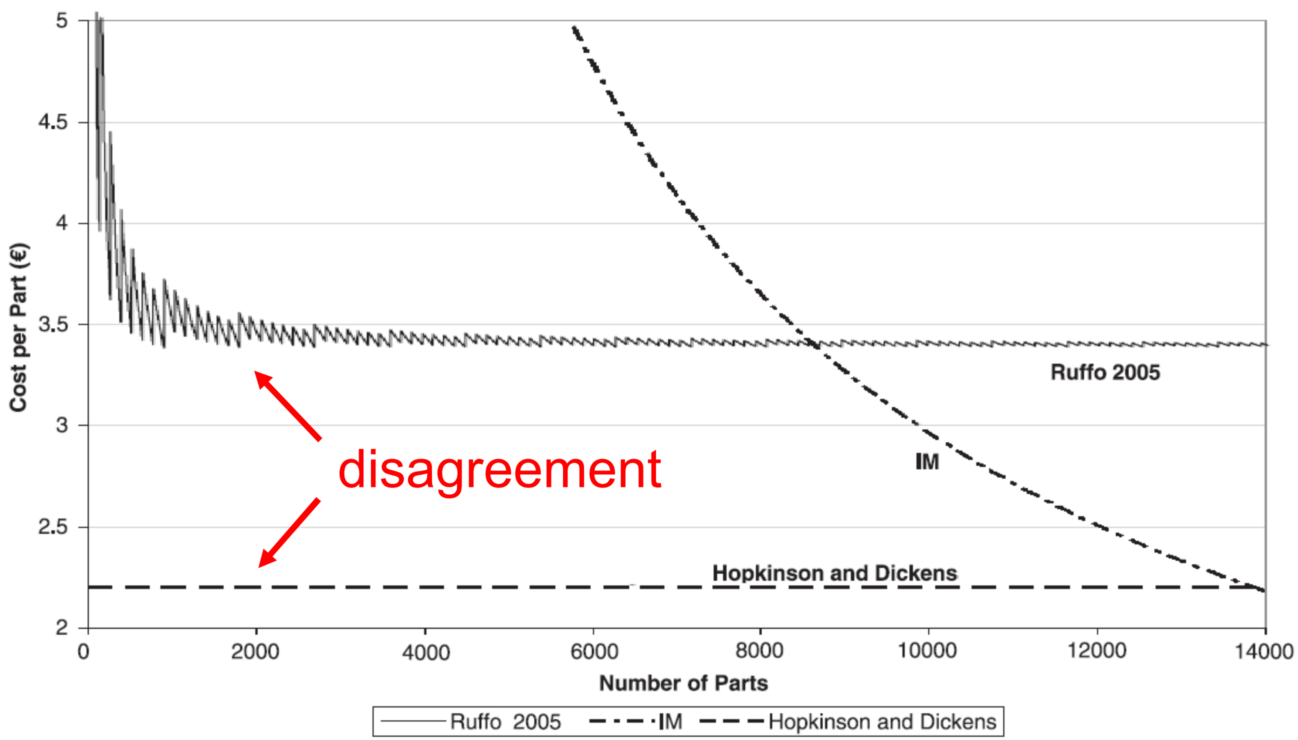

Image adapted from Ruffo et al., 2006

Injection moulding (IM): Average costs driven by high initial cost for the mould, then followed by low marginal unit cost

Hopkinson and Dickens (2003): look exclusively at full capacity AM

Ruffo et al., 2006: Average cost is pushed up by empty build volume space at low quantities (LS)

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Existing costing models

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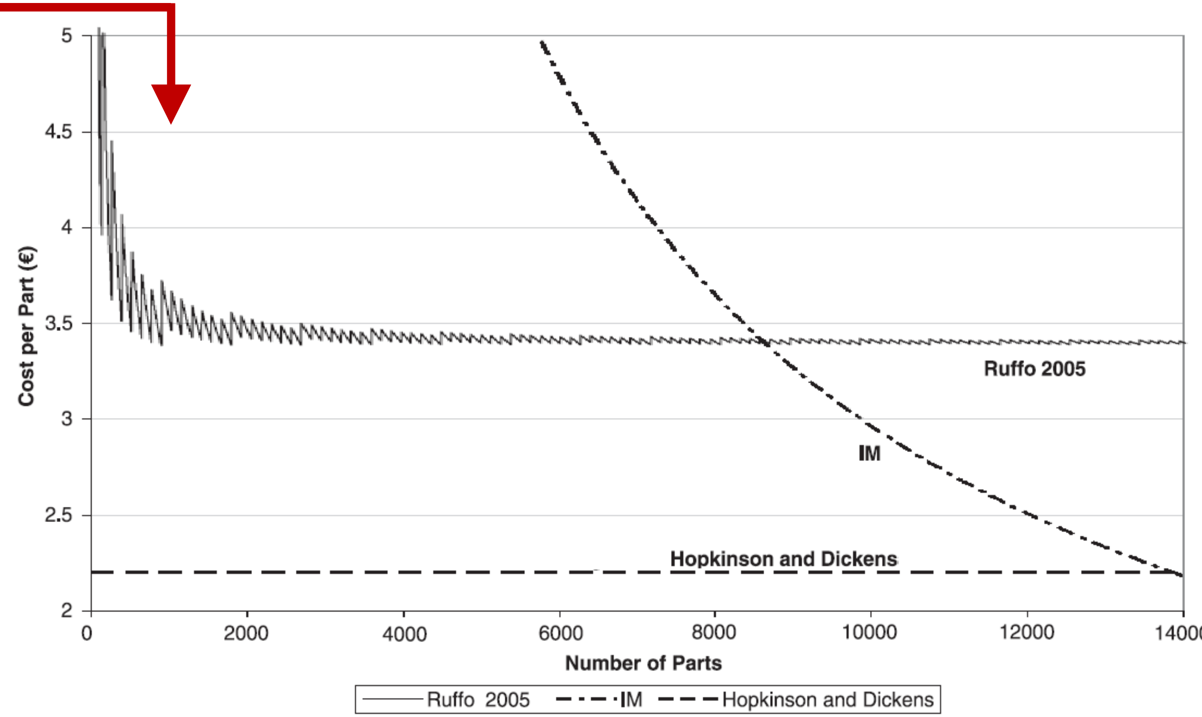
- Problem with models of the 'break even' type: Some AM machines don't operate efficiently if capacity is left empty

Build configurations with empty build volume space describe inefficient machine operation.

The user could:
1. Include other parts
2. Buy a smaller machine



Research requirement

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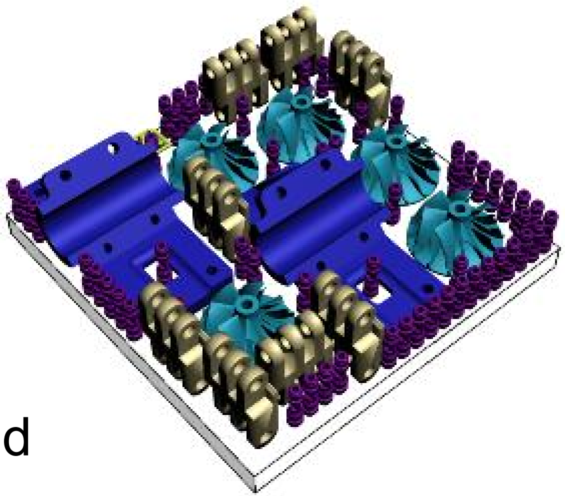
- Cost models ("functions") describe situations of technically efficient technology usage

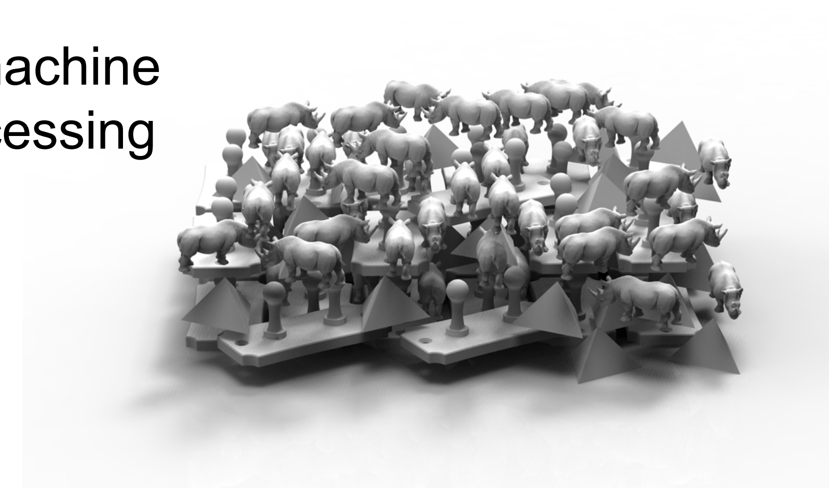
- To be relevant, they should reflect technology usage in reality

  → Efficient build configurations through packed build volumes

  → Surrounding process steps: file and machine preparation, clean-up, initial post-processing

  → Build failure considerations





Goals of work

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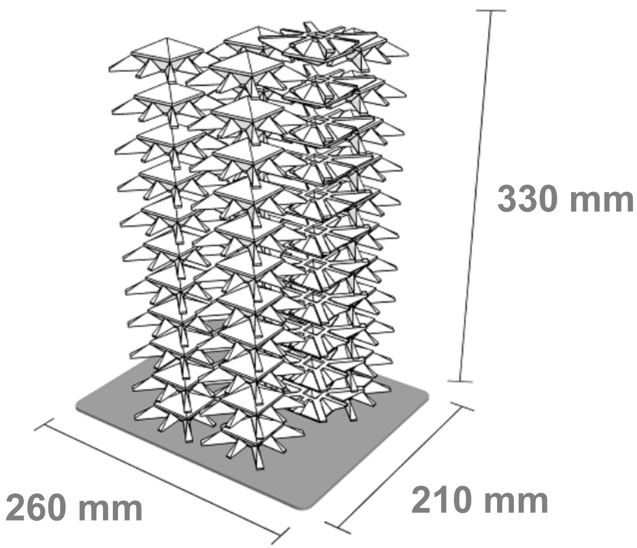
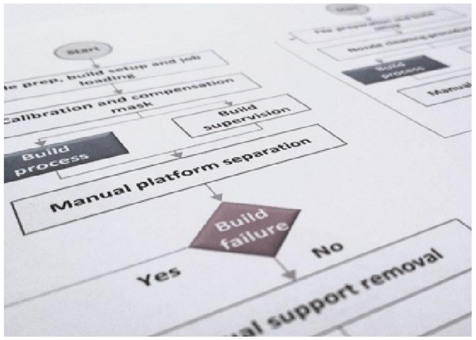
To combine three aspects into a total cost perspective for AM





- Minimum cost machine operation through full build volume utilisation (test specimen)
- Incorporation of ancillaries through process mapping
- Assessment of expected cost through inclusion of a probabilistic failure term

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Methodology

Element 1: Efficient technology utilisation

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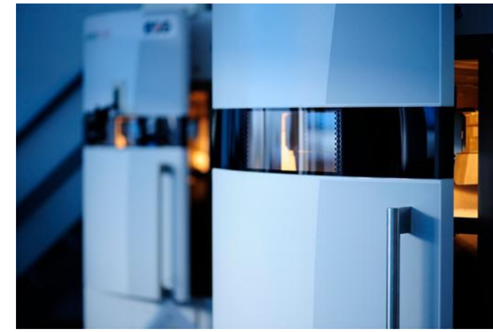
- Focus on Laser Sintering (LS) of polymers
  - Shown to be sensitive to sub-normal capacity utilisation



- Building on existing work, process model combining a build volume packing algorithm with cost modelling for AM
  - Limited novelty by itself (hasn't been done for LS)
  - Would like to argue it’s crucial for most future models of AM economics

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Element 2: Capturing the process chain of AM

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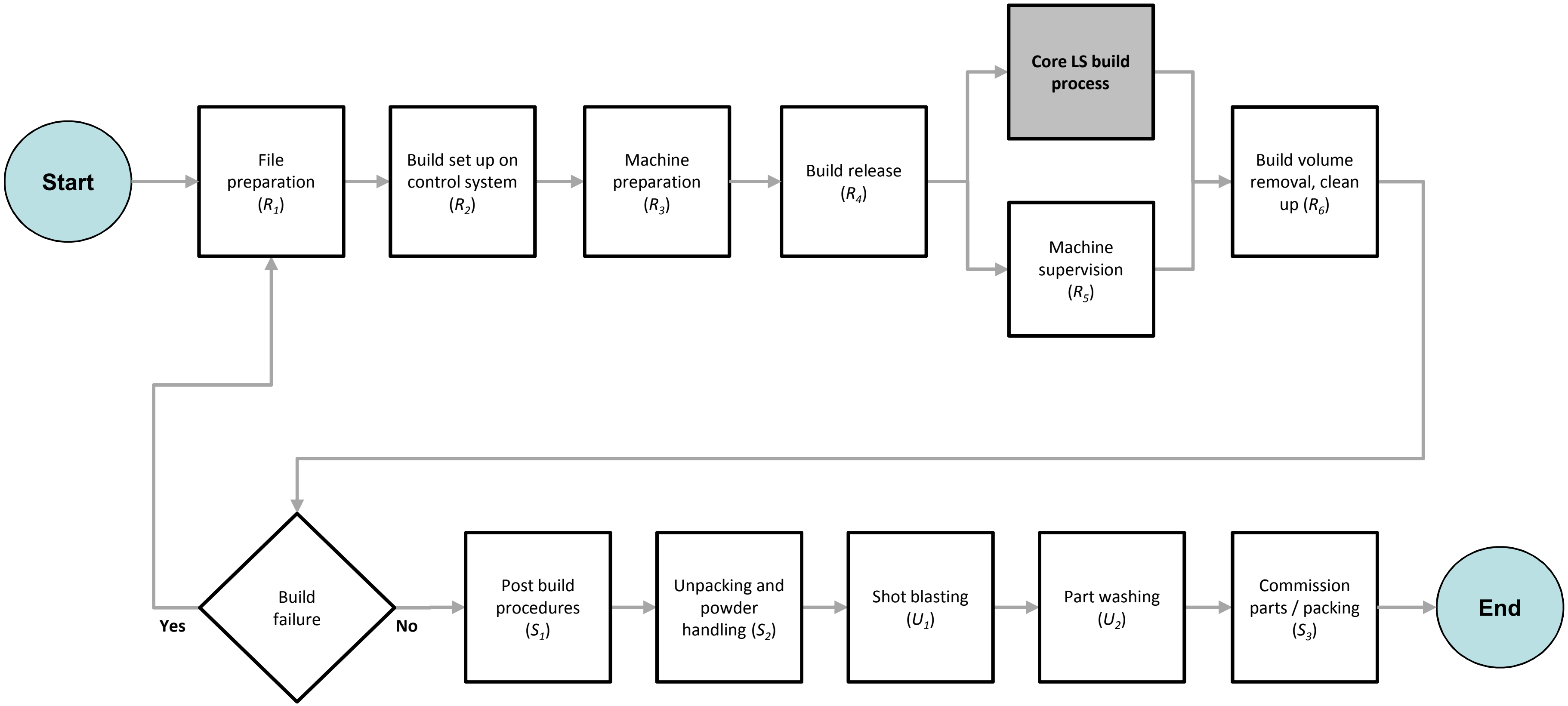
- Incorporation of ancillaries through process mapping
  - Specific to LS



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Element 3: Build failure and part rejection

- Three types of failure: Outright (catastrophic) build failure, part rejection and material failure
  - For simplicity: assuming these are unrelated (makes modelling effort far easier)

- Term of interest for outright build failure: cumulative number of depositable layers (x) before process failure
  - Non-deterministic term: assumed normally distributed

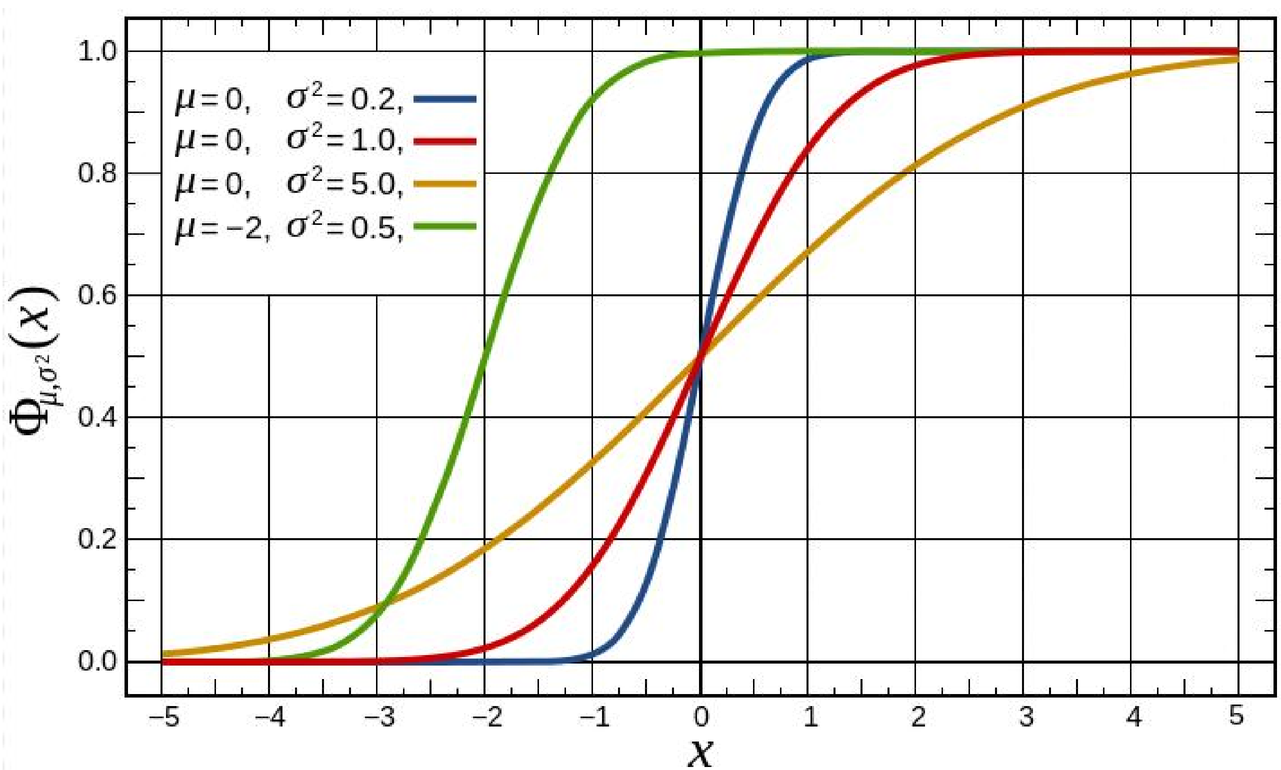
$$f(x \mid \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

  - Is assessed across subsequent build operations

Handling build failure

- Probability for a build with n layers to fail can then be modelled using the normal cumulative distribution function:

$$Normal\ cdf = \Phi(n \mid \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^n e^{\frac{-(t-\mu)^2}{2\sigma^2}} dt$$



Handling build failure

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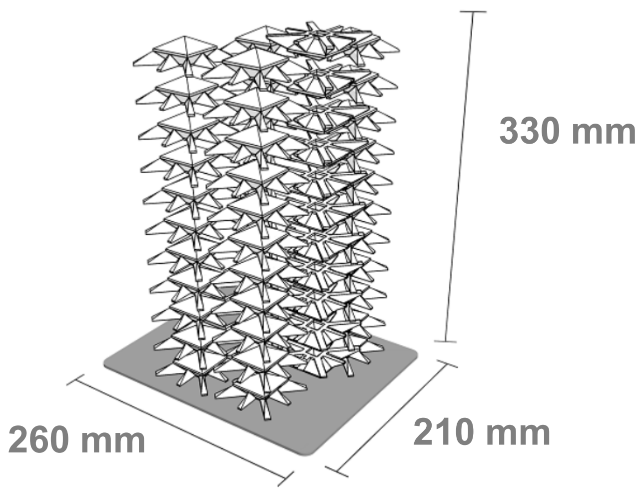
- Separation of risk of part rejection and outright failure means that this does not have to include the rejection model
  - Identical test part geometry allows rejection risk to be constant

- Simply put: failure applies to the build, rejection to the parts contained



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Model results

Results

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- Performed 17 build experiments
  - Built 63 test geometries and 56 tensile specimens
- Developed process map and measured mean duration of each element
- Observed failure modes and collected failure data

Failure mode	1. Outright build failure	2. Post-build part rejection	3. Material failure
Consequence	Loss of entire build, all contained parts are written off	Loss of individual parts	Loss of entire build, all contained parts are written off
Number of occurences	4 events	4 parts	None
Model element	Probability of build failure as a function of cumulative number of depositable layers (N)	Constant probability of part rejection due to identical test geometries	N/A
Specification	Cumulative distribution function (CDF) P(N) of normal distribution with mean μ and standard deviation σ	Fixed probability of rejection p_{reject}	N/A
Estimated parameters	$\mu = 4040.75$, $\sigma = 3267.95$	$p_{reject} = 0.07$	N/A

Shares of total costs

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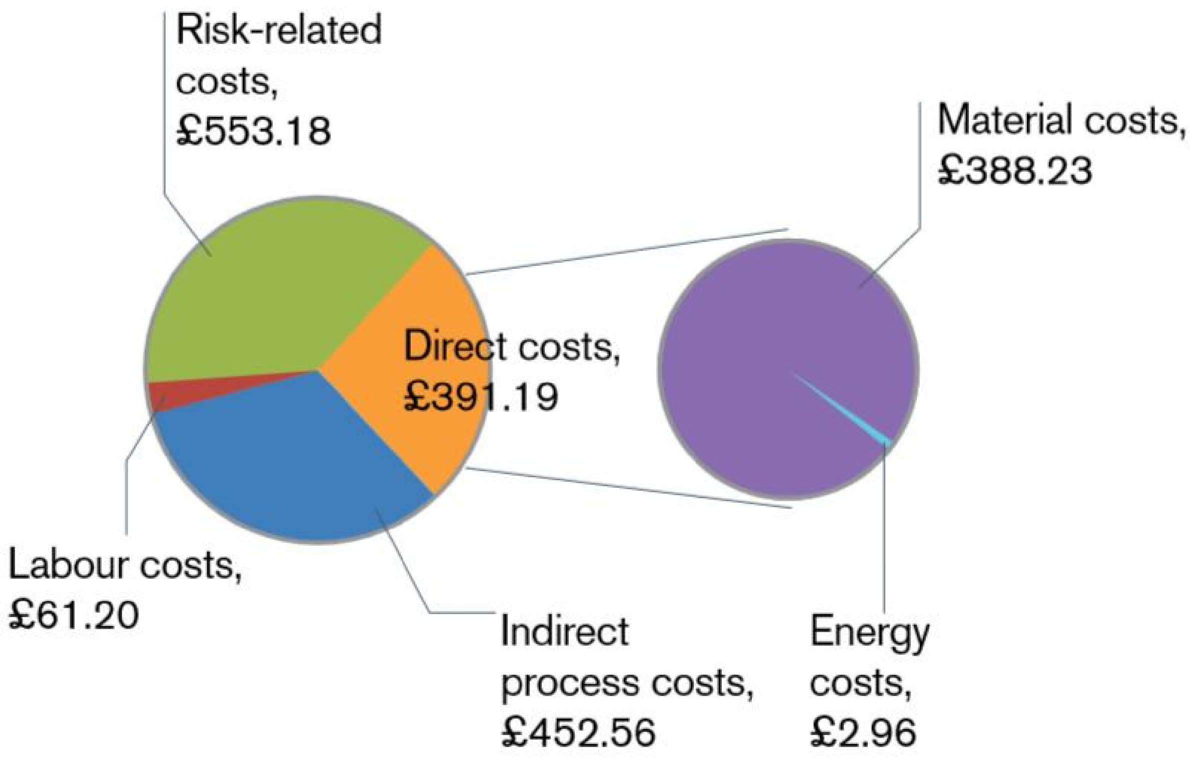
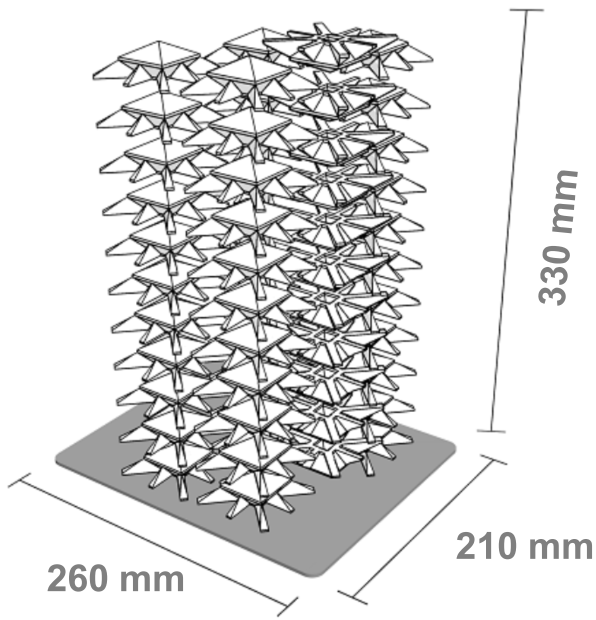
- At full capacity utilisation
  - Build containing 55 parts





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Unit cost model

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- Specified a new unit cost model

Direct and indirect costs of the core AM process

Costs of ancillary process steps (only labour)

$$Cost_{Unit} \approx \frac{\dot{C}_{Indirect} T_{build} + C_{Direct} + \sum_{i=1}^{I} R_i \, \dot{C}_{Labour}}{n\left(1 - p_{reject}\right)\left(1 - P(N)\right)} + \frac{\sum_{j=1}^{J} S_j \, \dot{C}_{Labour}}{n\left(1 - p_{reject}\right)} + \frac{\sum_{k=1}^{K} U_k \, \dot{C}_{Labour}}{1 - p_{reject}}$$

Elements subject to the risk of build failure

Elements not affected by outright build failure

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Unit cost model

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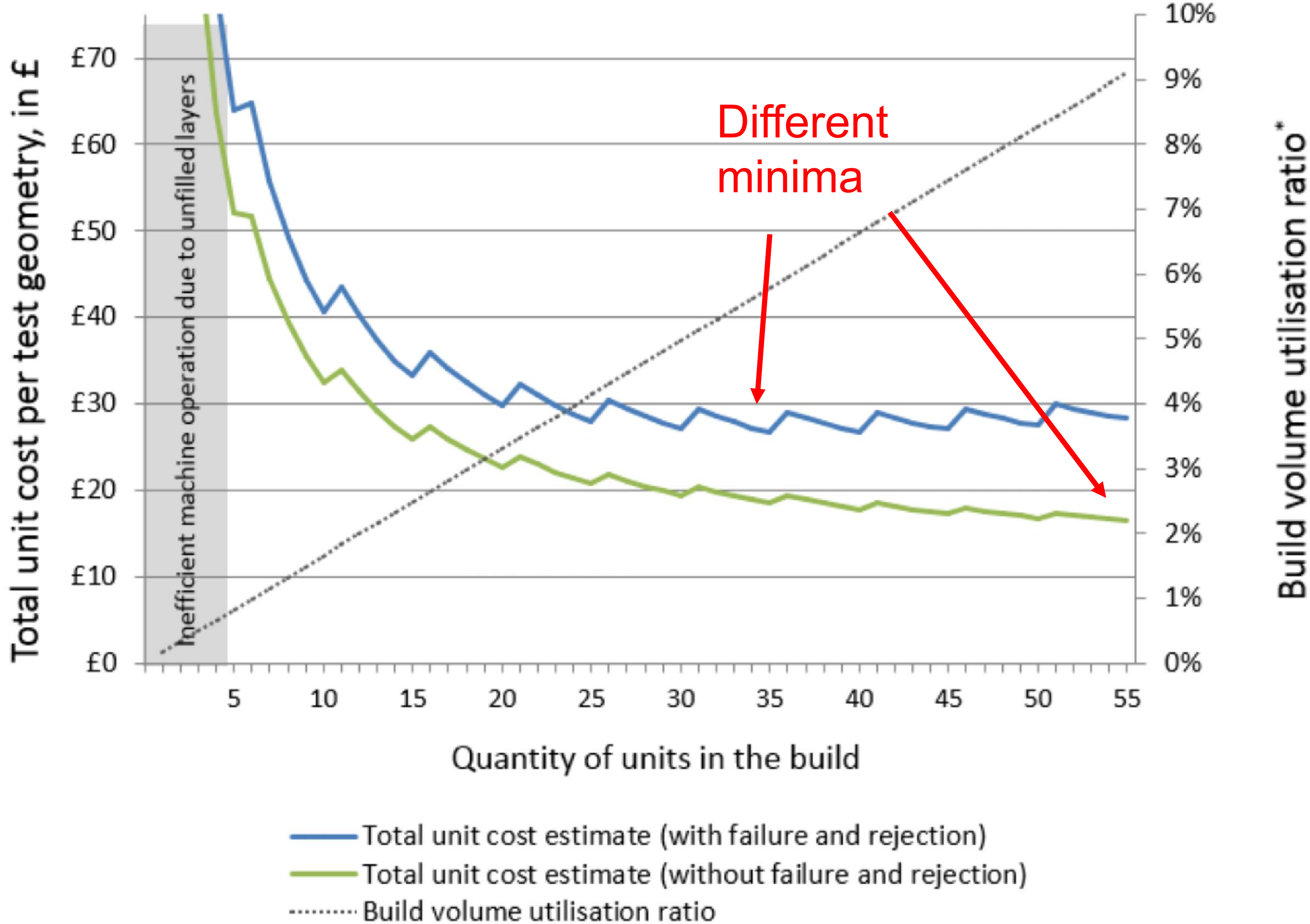

* in the used model, a ratio of 9.11% corresponds to full capacity utilisation

Learning effects

Learning effects

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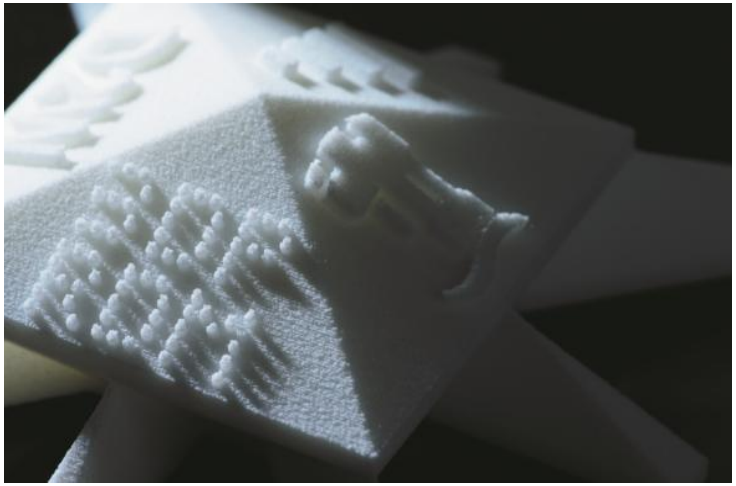
- Opportunity to assess if build repetition results in efficiency gains
- Ten builds were identical, performed in sequence by the same technician
- Analysed the total duration to complete all parts contained in each of these builds (makespan)



Learning effects

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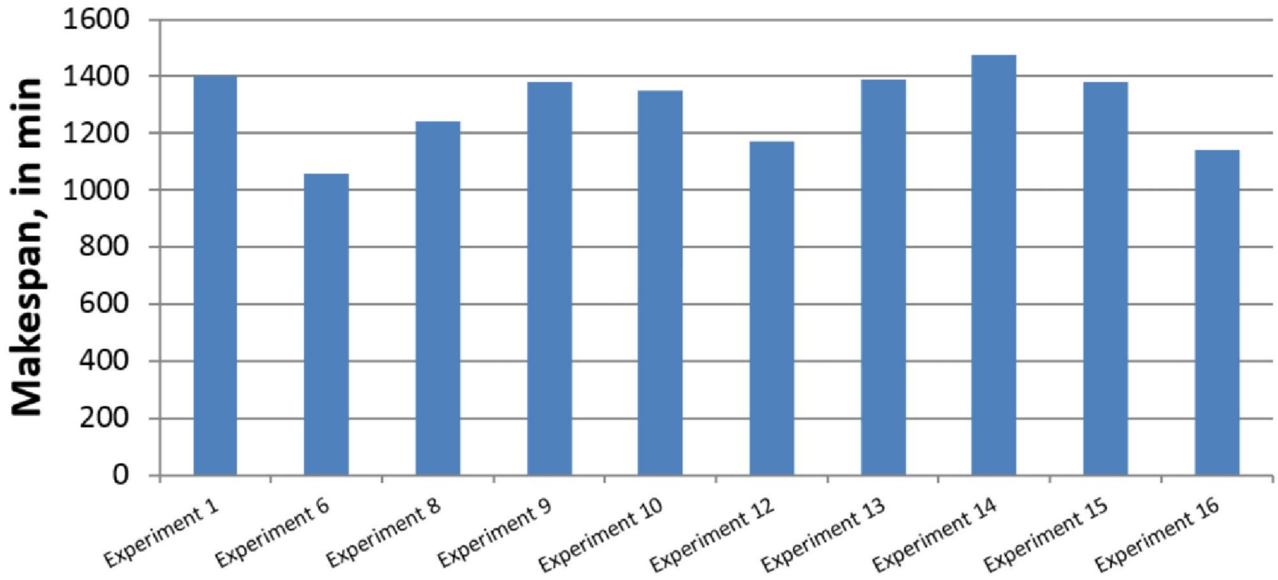
- Result: no negative trend → no evidence for learning effects



- Initial support for the theory that repetition does not make AM more efficient

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Conclusions

- Gives support to position that AM can deliver variety at no additional cost
  - May give rise to "economies of scope" through the manufacture of differentiated products
- In contrast to Hopkinson & Dickens and Ruffo et al., we have identified a fundamentally different cost function for AM
  - U-shaped average cost curve
  - Inefficient technology use leads to higher cost
  - Increasing build failure risk leads to higher cost for more layers in the build
- Both points are of high significance for the re-distributed manufacturing setting

Thank You!

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