Carnegie Mellon University
Computational Bio-Modeling Lab

Carnegie Mellon University

Thesis Proposal:

Design of Hybrid Lattice Support Structures Considering Practical Additive Manufacturing Constraints

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Committee Members:
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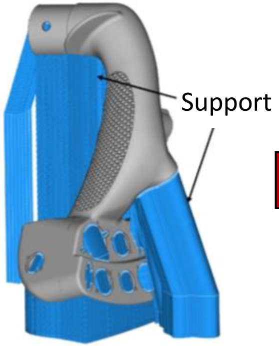
2. Carnegie Mellon University Department of Material Science and Engineering

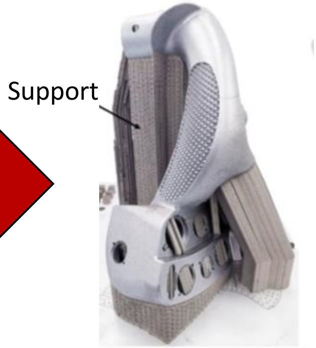
Additive Manufacturing (AM) of Metals[1]

✓ Pros	– Cons	• Example Techniques
✓ Complex geometry ✓ Mass customization ✓ No specialized tooling	– Initial start-up costs – Limited materials – Build time vs. accuracy	• Directed Energy Deposition • Material Extrusion • Powder Bed Fusion



Part to Build[2]

AM Metal Technique

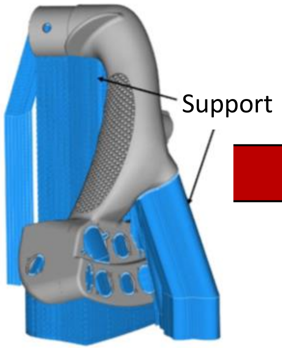


Final Build[2]

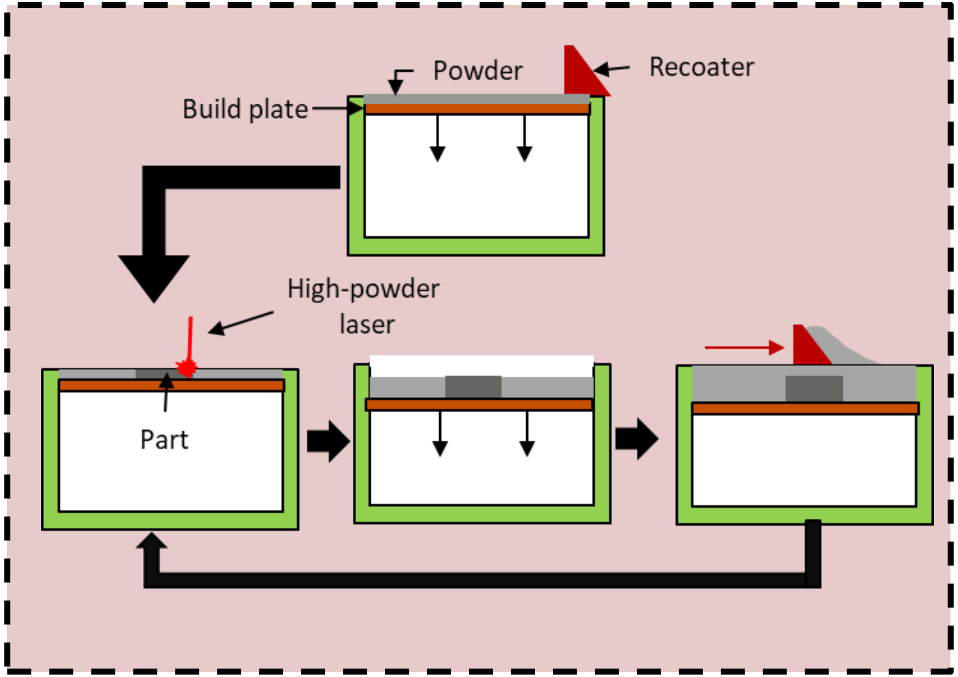
1. Vafadar, A., et. al (2021) 2. Wang, D., et.al (2022)

Laser Powder Bed Fusion (LPBF)

Layer-wise addition of material to create a part using a high-power laser to melt metal alloy powder[1]



Part to Build[2]



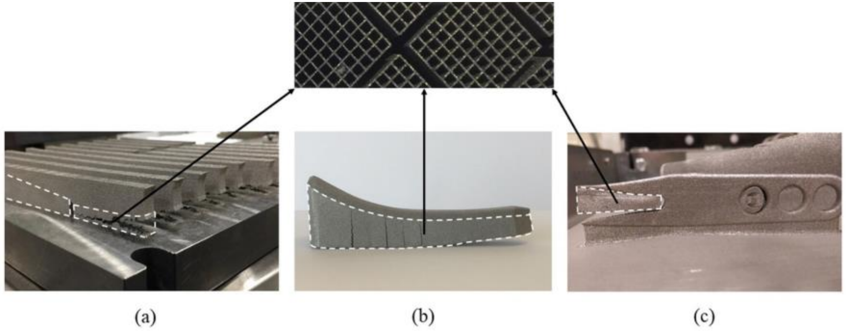
Final Build[2]

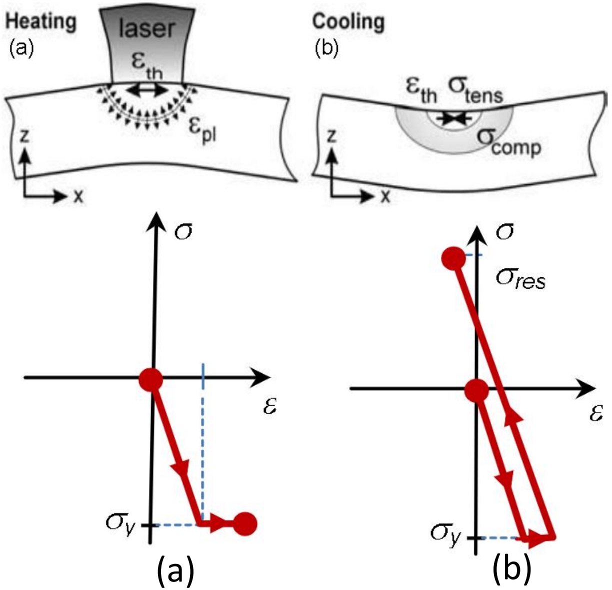
1. Vafadar, A., et. al (2021)   2. Wang, D., et.al (2022)

Geometric Inaccuracy: Residual Stress

- Thermal Cycle[3]
  - Rapid heating with steep gradients
  - Rapid solidification with high cooling
  - Melt-back involving simultaneous melting and remelting

Block shell support[4]





Model of one layer of stress for laser powder bed fusion(a) Heating phase and (b) cooling phase[3]

Support Structures

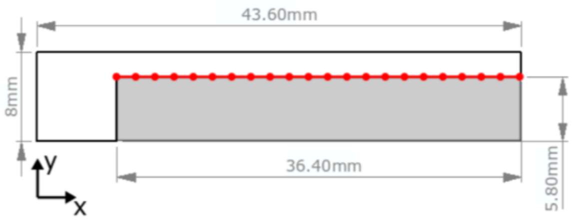
Purpose[5,9]:

- **Dissipate Heat**[6,9,10]
- Maintenance of structural integrity[4,7,11]

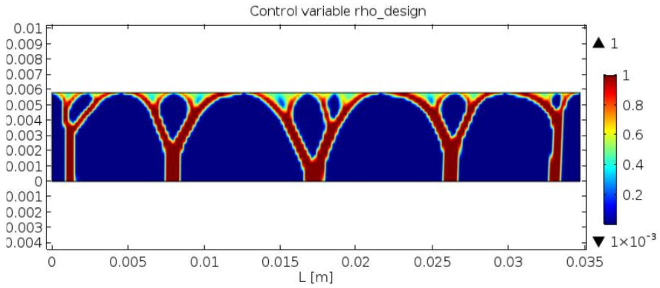
Methods to generate Support structures

- Topology Optimization for arbitrary states[6,7,11]
- Lattice Structures[5,8-10]

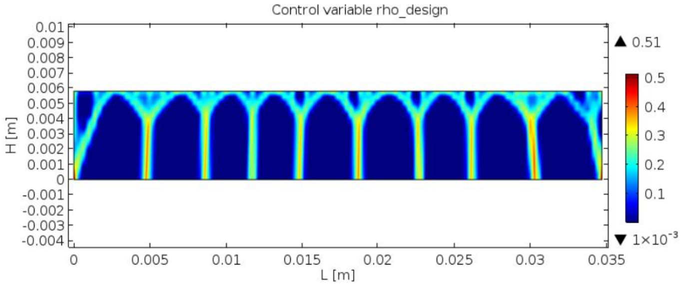
Cantilever Beam[6,7]



Design for heat dissipation[6]



Design for structural compliance[7]



5. Jiang, J, et. al (2018) 6. Bartsch, K., et. al (2019) 7. Bartsch,K., et. al (2018) 8. Miki, T. and Nishiwaki, S., (2022) 9. Huang, R., et. al (2020) 10. Lee, K.H., et.al (2022) 11. Pellens, J., et.al (2020)

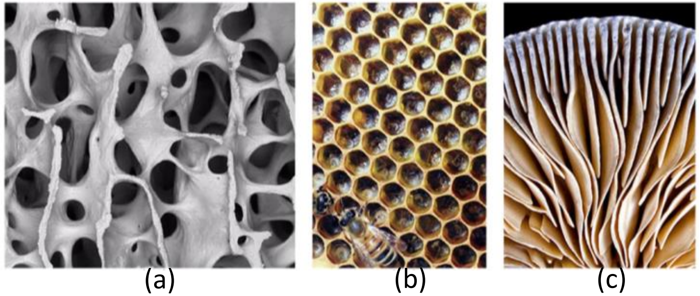
Lattices

Artificial microscopic structures with strategically designed geometry to control properties on the macroscopic level[12,13]

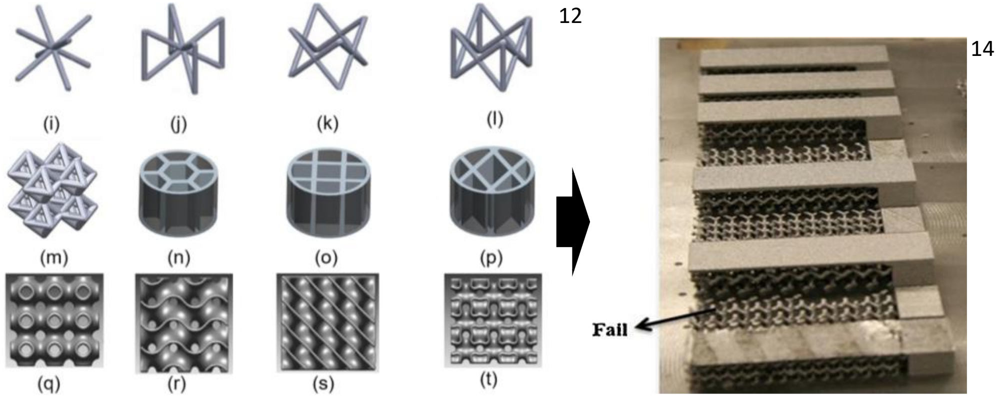
Lattice Support Structures[12-14]

- Self-supporting structure
- Light-weight design
- Tailorable physical properties
- Ease of powder removal

Lattice Structures in Nature[12]



Lattice Structures for AM



12. Nazir, A., et. al (2019) 13. Liang, H et. al (2011) 14. Hussein, A., et. al (2013)

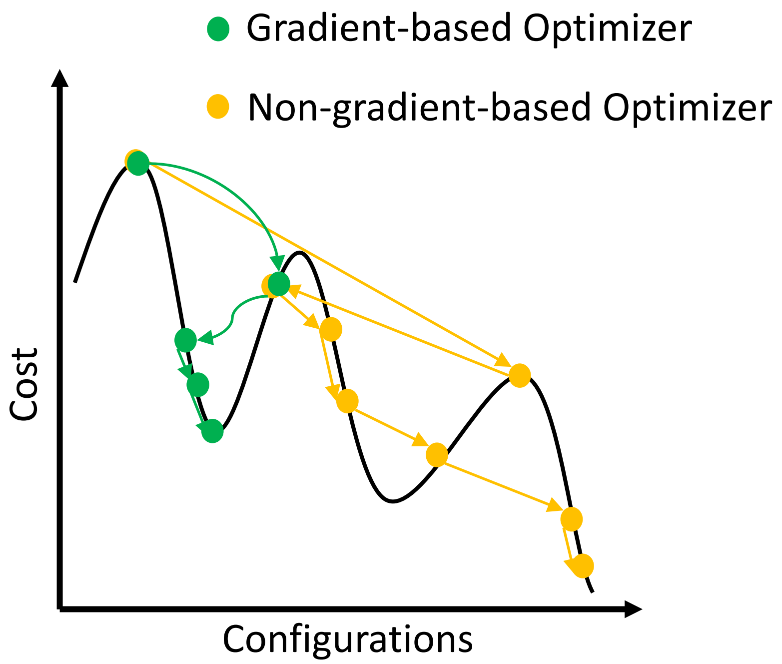
Commonly Used Optimizers

Gradient-Based Optimizer[15,16]

- Ideal for continuous design variables
- Fast convergence
- May only find local optima

Non-Gradient-Based Optimizers[16-18]

- Ideal for non-differentiable design variables
- Slow convergence
- Not been applied to optimizing lattice support structures in LPBF



15. Sigmund, O., and Maute, K. (2013) 16. Eberhard, P., et al (1999) 17. Porter, J., et al (2009) 18. Gosselin,L., et al (2009)

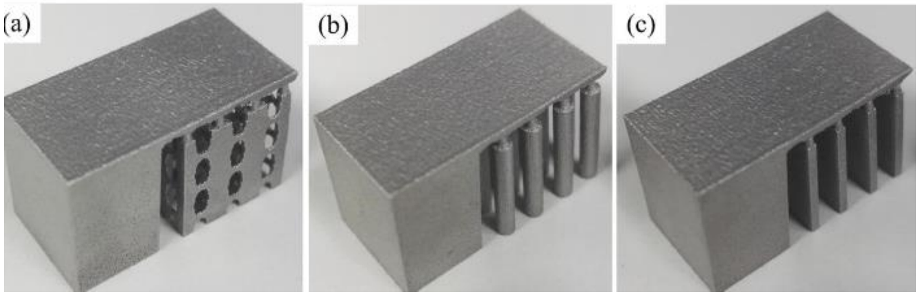
Existing Optimizers to Optimize Heat Dissipation Utilizing Lattice Support Structures

Optimize periodic unit cell[9,14]

- Minimize thermal compliance[9]
  - Did not consider non-uniform heat distribution

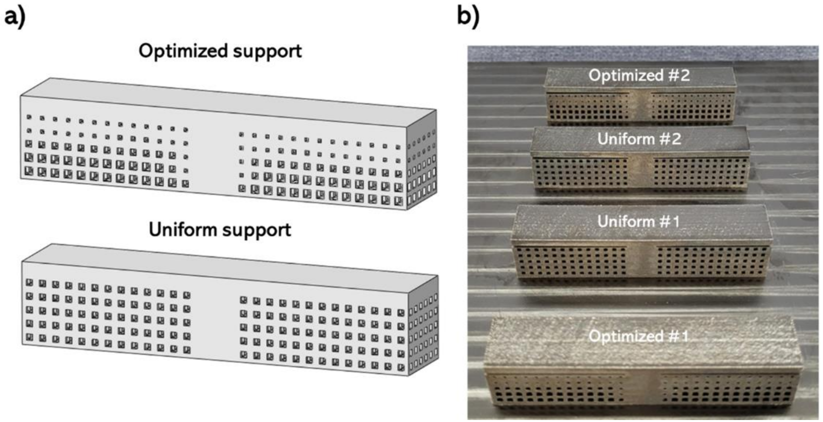
Optimized support

Traditional supports



Optimize density distribution[4,10,11,19]

- Minimize thermal gradient w.r.t density[17]
  - Accumulated error from approximations
  - Limited AM constraints



4. Cheng, L., et. al (2019) 9. Huang, R., et. al (2020) 10. Lee, K.H., et.al (2022) 11. Pellens, J., et.al (2020) 14. Hussein, A., et. al (2013) 19. Cheng, L., et. al (2018)

What is an efficient approach designers can employ for the generation of support structures that adhere to AM constraints?

What modifications can be made to existing optimization approaches for application to design lattice support structures?

Thesis Statement

Lattice support structure design for additive manufacturing (AM) is performed by reframing the optimization problem as a configuration optimization problem to maximize the dissipation of heat while constraining residual stress. By utilizing a modified non-gradient-based optimizer coupled with homogenization approximation to generate support structures, designers can create manufacturable lattice support structures for complex components optimized for the major functionality of heat dissipation while adhering to AM constraints for practical utilization, including structural integrity.

Thesis Statement

*By utilizing a modified non-gradient-based optimizer coupled with homogenization approximation to generate support structures, designers can create **manufacturable lattice support structures** for complex components **optimized for the major functionality of heat dissipation** while adhering to AM constraints for practical utilization, including structural integrity.*

Objective 1: Coupling Simulated Annealing and Homogenization to Design Thermally Conductive Hybrid Lattice Support Structures for LPBF

Thesis Statement

By utilizing a modified non-gradient-based optimizer coupled with homogenization approximation to generate support structures, designers can create manufacturable lattice support structures for complex components optimized for the major functionality of heat dissipation while adhering to AM constraints for practical utilization, including structural integrity.

Objective 1: Coupling Simulated Annealing and Homogenization to Design Thermally Conductive Hybrid Lattice Support Structures for LPBF

Objective 2: Designing Thermally Conductive Hybrid Lattice Support Structures Constrained by Residual Stress and Deformation for LPBF

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Objective 3: Extending Lattice Support Structure Design to Curved Interfaces

Overview

Objective 1: Coupling Simulated Annealing and Homogenization to Design Thermally Conductive Hybrid Lattice Support Structures for LPBF

- Objective 1.1: Maximize heat dissipation
- Objective 1.2: Expedite evaluation and design exploration

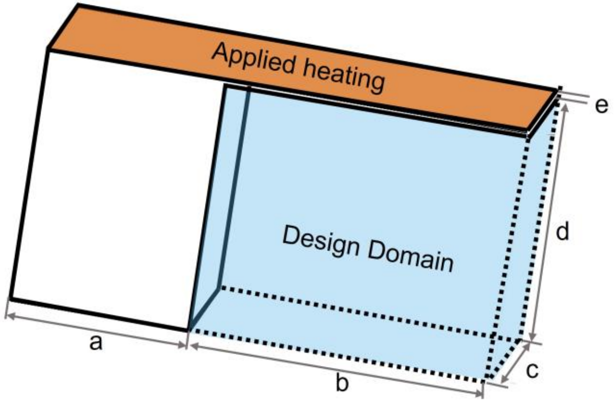
Objective 2: Designing Thermally Conductive Hybrid Lattice Support Structures Constrained by Residual Stress and Deformation for LPBF

- Objective 2.1: Incorporating structural Constraints
- Objective 2.2: Expediting thermal and structural property predictions

Objective 3: Extending Lattice Support Structure Design to Curved Interfaces

- Objective 3.1: Calibrating for Structural Accuracy
- Objective 3.2: Designing for complex surfaces
- Objective 3.3: Validating framework experimentally

Problem Overview

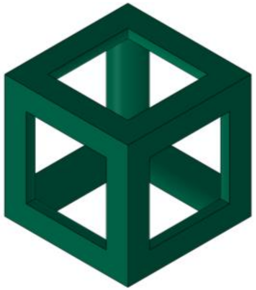


Find $x = [x_1, x_2, \ldots, x_n]$ to

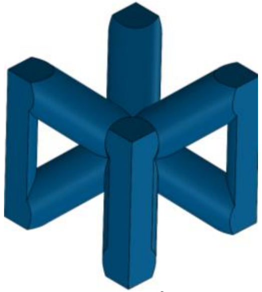
minimize $Q_{out} = Q(x)$,

subject to $\mathbf{KT} = \mathbf{q}$,
$V(x) < \varepsilon_V * V_{max}$ and
$A(x) < \varepsilon_A * A_{max}$,

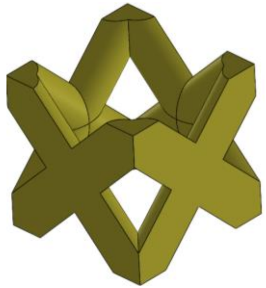
Design Variables (x)



Simple Cubic [4,12,10,19] (SC)



BC Vertical Struts[20,21] (BV)



Face-Centered [9,21,22] (FC)

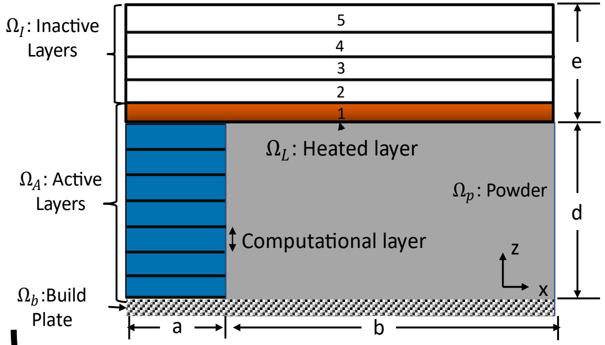
Physical properties of the unit cells for AlSi10Mg

Unit Cell	K_{eff} [W/m℃]	Volume [mm^3]	$Area_{XY}$ [mm^2]	$Area_{XZ}$ [mm^2]
Solid	110	8	4	4
SC	12.37	**1.82**	2.31	2.31
BV	24.39	2.82	**0.567**	**1.30**
FC	**39.43**	3.69	0.846	3.24

4. Cheng, L., et. al (2019) 12. Nazir, A., et. al (2019) 10. Lee, K.H., et.al (2022) 19. Cheng, L., et. al (2018) 20. Vaissier, B., et. al (2019) 21. Downing, D., et. al (2020) 22. Echeta, I., et. al (2020)

Defining design domain and boundary conditions

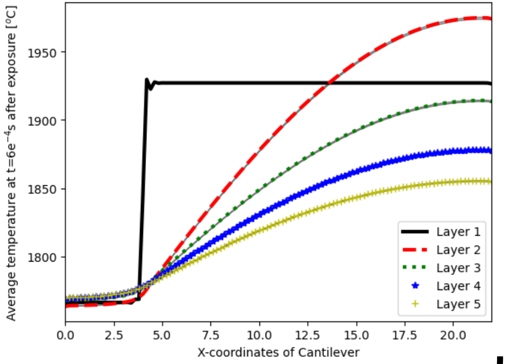
Equivalent Flash Heating Part-Scale[10,23,24]:



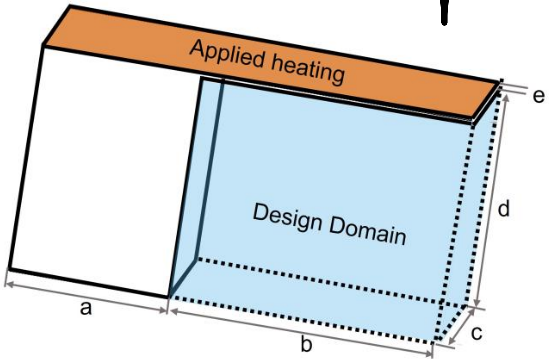
Heating + Cooling

$$\begin{cases} \rho c \dfrac{dT_i(t,x)}{dt} = \nabla \cdot (\mathrm{k}\nabla T_i(t,x)) + q(\boldsymbol{x}) \\ -(\mathrm{k}\nabla T_i(t,x)) \cdot n = h\nabla T_i(t,x) \\ T_i(t,\boldsymbol{x}) = T_{base} \\ T = T_{powder} \end{cases}$$

Layer-by-Layer Temperature



Equivalent steady-state:



$$\begin{cases} \nabla \cdot (K\nabla \boldsymbol{T}) + \boldsymbol{q} = 0 \\ T(x,y,0) = T_{base} \\ T(x,y,g) = T_{source} \end{cases}$$

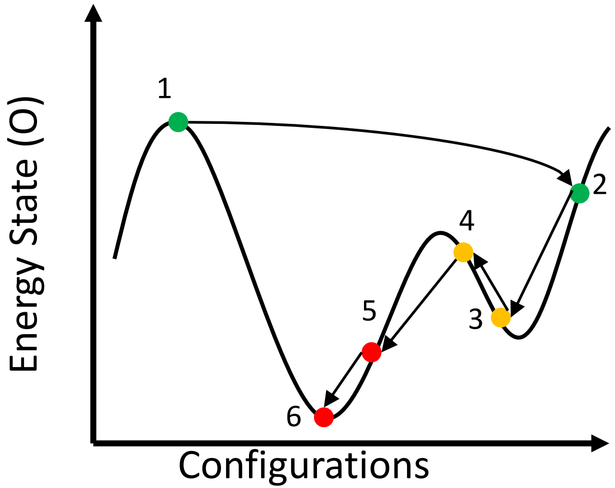
10. Lee, K.H., et.al (2022) 23. Li, C., et.al (2017) 24. Subedi, S. C., et.al (2022)

Simulated Annealing (SA)

Analogous to the annealing of metals

Stages:

1. High temperature: **Exploration (1→ 3)**
2. Mid-temperature: **Intermediate (3 → 5)**
3. Low temperature: **Fine-tuning(5 → 6)**



- Probabilistic acceptance of designs:

$$P_{acc} = exp\left(-\frac{O_2 - O_1}{T'_k}\right)$$

- Annealing Schedule:

$$T_{k+1} = \alpha * T'_k$$

Pros:

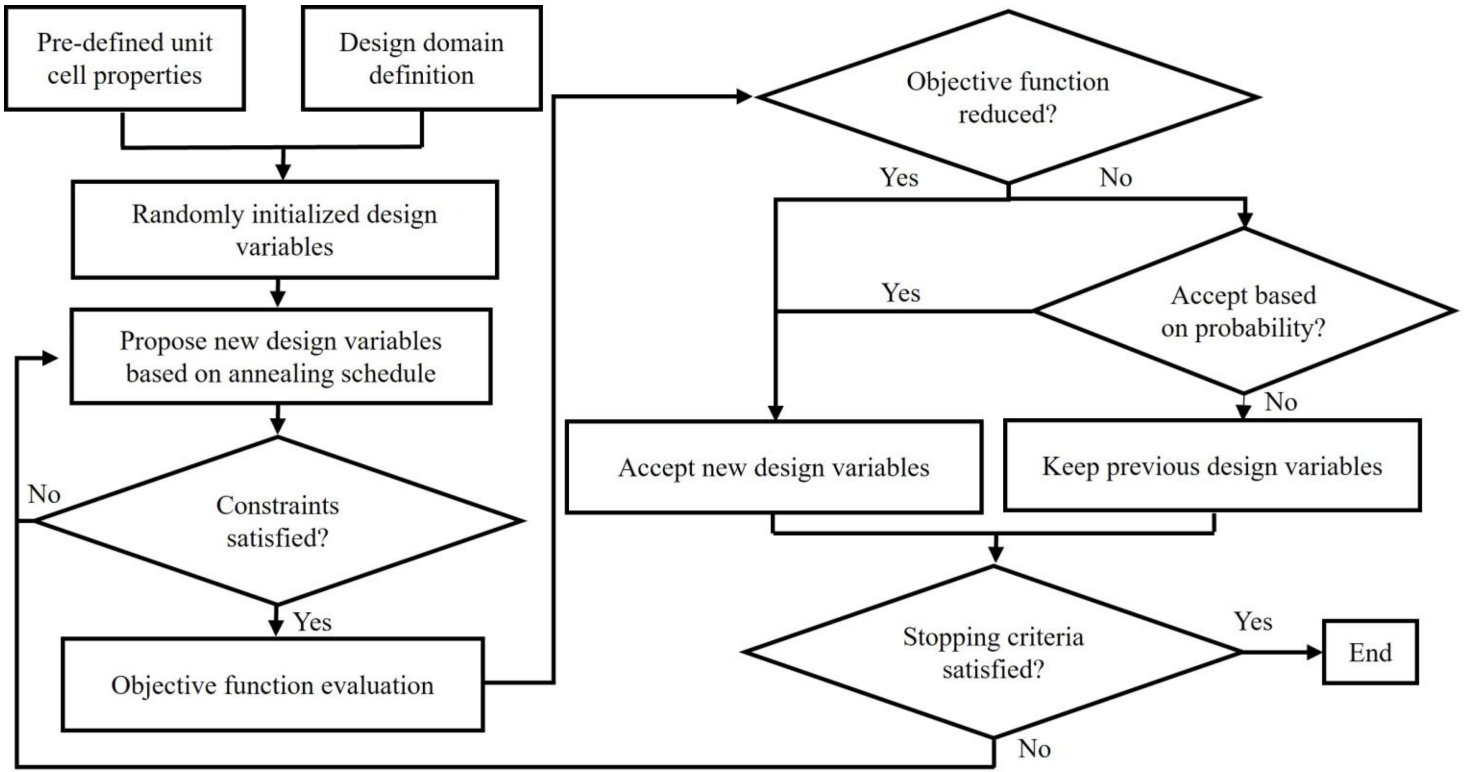
- Wider exploration of design space
- Allows hill climbing even at later stages (3 → 4)

Cons:

- Computationally expensive

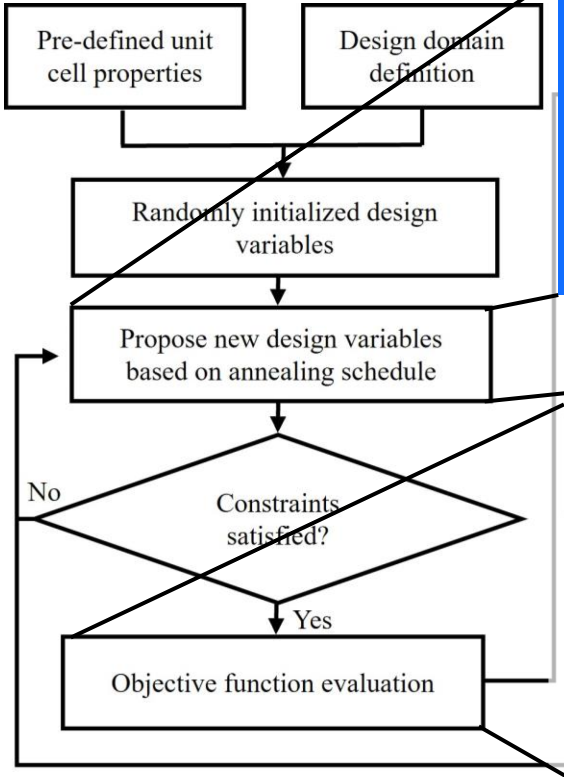
17. Porter, J., et al (2009) 25. Kirkpatrick, S., et. al (1983) 26. Campbell, M., et. al (1997)

Flowchart of Traditional SA Optimizer



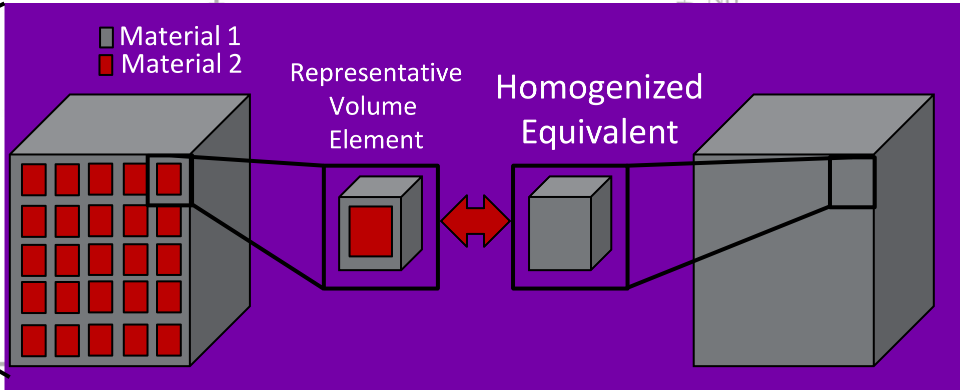
26. Kirkpatrick, S. et. al (1983)

Flowchart of modified-SA Optimizer



Stage-dependent actions

$$No.\ swaps \begin{cases} N_x * N_y * N_z & \text{if } T_k > 0.5*T_0 \\ \frac{N_x * N_y * N_z}{5} & \text{if } 0.1*T_0 < Tk > 0.5*T_0 \\ 1 & \text{If } T_k < 0.1*T_0 \end{cases}$$



Flowchart of modified-SA Optimizer

SA Hyperparameters:

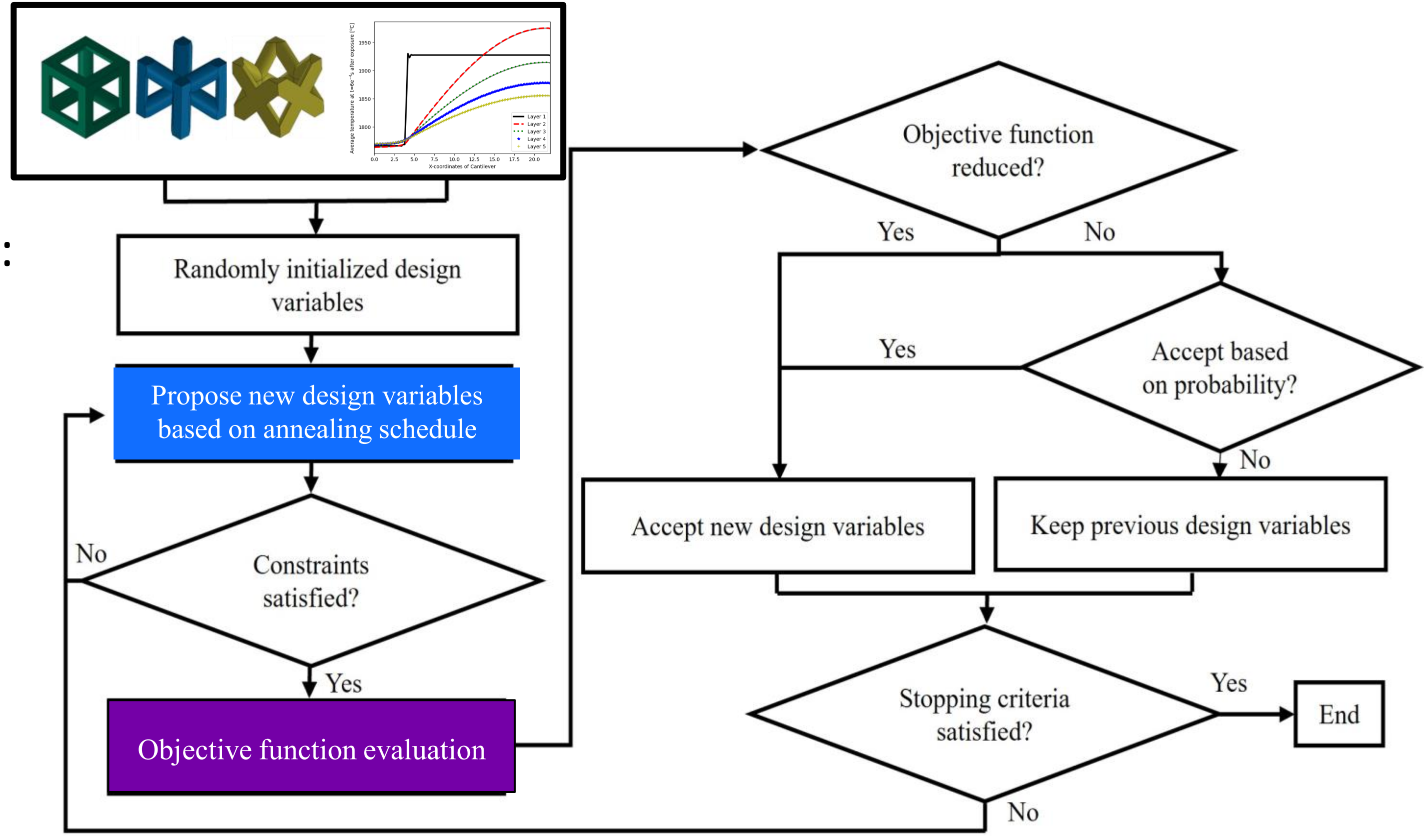
T_0=50

α=0.5

Constraints:

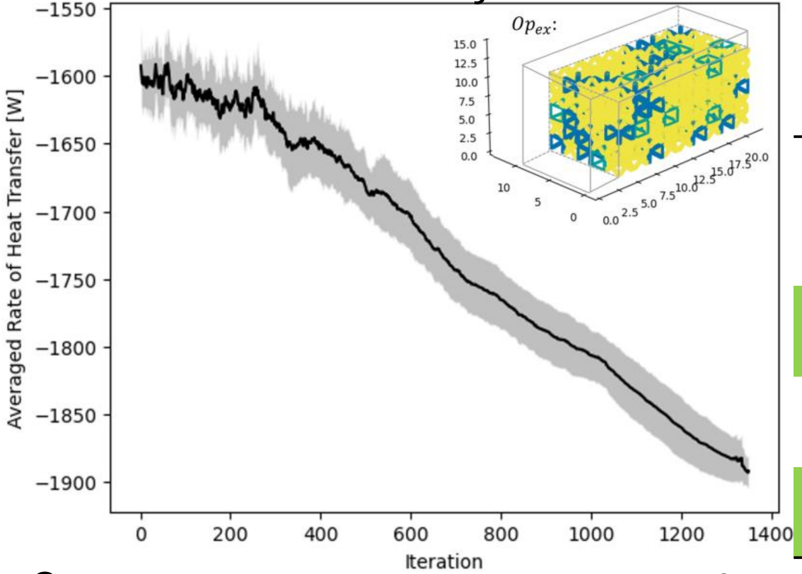
V_{max} = 750 mm^3

A_{max} = 140 mm^2



Case Study of Cantilever Beam

Iteration History of 30 runs



Op_{ex}: Objective = -1,900 W, Volume = 615 mm^3, Area = 106 mm^2.

Comparison of support designs*

	$\|Q_{out}\|$ [W]	Volume $V(x)$ [mm^3]	Area $A(x)$ [mm^2]	SC/BV/FC	Constraint Satisfaction $V(x) < 750$ $A(x) < 140$
Solid	4,546	1,800	280	0/0/0	No
SC Only	1,196	409	161	225/0/0	No
BV Only	1,607	634	57	0/225/0	Yes
FC Only	2,124	830	120	0/0/225	No
Op_{Avg}	**1,887 (15.0)**	**745 (5.56)**	**108 (4.94)**	**18/58/149 (3.23/5.43/5.34)**	**Yes**

*standard deviation in ( )

Compared to BV Only ↑ Average of ~16% Heat dissipation

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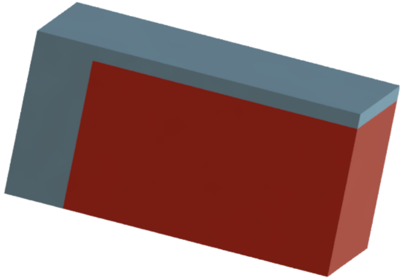
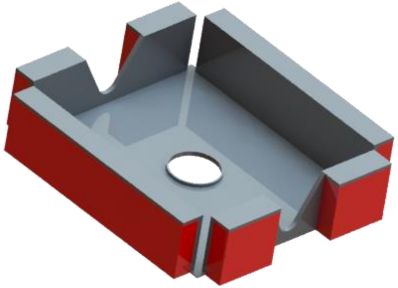
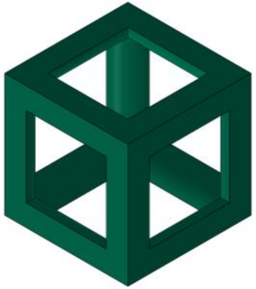


Cantilever Beam



Aerospace Bracket[26]



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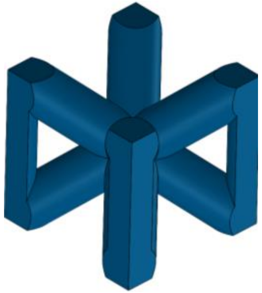

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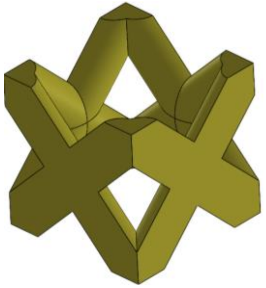

Face-Centered [9,21,22] (FC)

Find $x = [x_1, x_2, \ldots, x_n]$ to

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subject to
$\mathbf{KT} = \mathbf{q}$,
$V(x) < \varepsilon_V * V_{max}$ and
$A(x) < \varepsilon_A * A_{max}$,
$\mathbf{CU} = \mathbf{F}$
$\frac{\sigma_j^{PN}}{\sigma_y}\max \leq 1$
$U_z \leq U_{max}$

Physical properties of the unit cells for AlSi10Mg

Unit Cell	$K_{eff}\left[\frac{W}{mC}\right]$	$Volume\ [mm^3]$	$Area_{XY}\ [mm^2]$	$Area_{YZ}\ [mm^2]$	$E_{eff_Z}\ [Pa]$	$E_{eff_{Y,X}}\ [Pa]$	G_{xy} [Pa]	G_{xz}/G_{yz} [Pa]
Solid	110	8	4	4	7.4E+10	7.4E+10	2.782E+10	2.782E+10
SC	12.37	1.82	2.31	2.31	7.64E+09	7.64E+09	5.419E+08	5.419E+08
BV	24.39	2.82	0.567	1.30	9.73E+09	3.69E+09	**4.375E+09**	4.175E+09
FC	39.43	3.69	0.846	3.24	**1.95E+10**	**1.34E+10**	1.598E+08	**6.873E+09**

27. Xiaohui, J., et. al (2022)

Structural Constraints

P-Norm Stress[4,28]:

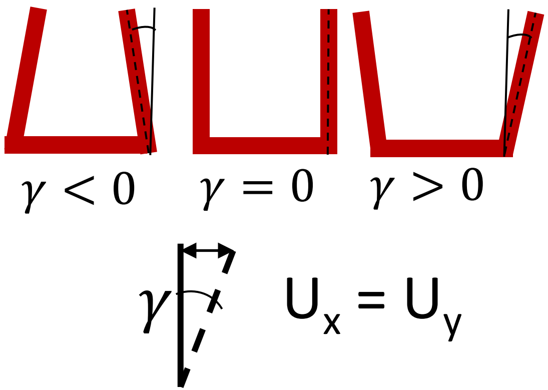
$$\sigma_j^{PN}(x) = \left(\frac{1}{N_j}\sum_{a\in\Omega_j}\left(\sigma_a^{vM}(x)\right)^p\right)^{\frac{1}{p}}$$

$\sigma_j^{PN} > \sigma_y$:= plastic deformation

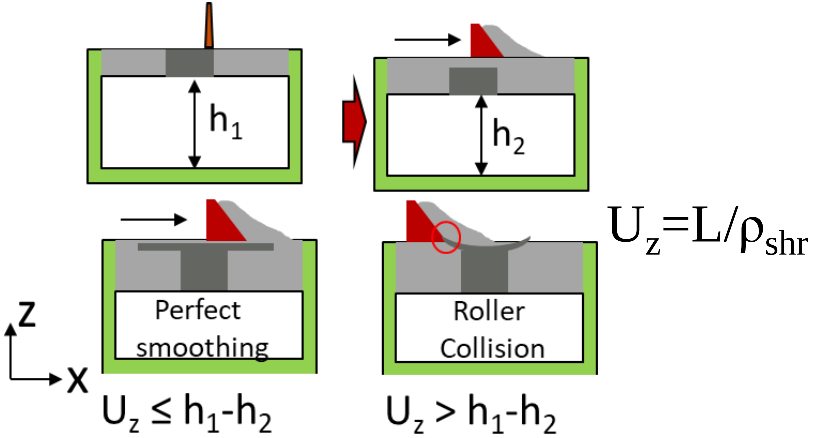
$\sigma_j^{PN} < \sigma_y$:= elastic deformation

Maximum Total Displacement: $U_{max} = \sqrt{U_x^2 + U_y^2 + U_z^2}$

Draft Angle (γ)[29]



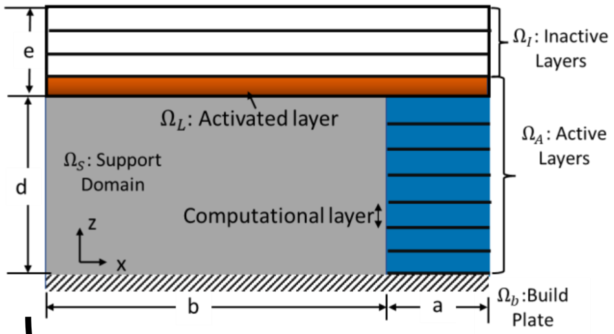
Roller Collision[11,30,31]



4. Cheng, L., et. al (2019) 11. Pellens, J., et.al (2020) 28. Holmberg, E., et. al (2013) 29. Sulaiman, S., et. al (2013) 30. Zhang, Z. D,. et. al (2020) 31. Misiun, G., et. al (2013)

Defining design domain and boundary conditions

Part Scale Modeling



1. Inherent Strain Method (ISM) [4,11,30,31,32,33]

$$\begin{cases} \nabla \cdot \sigma_i = 0 \\ \sigma_i = \mathbf{C}\varepsilon_e^i \\ \varepsilon_{tot}^i = \varepsilon_e^i + \varepsilon_p^i + \varepsilon_{in}^i, \end{cases}$$

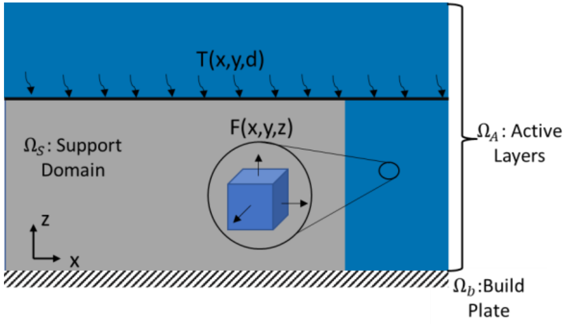
+

2. Equivalent Flash Heating (EFH) [10,23,24]

Heating + Cooling

$$\begin{cases} \rho c \dfrac{dT_i(t,x)}{dt} = \nabla \cdot (\mathrm{k}\nabla T_i(t,x)) + q(\boldsymbol{x}) \\ -(\mathrm{k}\nabla T_i(t,x)) \cdot n = h\nabla T_i(t,x) \\ T_i(t,\boldsymbol{x}) = T_{base} \\ T = T_{powder} \end{cases}$$

Equivalent Steady-State



Static Structural

$$\begin{cases} \nabla \cdot \sigma + F = 0 \\ U(x,y,0) = 0 \end{cases}$$

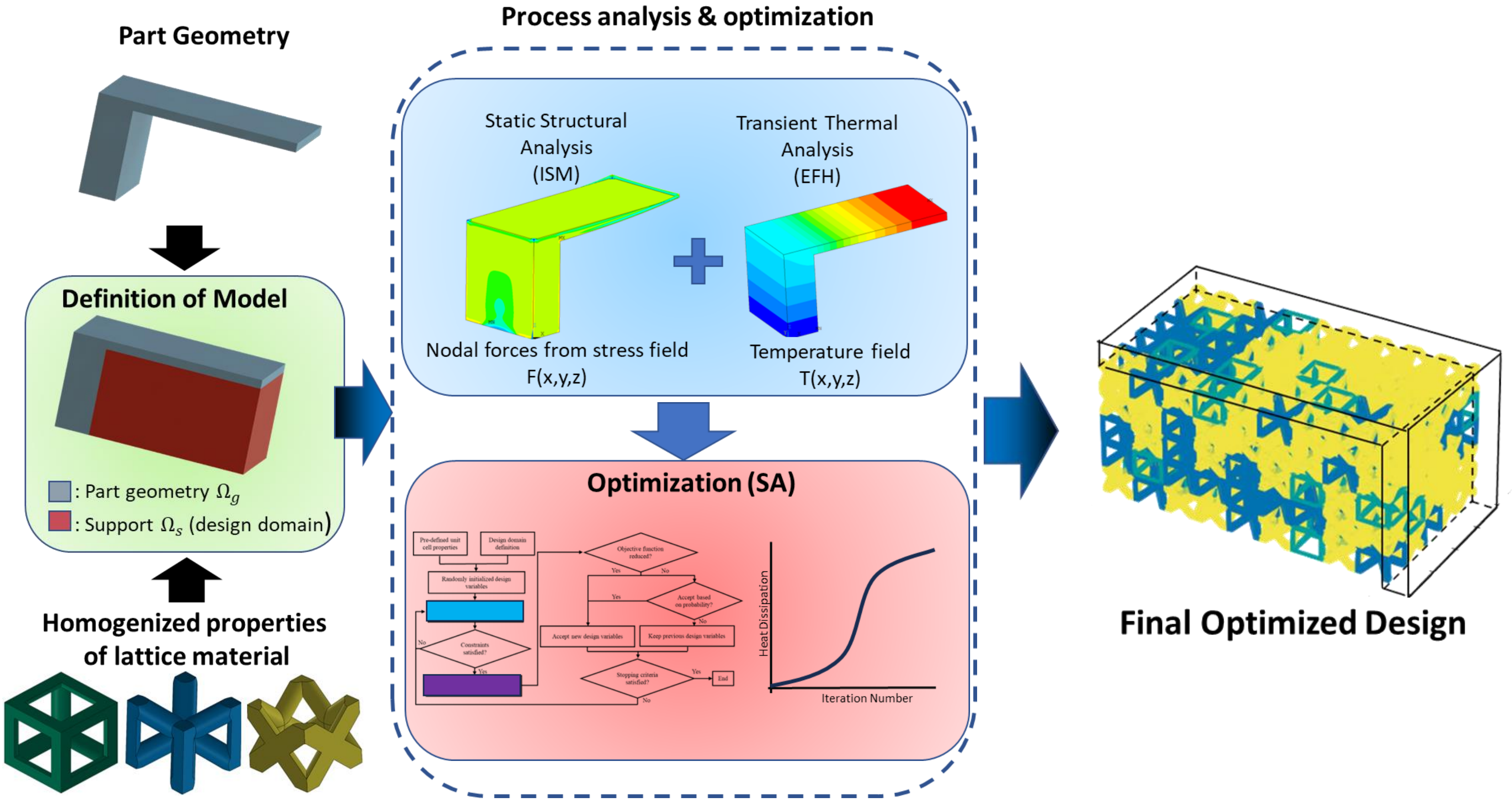
+

Steady-State Thermal

$$\begin{cases} \nabla \cdot (K\nabla \boldsymbol{T}) + \boldsymbol{q} = 0 \\ T(x,y,0) = T_{base} \\ T(x,y,d) = T_{source} \end{cases}$$

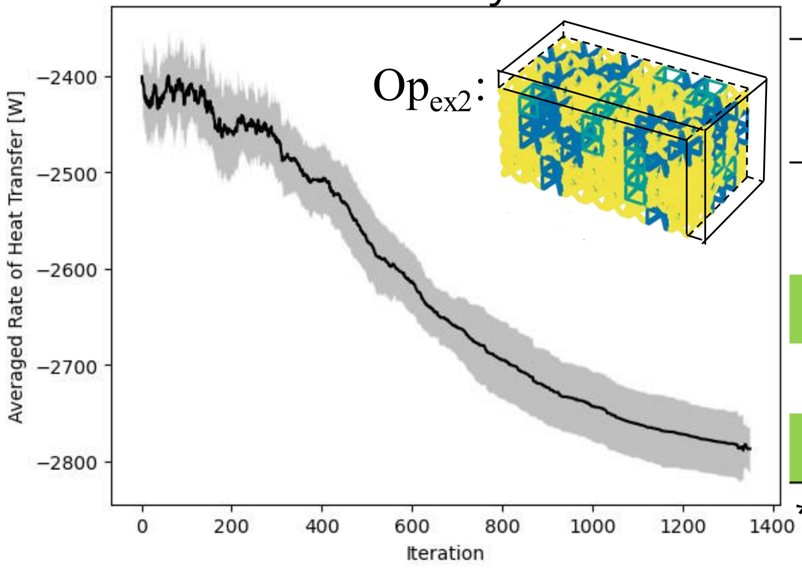
4. Cheng, L., et. al (2019) 11. Pellens, J., et.al (2020) 30. Zhang, Z. D,. et. al (2020) 31. Misiun, G., et. al (2013) 32. Liang, X., et. al (2018) 33. Chen, Q., et. al (2019)

Framework Flowchart



Case Study of Cantilever Beam

Iteration History of 30 runs



Op$_{ex2}$: Objective = -2,815 W, Volume = 735 mm^3, Area = 108 mm^2, p-Norm = 0.366, U_{sum} = 24.2 mm

Comparison of support designs*

	$\lvert Q_{out} \rvert$	V(x)	A(x)	P-norm Stress	Max(U_{sum}) [μm]	SC/BV/FC	V(x)<750 A(x)<140 P-norm < 0.66 Max(U_{sum}) < 32
Solid	7,128	1,800	280	0.293	8.06	--	No
SC Only	1,743	409	161	0.359	31.7	225/0/0	No
BV Only	2,405	634	57	0.365	30.8	0/225/0	Yes
FC Only	3,235	830	120	0.352	15.6	0/0/225	No
Op$_{avg,2}$	**2,773 (47.1)**	**722 (11.7)**	**107 (6.82)**	**0.360 (0.00614)**	**24.0 (1.34)**	**27/63/133 (5.3/8.0/9.4)**	**Yes**

*standard deviation in ( )

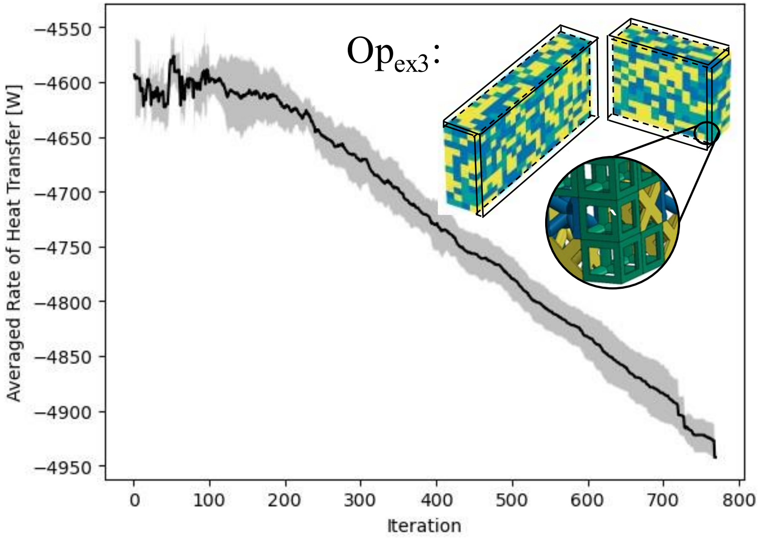
Compared to BV Only

Average of ~14% Heat dissipation

Average of ~25% Distortion

Case Study of Aerospace Bracket

Iteration History of 5 runs



Op_{ex3}: Objective = -4,860 W, Volume = 5,264 mm3, Area = 1,201 mm2, Displacement = 74 μm and P-norm = 0.646

Comparison of support designs*

	$\lvert Q_{out} \rvert$	V(x)	A(x)	P-norm Stress	$Max(U_{sum})$ [μm]	SC/BV/FC	V(x) < 5,900 A(x) < 1,360 P-norm < 0.66 $Max(U_{sum})$< 76
Solid	12,479	14,208	2,368	0.609	14	--	No
SC Only	3,524	3,232	1,367	0.648	96.0	1,776/0/0	No
BV Only	4,624	5,008	661	0.648	97.5	0/1,776/0	No
FC Only	6,004	6,553	1,568	0.637	74.7	0/0/1,776	No
$Op_{avg,3}$	**4,902 (29.4)**	**5,315 (36.2)**	**1,222 (13.7)**	**0.643 (0.0037)**	**72.8 (2.3)**	**388/589/799 (16/20/30)**	**Yes**

*standard deviation in ( )

Compared to BV Only

Satisfies Constraints

Average of ~5% Heat dissipation

Average of ~29% Distortion

Overview

Objective 1: Coupling Simulated Annealing and Homogenization to Design Thermally Conductive Hybrid Lattice Support Structures for LPBF

- Objective 1.1: Maximize heat dissipation
- Objective 1.2: Expedite evaluation and design exploration

Objective 2: Designing Thermally Conductive Hybrid Lattice Support Structures Constrained by Residual Stress and Deformation for LPBF

- Objective 2.1: Incorporating structural constraints
- Objective 2.2: Expediting thermal and structural property predictions

Objective 3: Extending Lattice Support Structure Design to Curved Interfaces

- Objective 3.1: Calibrating for structural accuracy
- Objective 3.2: Designing for complex surfaces
- Objective 3.3: Validating framework experimentally*

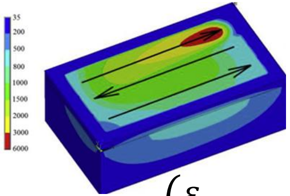
*Performed with Rollett Research Lab

Calibrating simulation results for inherent strain inputs for arbitrary materials

Haynes 282[34]

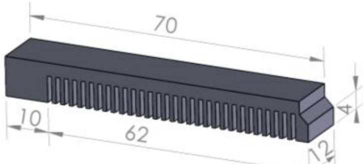
- Nickel-based superalloy
  - High strength
  - Resistance to corrosion and oxidation
  - Good creep and fatigue performance
- Applications
  - Industrial gas turbines
  - Powerplant parts

Thermo-mechanical Model[33]



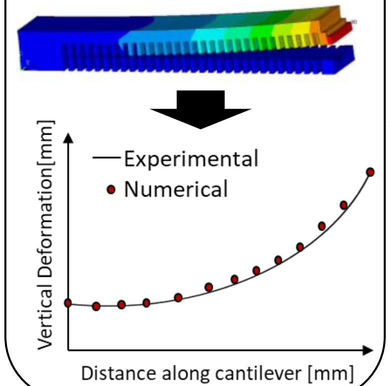
$$\varepsilon_0^{inh} = \begin{cases} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \end{cases}$$

Experimental Results*[35,36]



*Performed by Rollett Research Lab

Regression Model[34]

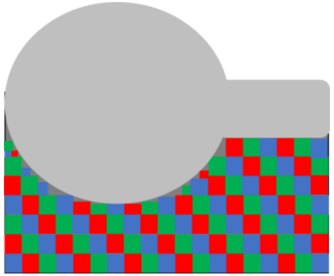


$$\varepsilon^{inh} = \begin{cases} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \end{cases}$$

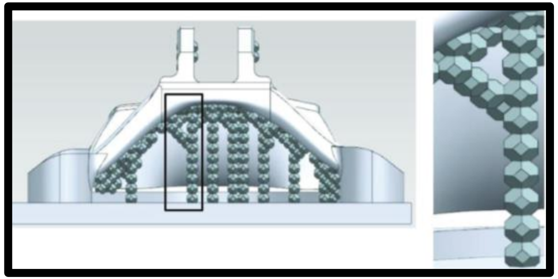
33. Chen, Q., et. al (2019) 34. Shaikh, A.S., et. al (2021) 35. Miki, T., and Yamada, T. (2021) 36. Setien, I., et. al (2019)

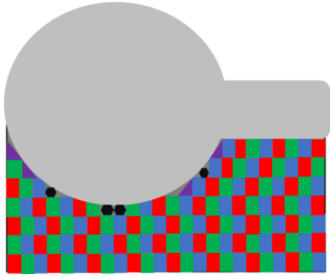
Incorporating complex, curved structures for lattice support generation

1. Multisize unit cells[37]

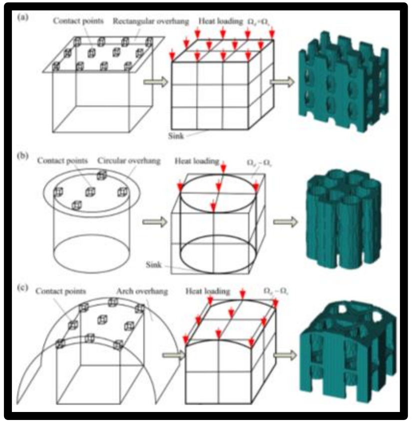


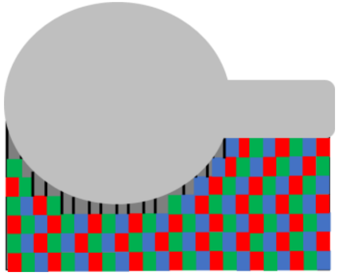
2. Extended unit cell library[38]





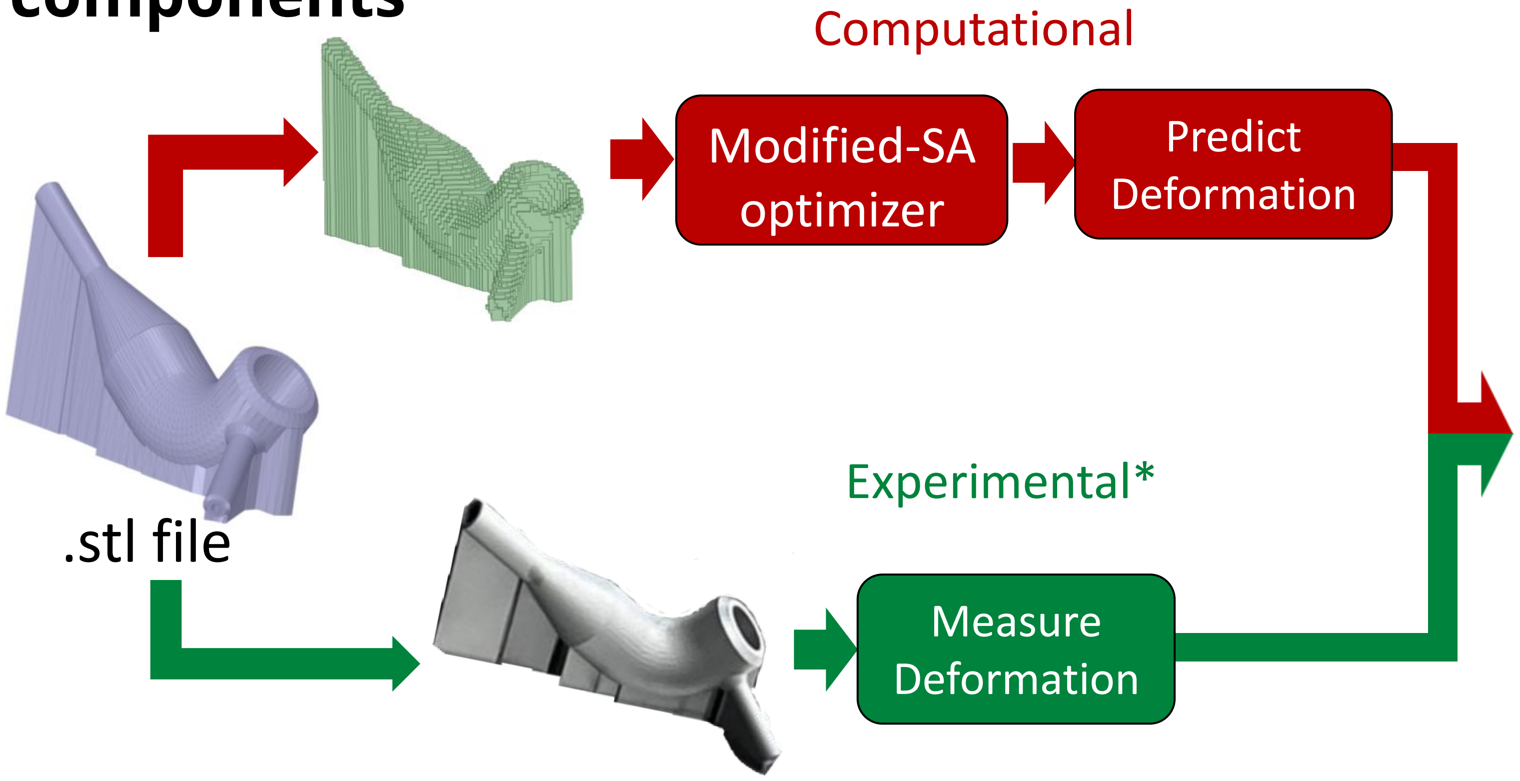
3. Forced flat domain[9,20,36]





9. Huang ,R., et al. (2020) 20. Vaissier, B., et. al (2022) 37. Boos, E., et. al (2022) 38. Vaidya, R., and Anand, S. (2016)

Validating the framework through experimental components



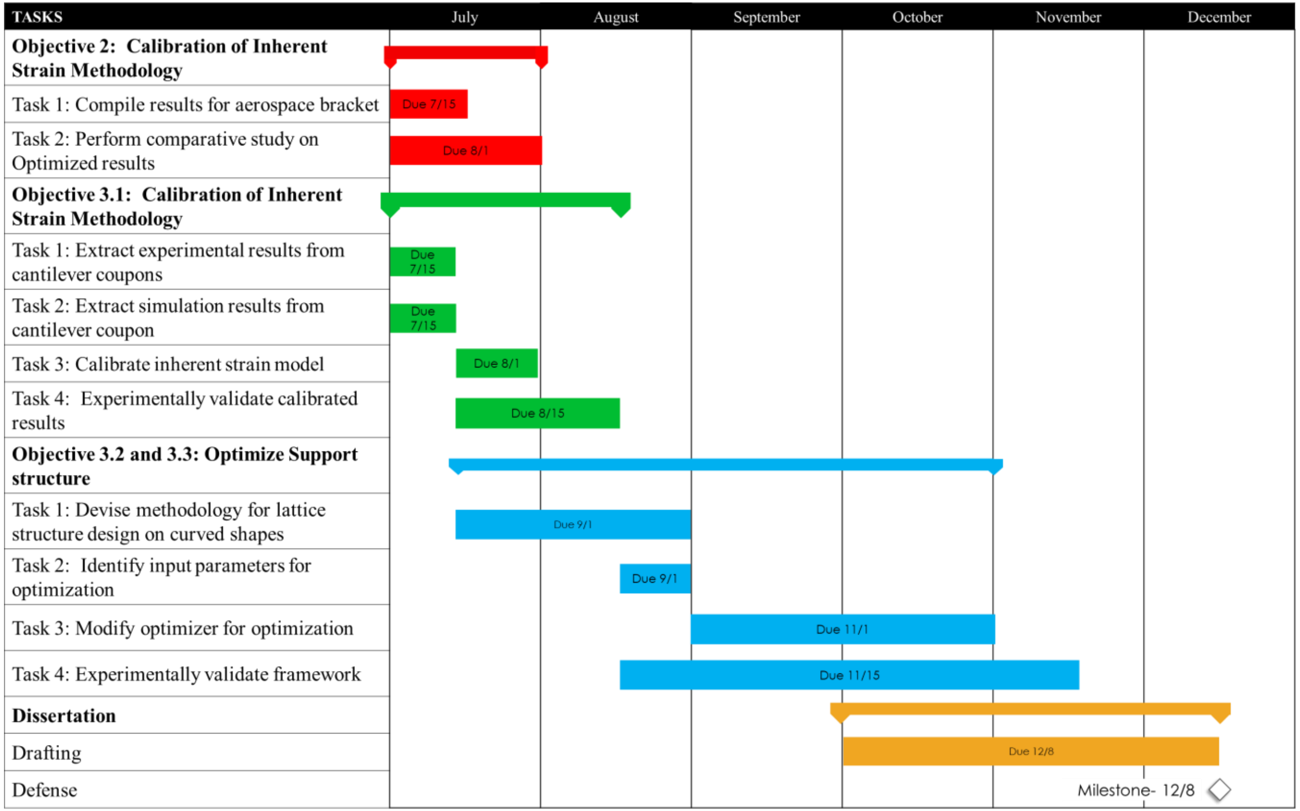
$$\sqrt{\frac{\sum(U_c - U_E)^2}{N}}$$

*Performed by Rollett Research Lab

Expected Outcomes

1. Approach to incorporate design for AM constraints into optimization.
2. Computational modeling of transient loading to an equivalent static loading.
3. Further investigation into advancing the application of non-gradient-based optimizers within AM.
4. Methodology to couple experimental results within optimization.

Timeline


TASKS
July
August
September
October
November
December
Objective 2: Calibration of Inherent Strain Methodology
Task 1: Compile results for aerospace bracket
Due 7/15
Task 2: Perform comparative study on Optimized results
Due 8/1
Objective 3.1: Calibration of Inherent Strain Methodology
Task 1: Extract experimental results from cantilever coupons
Due 7/15
Task 2: Extract simulation results from cantilever coupon
Due 7/15
Task 3: Calibrate inherent strain model
Due 8/1
Task 4: Experimentally validate calibrated results
Due 8/15
Objective 3.2 and 3.3: Optimize Support structure
Task 1: Devise methodology for lattice structure design on curved shapes
Due 9/1
Task 2: Identify input parameters for optimization
Due 9/1
Task 3: Modify optimizer for optimization
Due 11/1
Task 4: Experimentally validate framework
Due 11/15
Dissertation
Drafting
Due 12/8
Defense
Milestone- 12/8

Thank you

Questions?

References

Conference Paper

1. **White, L.**, Liang, X., Zhang, G., Cagan, J., and Zhang, Y. J. “Coupling Simulated Annealing and Homogenization to Design Thermally Conductive Hybrid Lattice Support Structures for LPBF”. Accepted in Proceedings of the ASME 2024 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Boston, Massachusetts, 2023.

Journal Papers

1. **White, L.**, Liang, X., Zhang, G., Cagan, J., and Zhang, Y. J. “Designing Thermally Conductive Hybrid Lattice Support Structures Constrained by Residual Stress and Deformation for LPBF”. *In preparation for Journal of Mechanical Design*, 2023.
2. **White, L**., Seo, J., Lamprinakos, N., Zhang, G., Liang, X., Rollett, A., Cagan, J., and Zhang, Y. J. “Extending Lattice Support Structure Design to Curved Interfaces”. *In preparation for journal*, 2023.