

Integrated Modeling of Digital Product Design and Manufacturing for Improved Productivity, Quality, and Sustainability

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IDEAS TO IMPACT

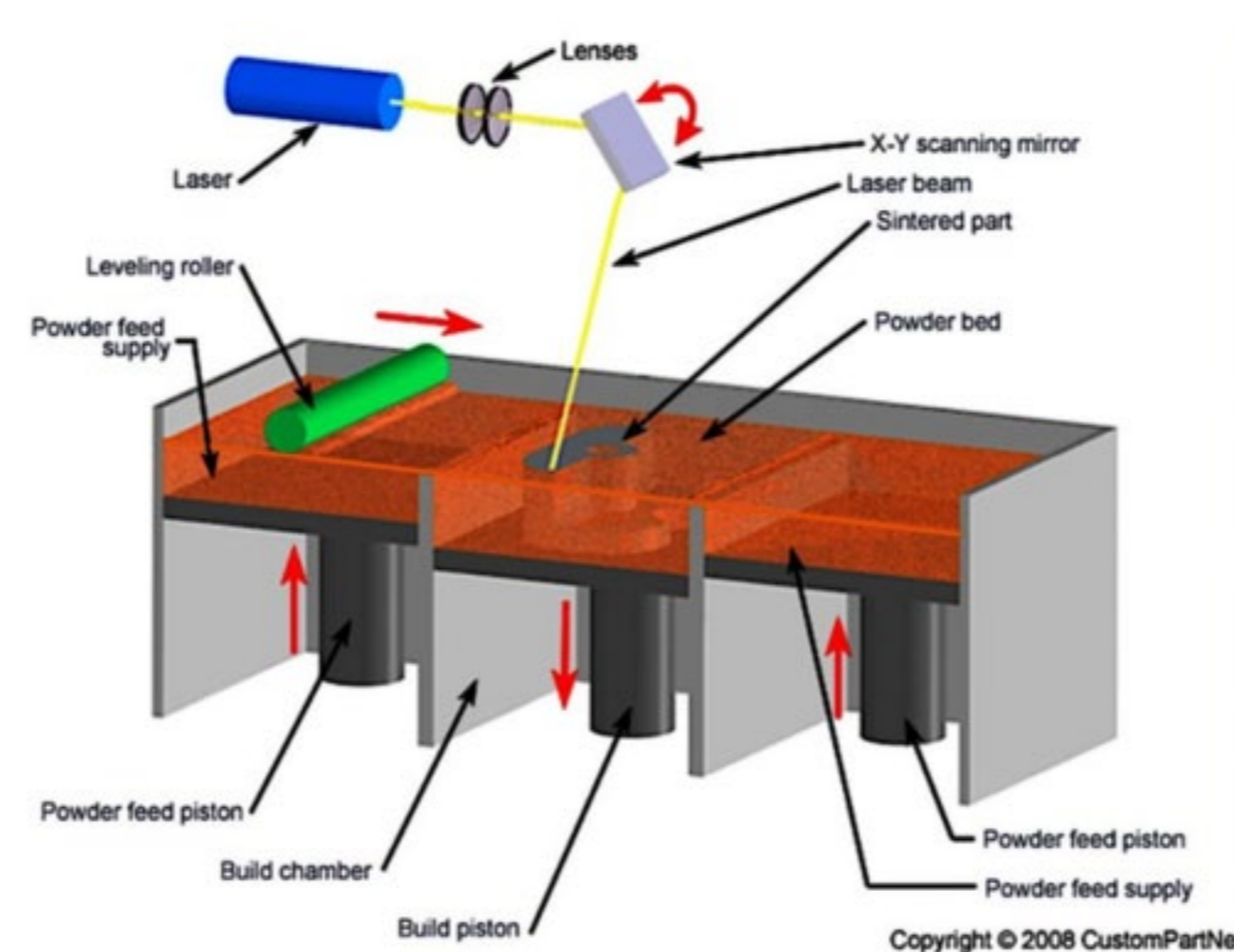
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Importance of Models + Simulation in Digital Manufacturing

To attain high-performance, resilient, sustainable production, the manufacturing industry requires enhanced decision-making and design capability. This need is particularly pronounced for digital manufacturing technologies with large geometric and operational flexibility.

Laser powder bed fusion (LPBF) is a digital and additive manufacturing technology for producing high-performance metal components for the automotive, aerospace, and medical sectors.

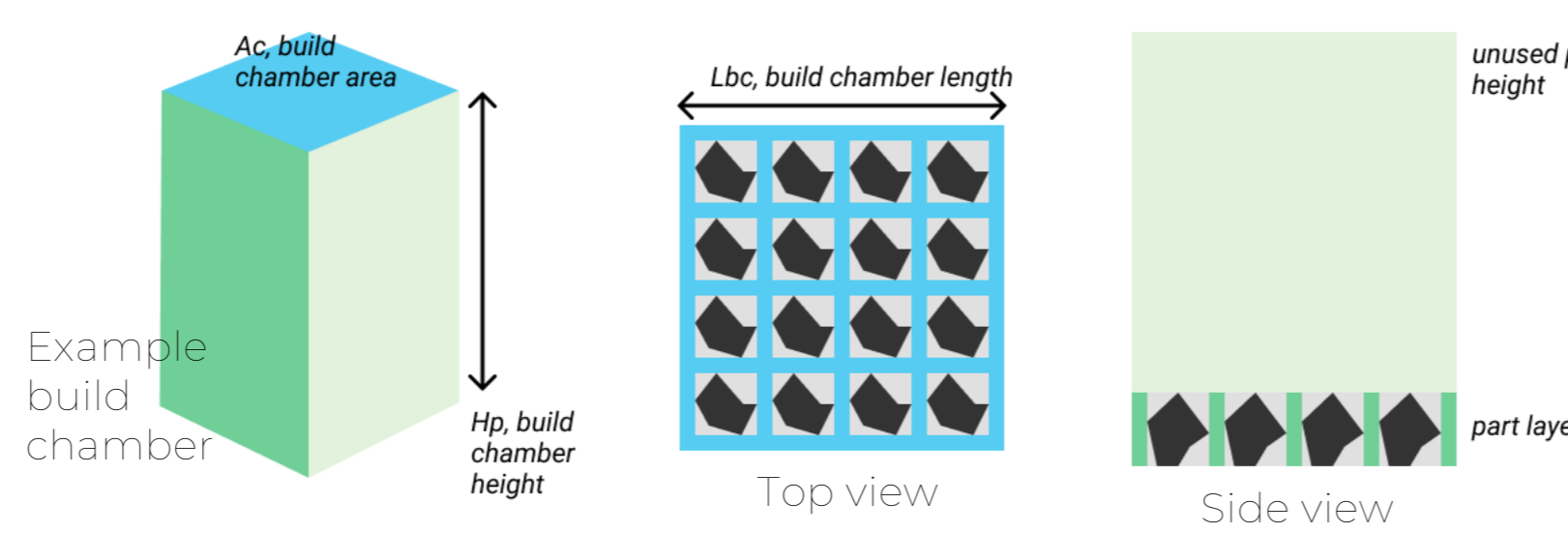
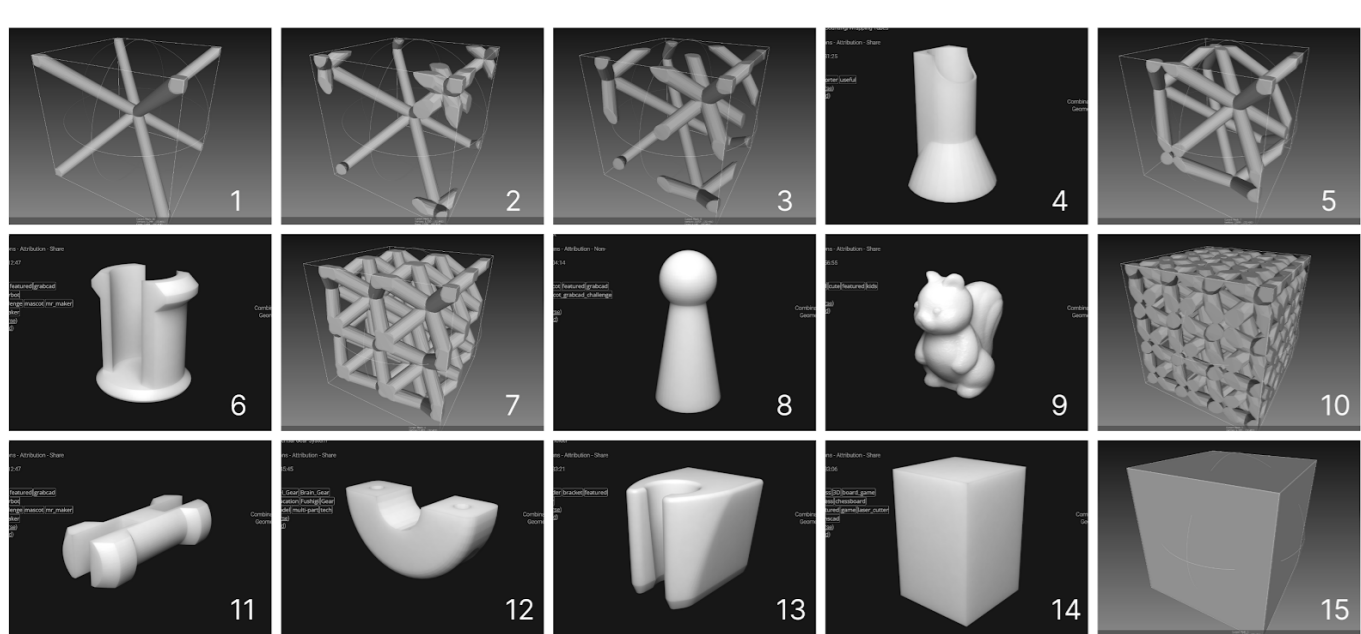
Modeling and simulation can support the adoption of LPBF as well as the advancement of manufacturing at large through articulating key value-led opportunities and manufacturing tradeoffs. Computational methods enable the rapid traversal of design considerations across part selection, process design, and factory configurations.



Aims of the Work

- To enable manufacturers to design high-performing, resilient and sustainable production systems
- To quantitatively articulate the implications of part and production design decisions on throughput, cost, and environmental burden for LPBF
- To rapidly assess diverse production configurations for productivity and cost through the development of custom factory simulation tools

Computing Build Time and Energy Consumption for LPBF



Build layout, modelled with a 2D packing scheme, enabling machine- and geometry-specific estimations of build time and energy consumption.

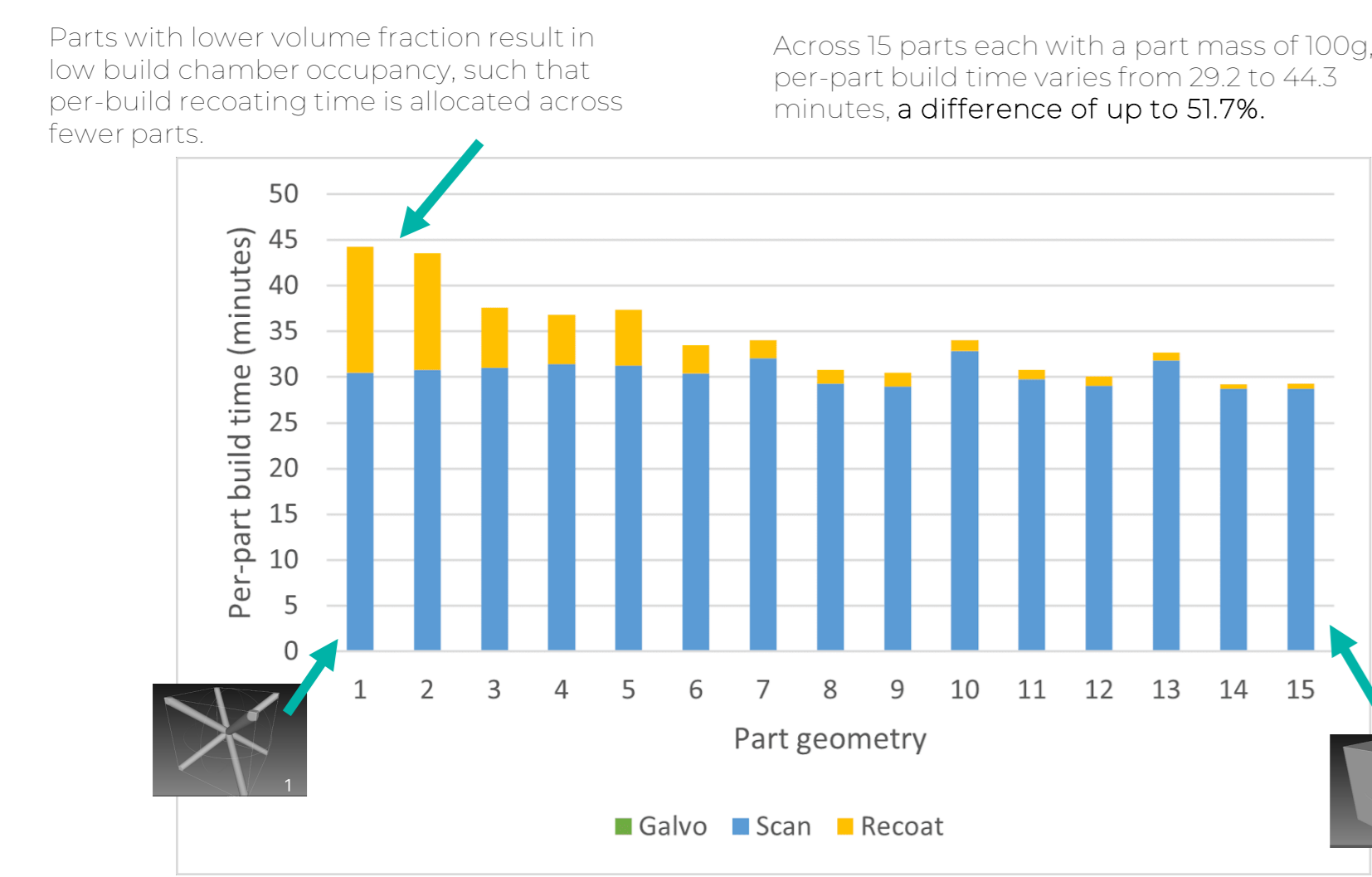
Energy consumption estimation, using unit process life cycle inventory for printing. Total energy consumption is a linear sum of:

- E_L , laser energy
- E_I , idle energy
- E_S , sieving energy
- E_W , printer warming energy
- E_C , printer cooling energy

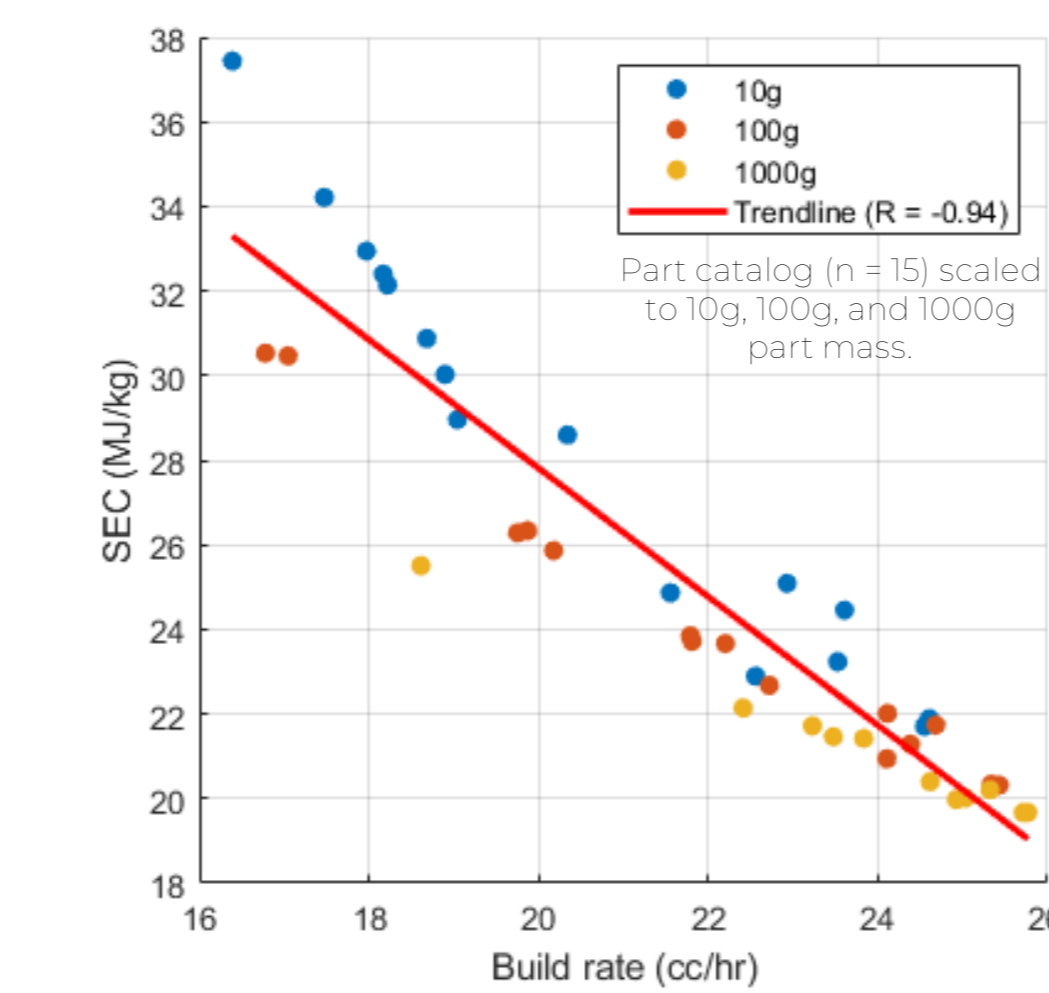
Parameter	Value	Source
P_{sieve} , power consumption of powder sieving	150 W	[2]
P_W , power consumption of printer warm-up	1450 W	[2]
P_I , power consumption of printer idling	420 W	[2]
P_C , power consumption of printer cooling	1507 W	[3]
P_{laser} , power consumption of laser while scanning	1130 W	[2]
T_{sieve} , time to sieve powder	660 s	[2]
T_W , time to warm printer	1163 s	[2]
T_C , time to cool printer	1800 s	-

Numerical build time computation, using custom-built ecosystems of models in Julia scientific programming language. Parts are sliced and contour paths generated. Parameters specific to simulated EOS m290: 370W laser power, 30um layer height, 100um laser spot size, 1.3 m/s scan speed [1]

How Part Geometry Drives Build Time and Energy Consumption for LPBF



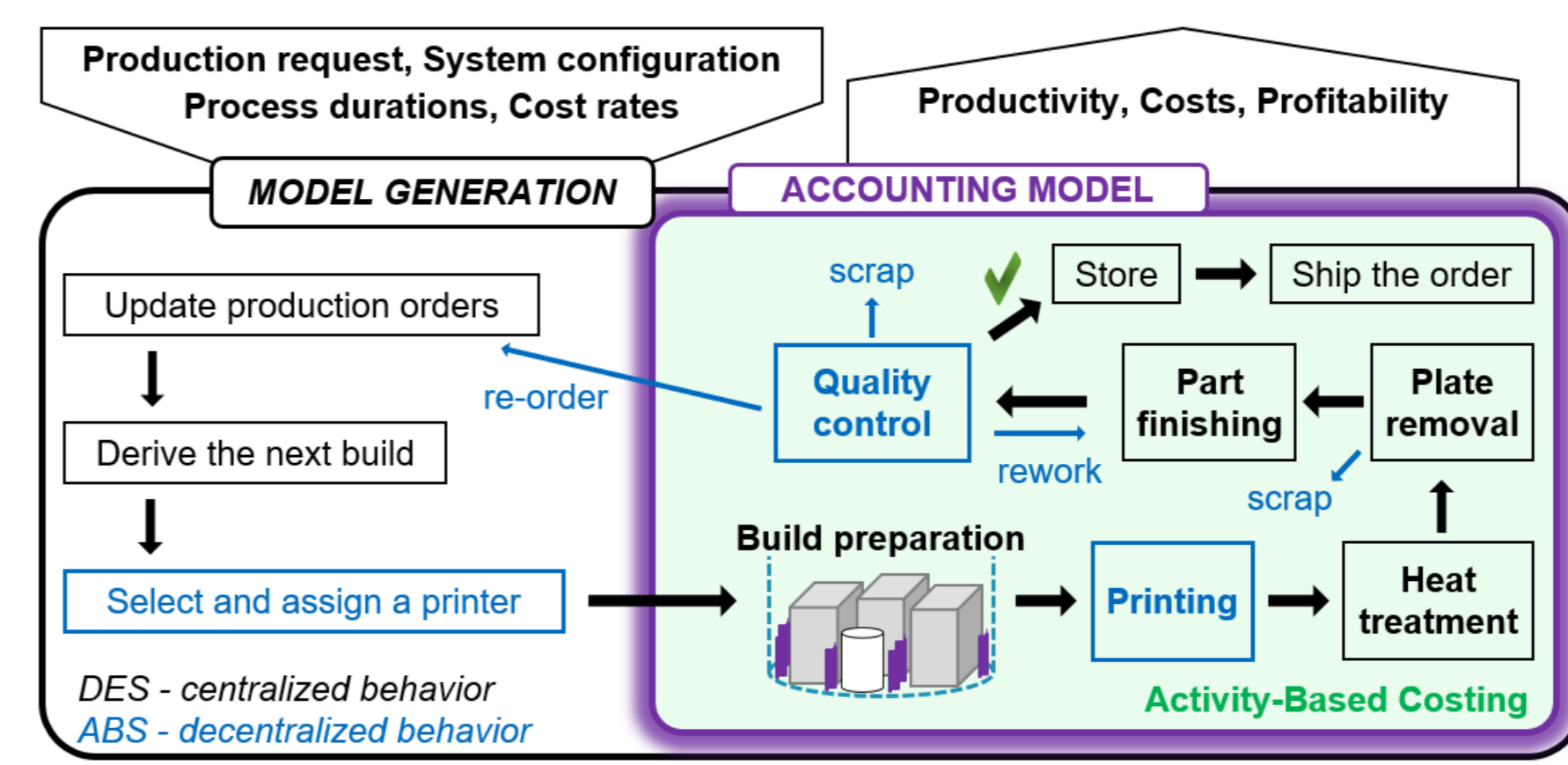
Galvo accounts for galvanometer setting times as laser decelerates between scans. Scan accounts for laser scanning time. Recoat accounts for powder recoating in between print layers.



Specific energy consumption (SEC) and build rate are strongly positively and linearly related. This relationship is explained by the coupling among scanning time, build time, and energy consumption.

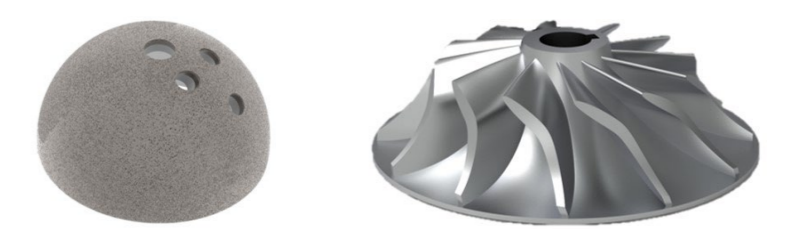
- Part geometry has a pronounced impact on per-part build time due to differing occupancies of the build chamber.
- Parts with high volume fraction, minimal part height in the desired print orientation, and minimal part footprint are associated with highest throughput.
- These metrics could be used to evaluate candidate parts for LPBF, either in designing new components or re-designing components made with conventional manufacturing techniques, to improve throughput and sustainability.
- Across a range of part mass and geometries, energy consumption and build rate trend strongly together.
- Process design that increases build rate may have a secondary benefit of decreasing environmental burden (i.e. energy consumption)

Hybrid Factory Simulation Framework



The simulation framework, shown here for LPBF, covers an end-to-end production workflow and tracks its cash flows. It is implemented in Tecnomatix Plant Simulation version 2201.0005.

Data pertains to the production of an acetabular cup (7.5cc) and impeller (188cc), two components commonly produced by LPBF [4].

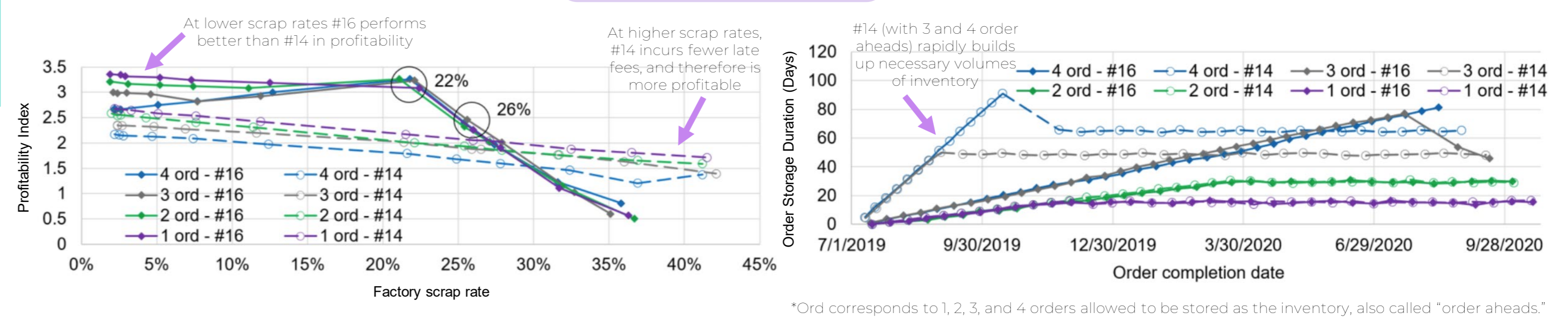


Identification of High-Performing Factory Configurations

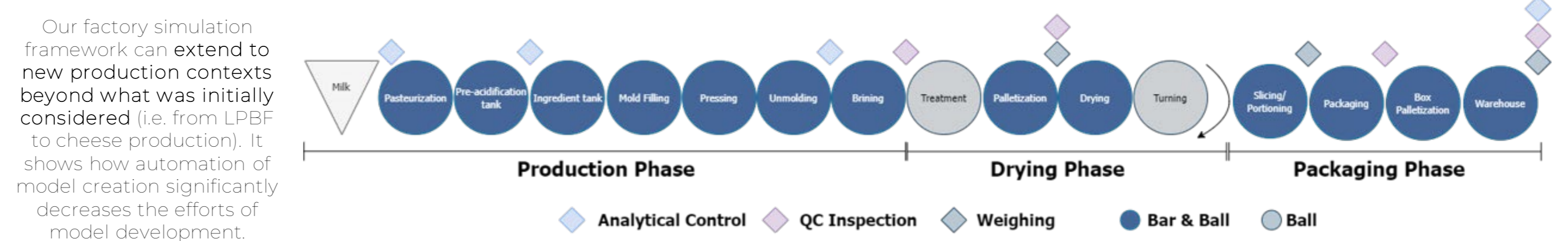
16 distinct factory configurations were modelled, each with varying machine capability and purchase cost. From these, two configurations were identified as highly profitable (#14 and #16).

Optimal factory configuration is context-dependent. For a high-profitability factory with low scrap rates, configuration #16 with 1 order ahead* is optimal. For a resilient factory, #14 with a 3 to 4 order aheads performs better.

Reliability and profitability are inversely coupled. High resiliency (i.e. more order aheads) results in lower profitability indices. Conversely, lean operations are less resilient but more profitable.



Future Work: Modeling Cheese Manufacturing with Lactogal in Portugal



Conclusion

We present an ecosystem of models that (A) articulate how part geometry impacts build time and energy consumption for LPBF, and (B) enable the rapid assessment of production scenarios to identify high-profit and high-productivity factory configurations. These models enable manufacturing engineers to make informed, intelligent production decisions, and advance the potential of modeling and simulation to improve digital manufacturing practices.

[1] Tang, M., Pistorius, P. C., Montgomery, C., and Beuth, J., 2019, "Build Rate Optimization for Powder Bed Fusion," J Mater Eng Perform, 28(2), pp. 641-647.
 [2] Ochs, D., Wehmer, K. K., Hartmann, J., Schiffer, A., and Schmitt, J., 2021, "Sustainable Aspects of a Metal Printing Process Chain with Laser Powder Bed Fusion (LPBF)," Procedia CIRP 98, pp. 613-618.
 [3] Ramirez-Cedillo, E., Garcia-Lopez, E., Ruiz-Huerta, L., Rodriguez, C. A., and Siller, H. R., 2021, "Reusable Unit Process Life Cycle Inventory (UPLCI) for Manufacturing Laser Powder Bed Fusion (LPBF)," Production Engineering, 15(5), pp. 701-716.
 [4] Shakirov, E., Quinlan, H., Hart, A. J., Virtual Planning of a Metal Additive Manufacturing Factory Using Techno-Economic Hybrid Simulation Models, Proceedings - Winter Simulation Conference 2023:1327-38. https://doi.org/10.1109/WSC60868.2023.10408640.

