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Taking Inspiration from Systems Engineering: a Framework for Requirement Flow Down in Lattice Design

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SERC DOCTORAL STUDENT FORUM 2022

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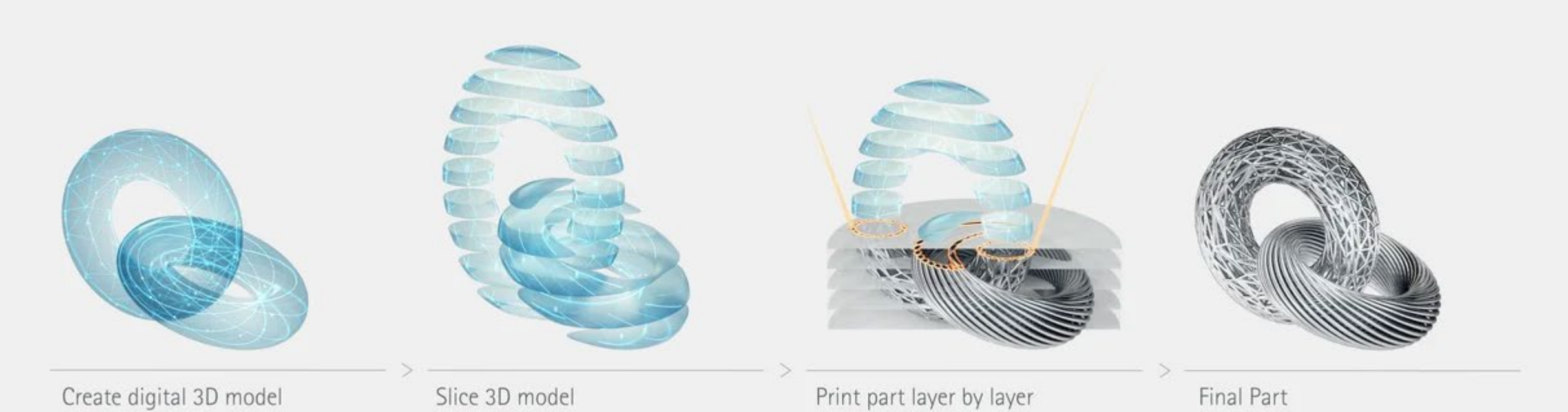
Overview

What are additive manufacturing and lattice structures

Framework development

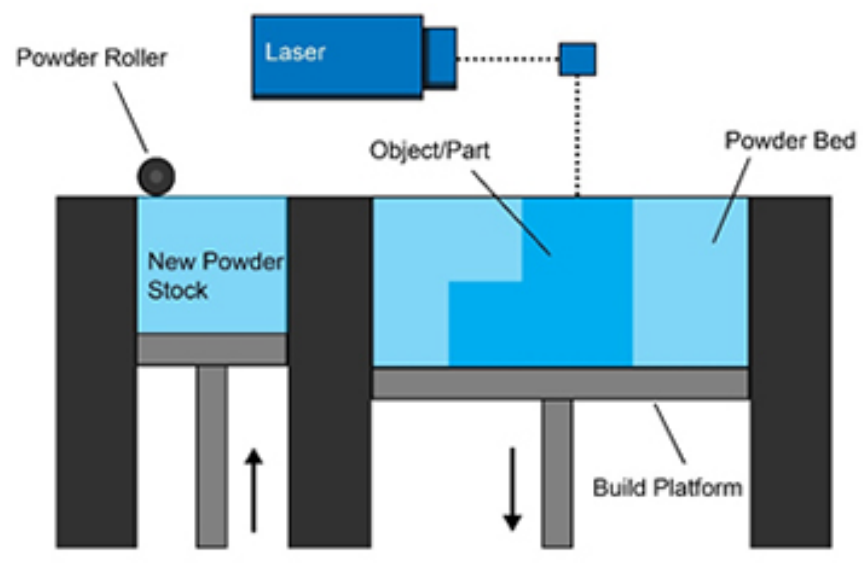
Application of the framework

Additive manufacturing is a collection of processes that build objects layer by layer



Credit: EOS

There are seven different AM processes that have different benefits and limitations, but we will talk only about Laser Powder Bed Fusion



Credit: Loughborough University

Credit: Stratasys

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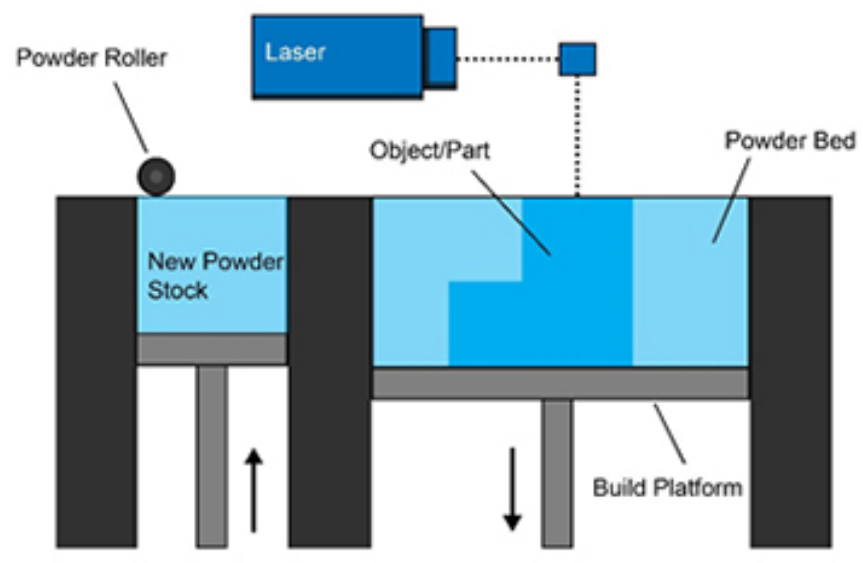
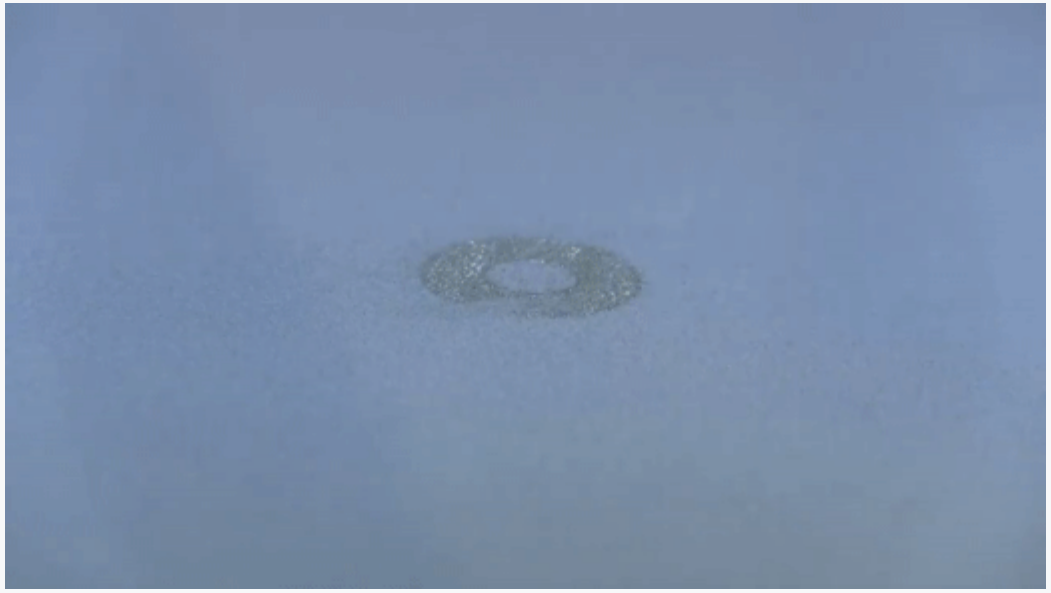


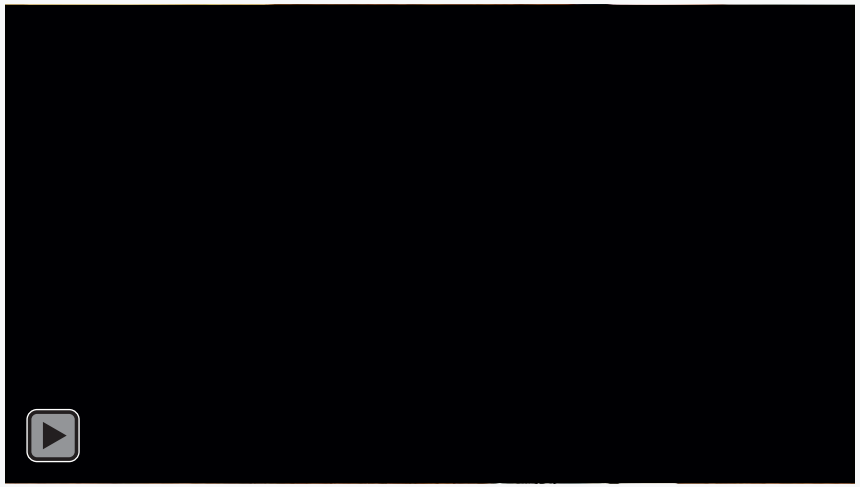
Credit: Loughborough University

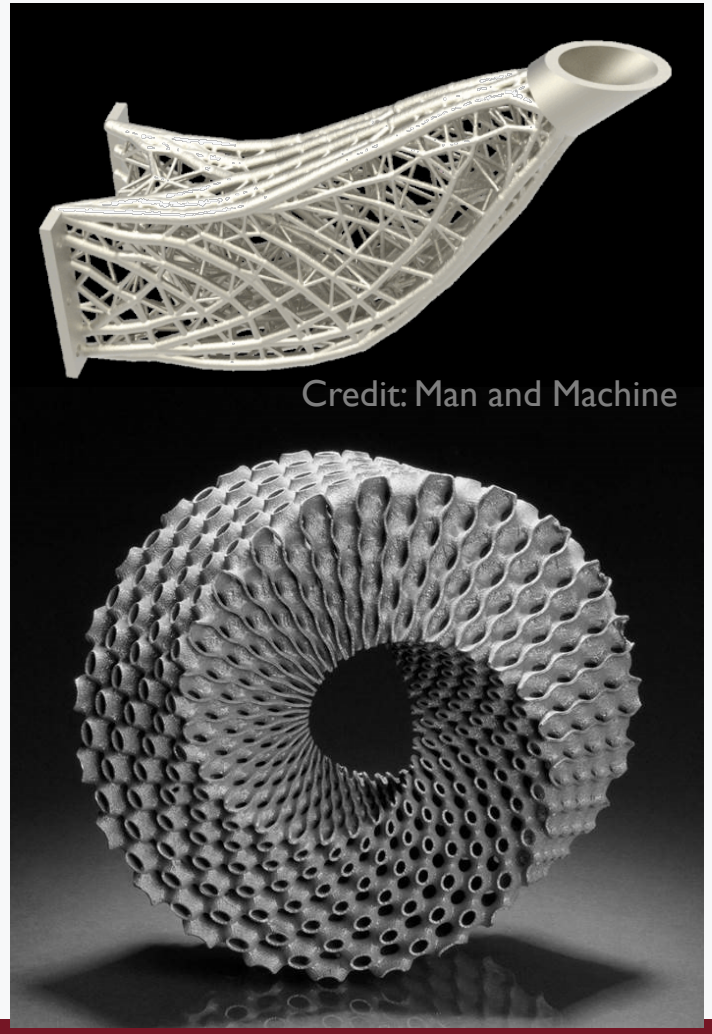


Credit: Stratasys

Additive Manufacturing enables us to produce complex geometries that were previously infeasible or not economical

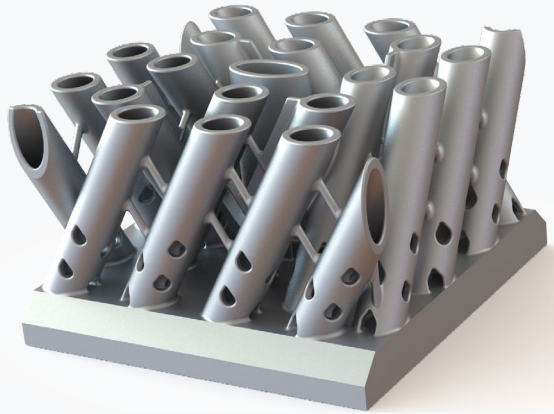
Credit: Arup



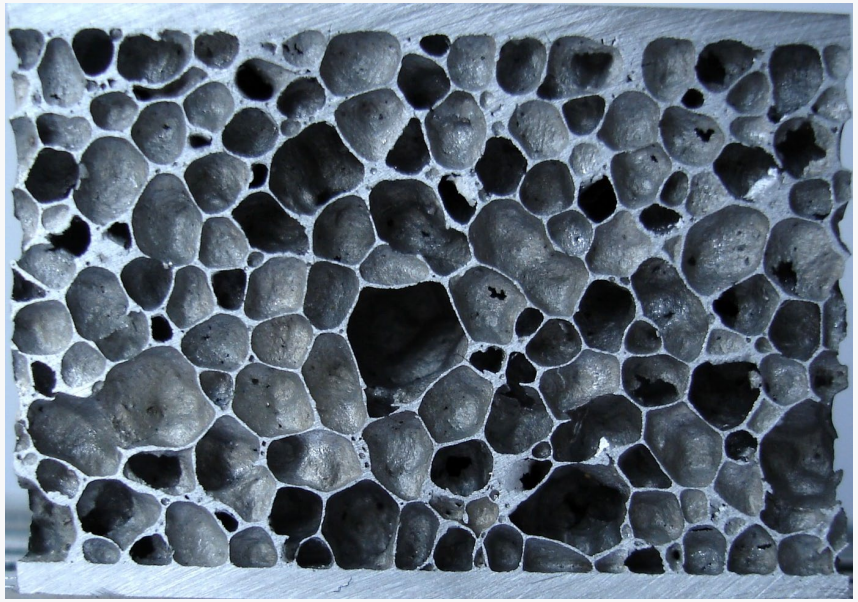


Credit: Man and Machine

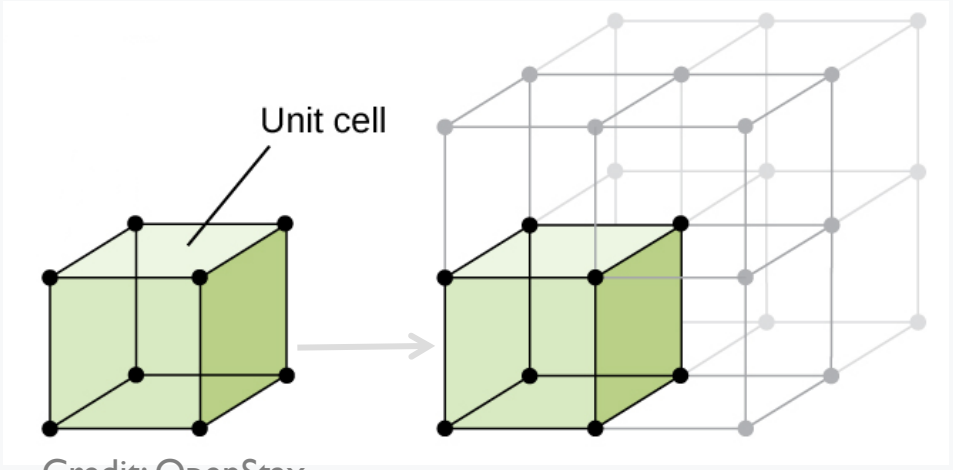
Credit: Autodesk



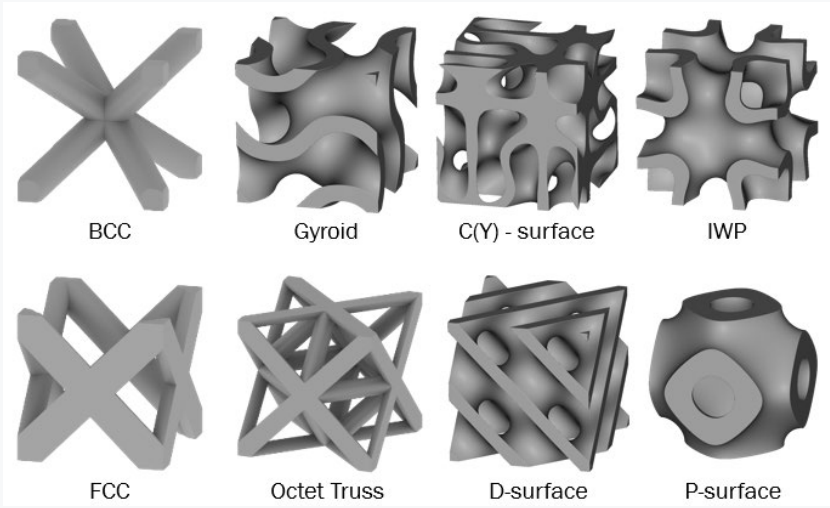
Lattice structures, like engineered foams, are a type of cellular solid but they are highly ordered



Credit: Metalfoam (via Wikimedia Commons)



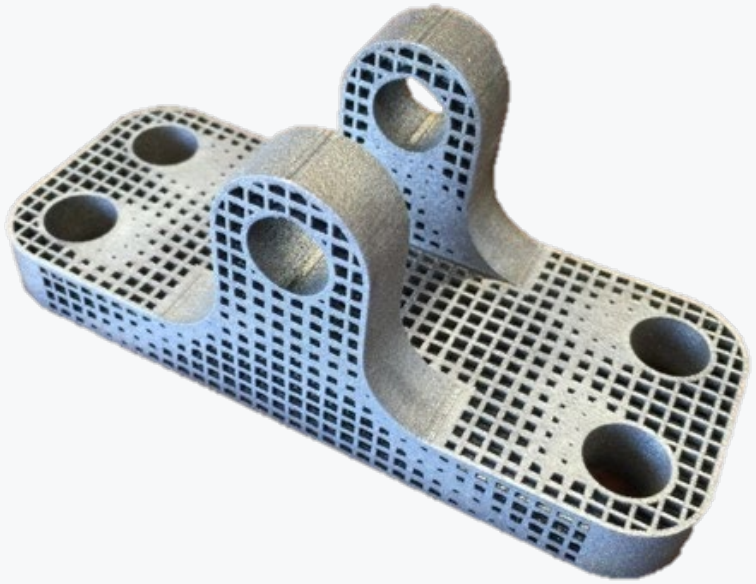
Credit: OpenStax



Lattice structures offer reductions in the weight and cost of additively manufactured parts and offer improvements to performance.

Credit: nTopology

Credit: nTopology

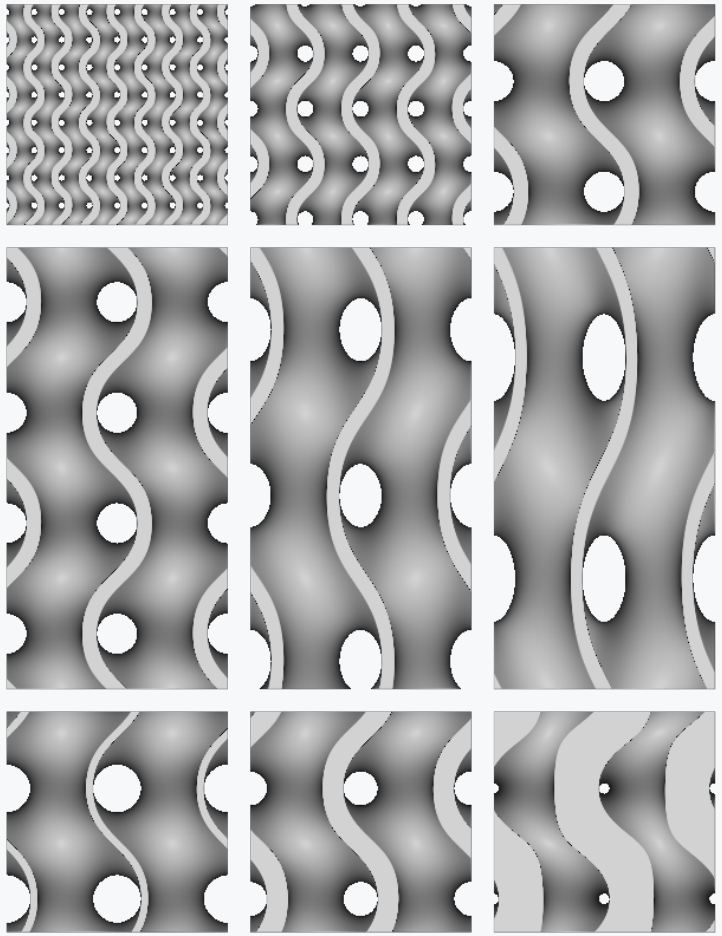


Credit: Cheng, et al. 2019

There are a vast number of different lattices to chose from, and even once one is chosen, there are still many factors that impact its performance

- Cell size
- Cell aspect ratio
- Volume fraction/relative density

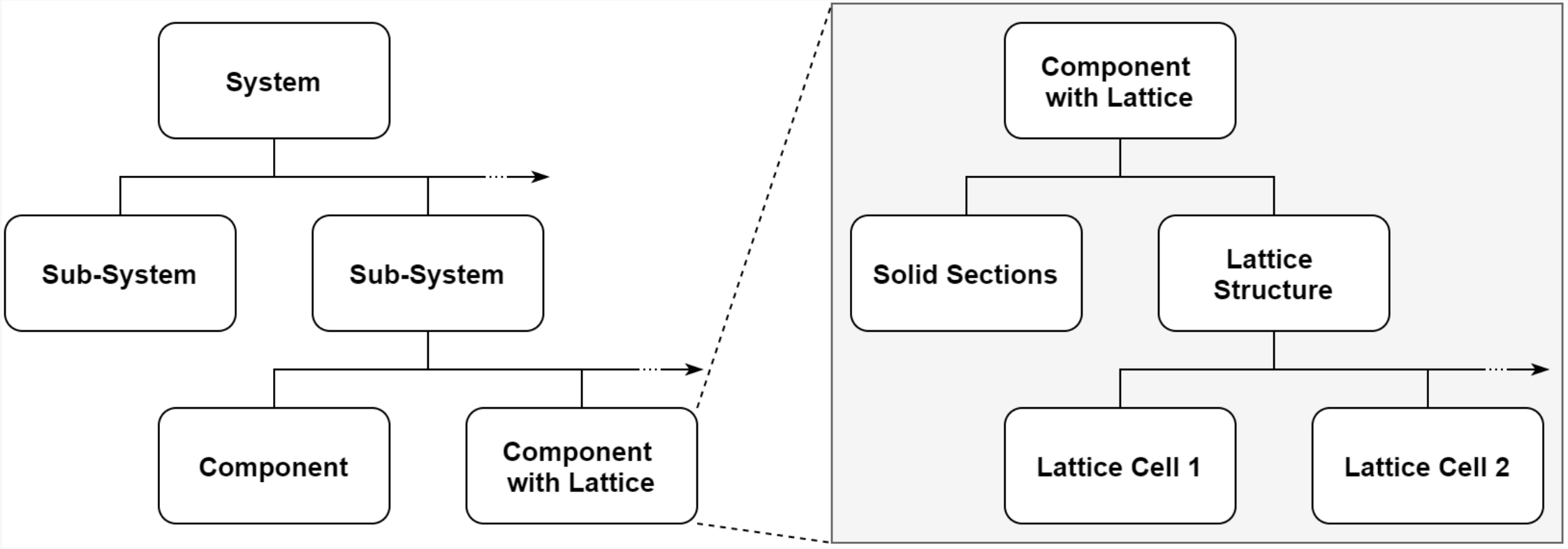
- Cell orientation
- Cell position



The goal of our framework is to provide a structured process for lattice design that is:

- Easy to understand, digest, and follow
- Requirement driven
- Independent of specific material and AM process
- Complete with verification and validation (V&V)
- Extensible (with different design and optimization techniques)
- Not limiting design freedom

We saw the hierarchy in a system as an analog to the hierarchy in a component with lattice

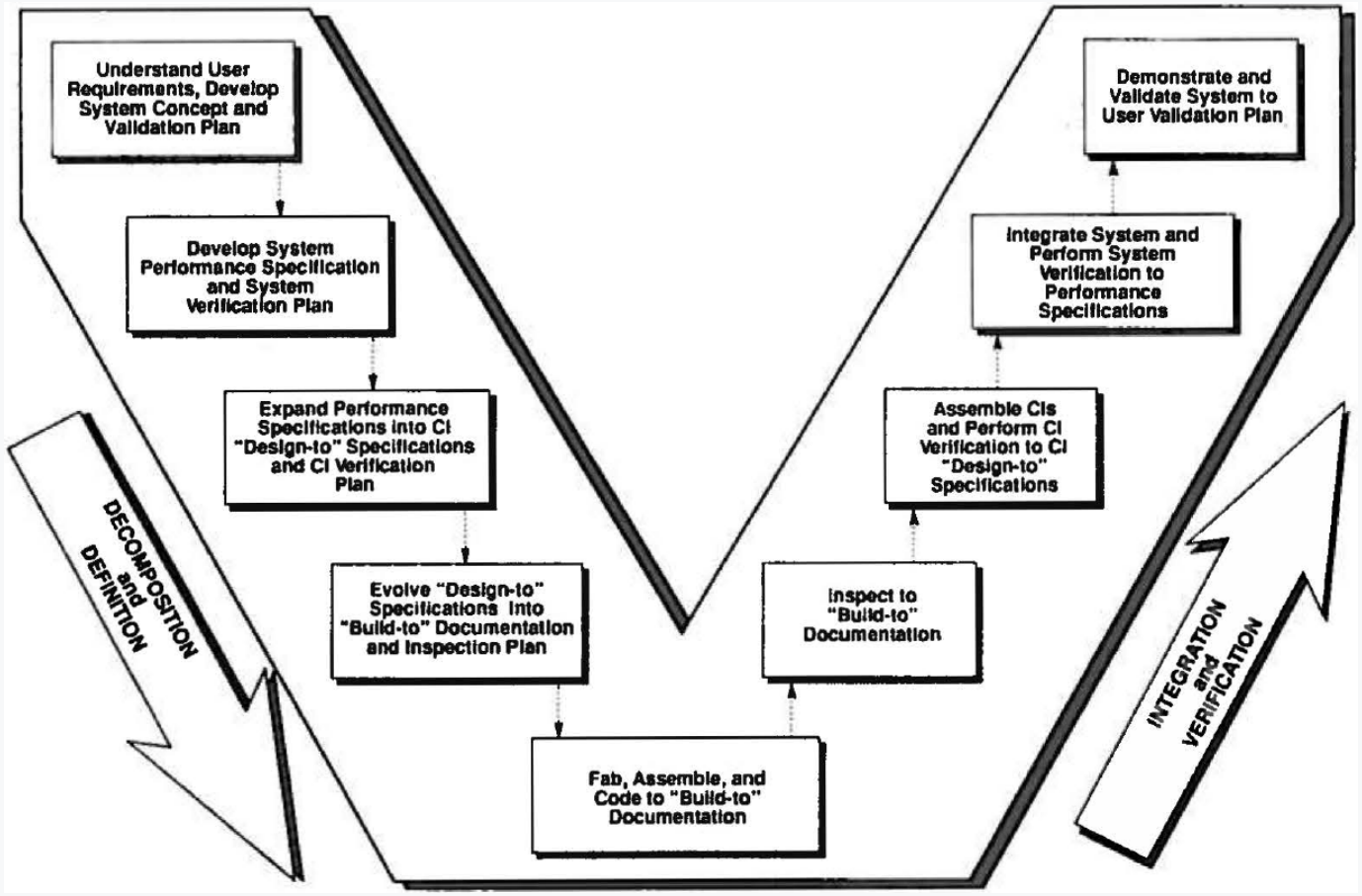


"A system is an arrangement of parts or elements that together exhibit behaviour or meaning that the individual constituents do not" – INCOSE 2019

Several different models for engineering design and system engineering have been proposed, we found the System Vee to be most adaptable to lattice design

Strong emphasis on:

- Hierarchy
- Requirement flowdown
- Integration
- Verification & Validation

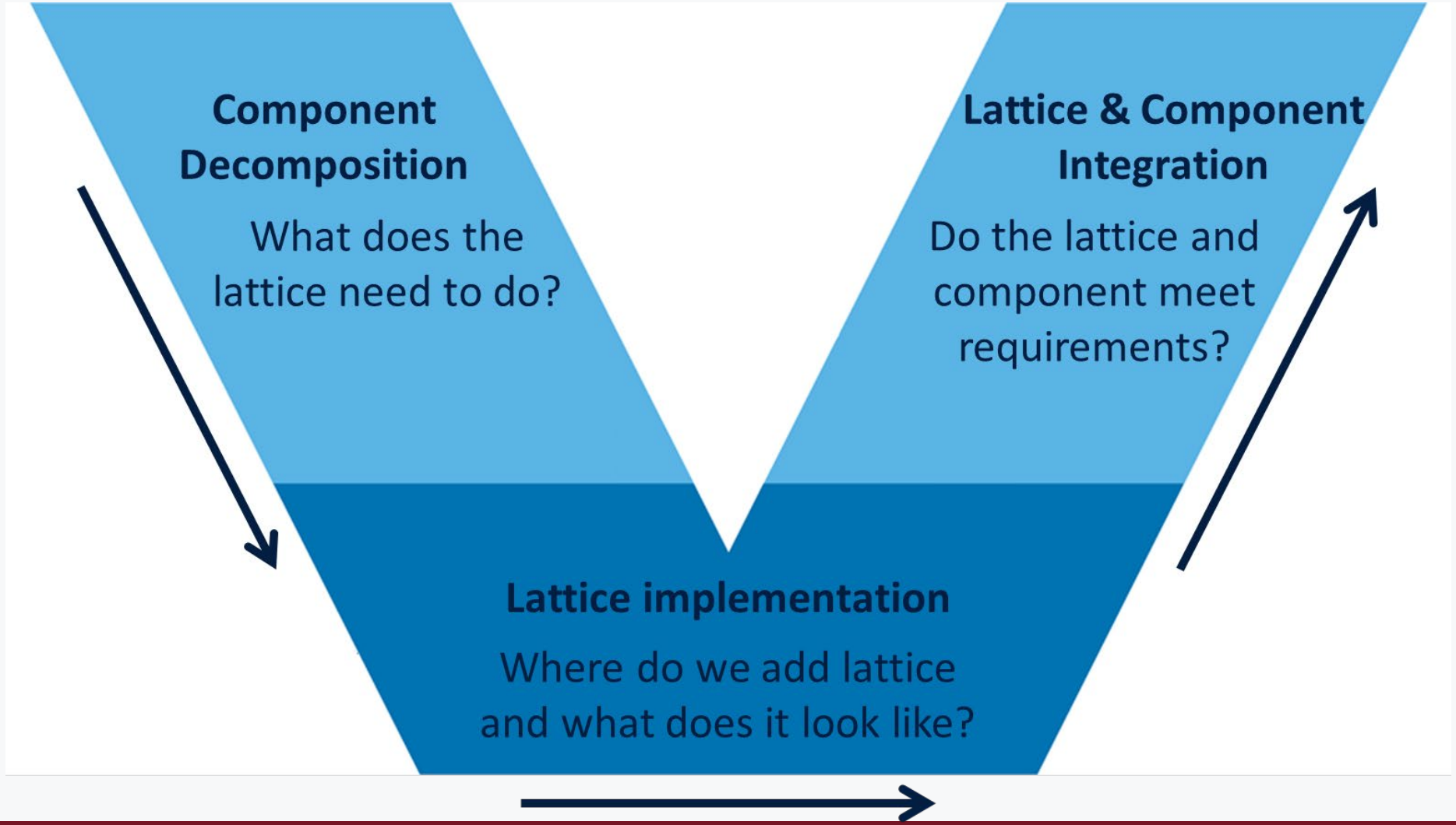


Forsberg and Mooz 1992

The Lattice Vee Framework (LVF) draws from the Systems Vee in some key ways and differs in others

- Planning on the left is directly related to testing on the right through V&V
- The LVF is significantly more prescriptive, and less descriptive
- The LVF acts on shorter time scales.

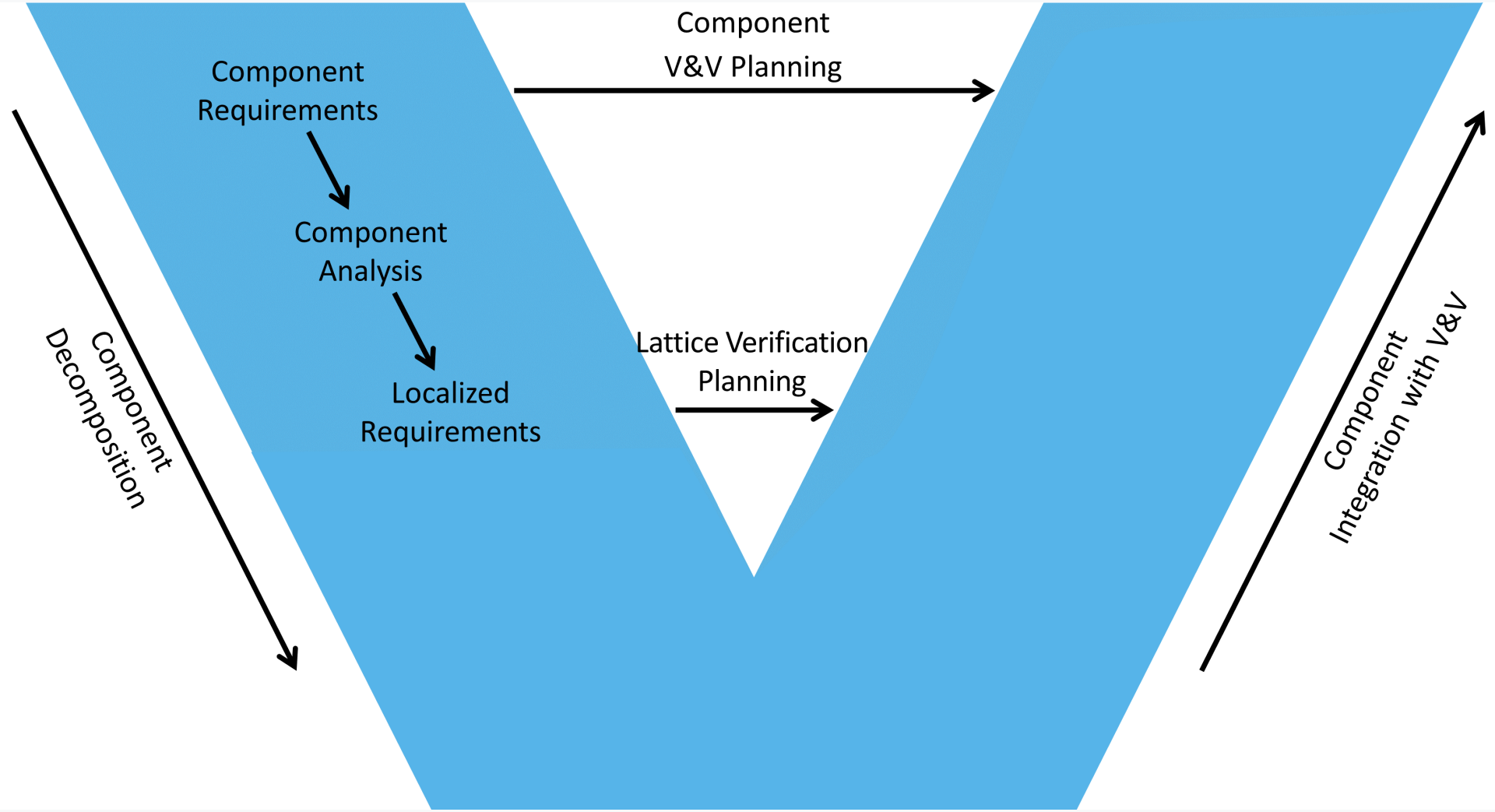
The steps of the Lattice Vee Framework can be grouped into three phases



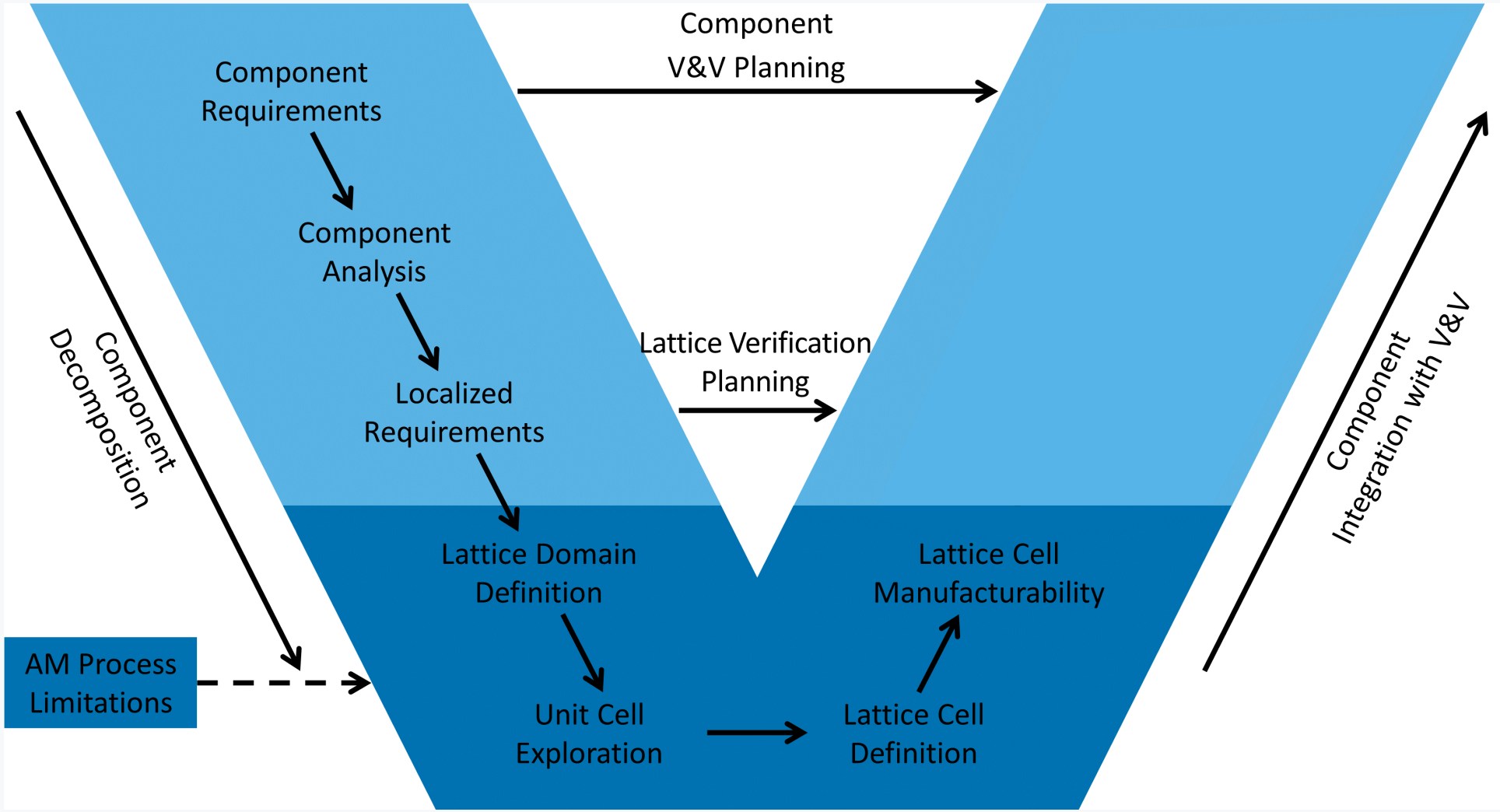
Assumptions for the Lattice Vee Framework

1. Material and AM process are specified
2. Component domain is of an appropriate scale (for given AM process)
3. A database of relevant lattice structure properties exists

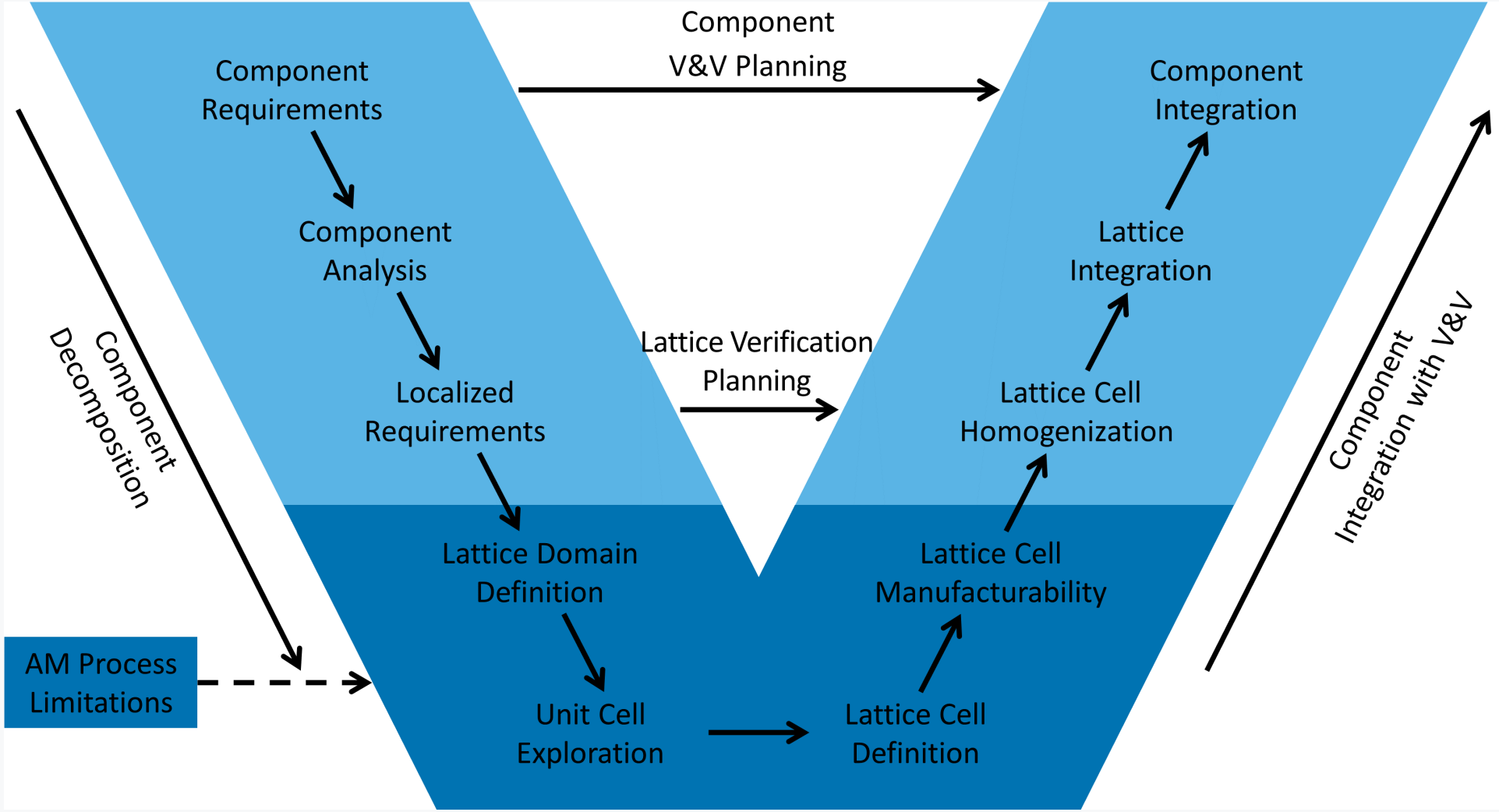
Component decomposition starts with the requirements from the system level and translates them into requirements for the lattice



The lattice domain, lattice topology, and cells of the lattice can be defined and checked for manufacturability based on the localized requirements



The performance of the lattice is verified prior to integration with the rest of the component which then undergoes verification and validation



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Structural redesign example with constant pressure

Minimum Factor of Safety: 1.5

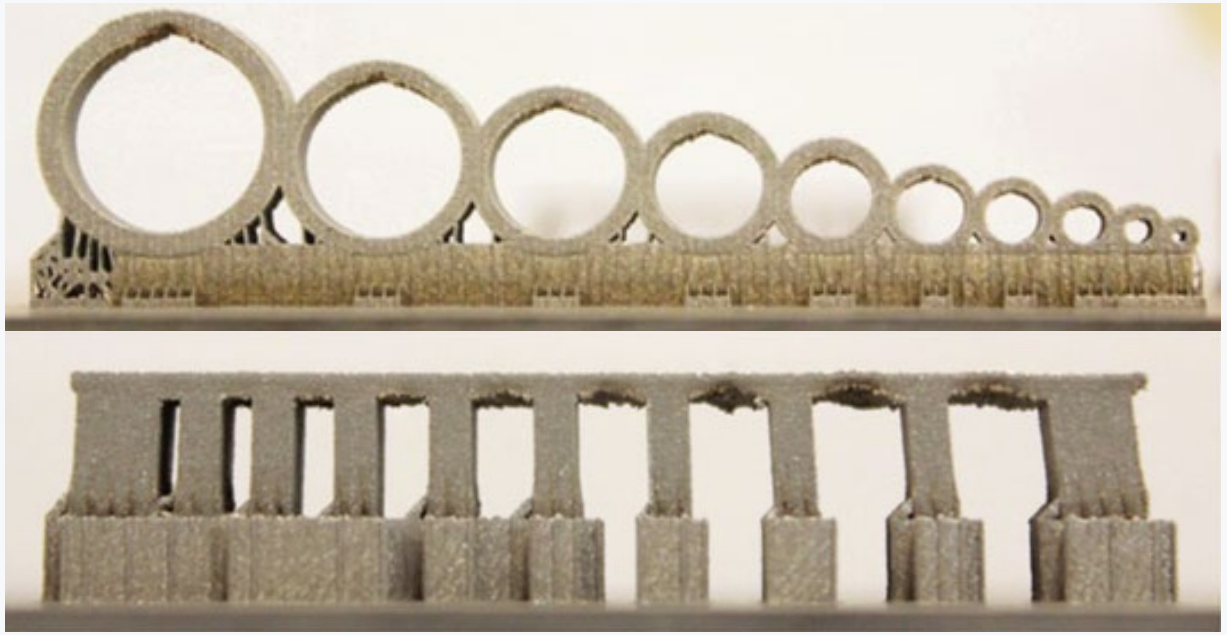
Material: Inconel 718

Pressurized surfaces have defined minimum thicknesses

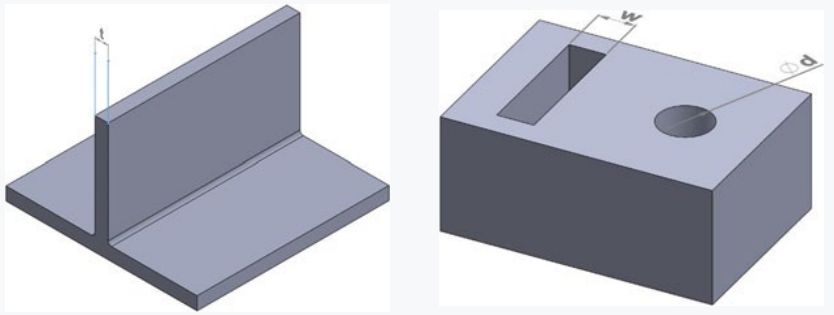
Process: Laser Powder Bed Fusion

Kantareddy et al. 2016

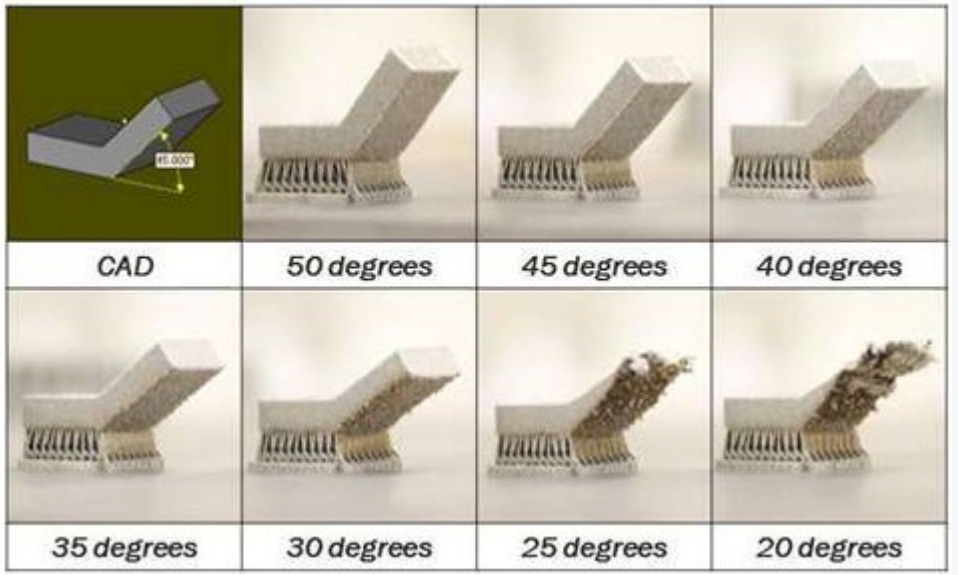
Three relevant AM process limitations are considered in this example



Arched bridging distance = 6mm
Flat bridging distance = 2mm



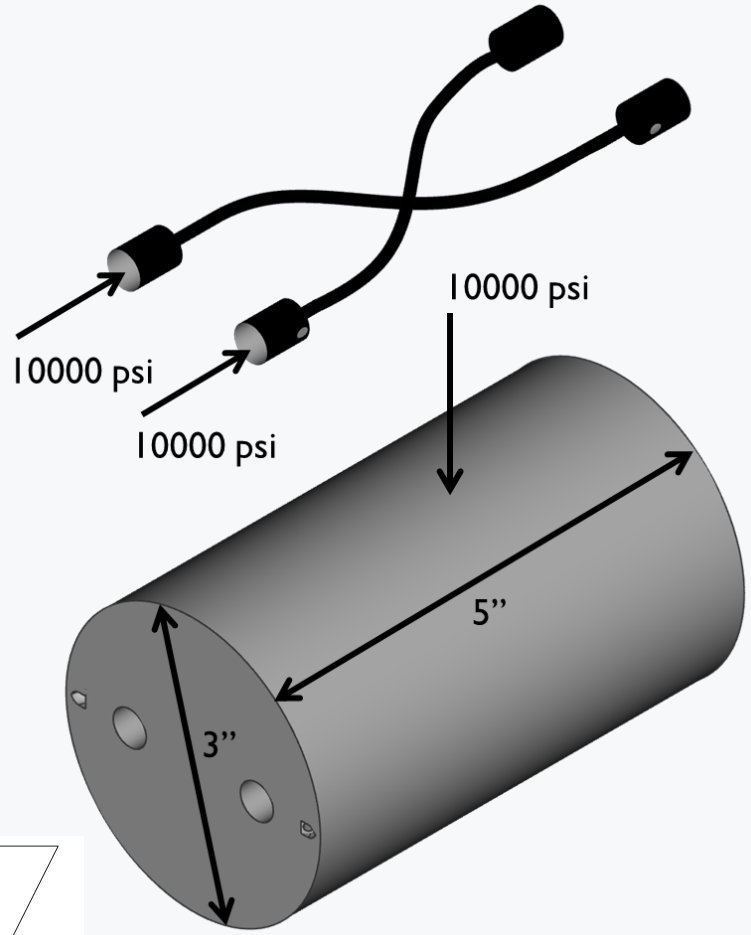
Minimum feature size = 0.5mm

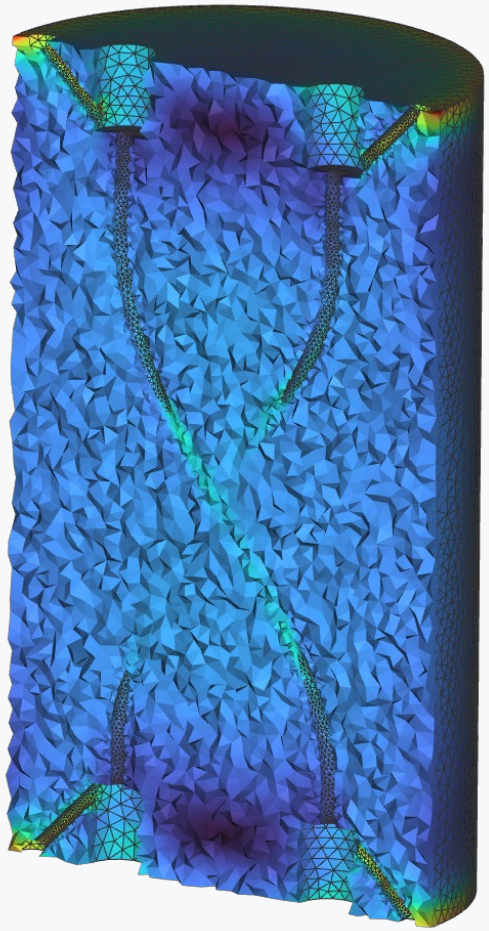


Overhang angle = 40°

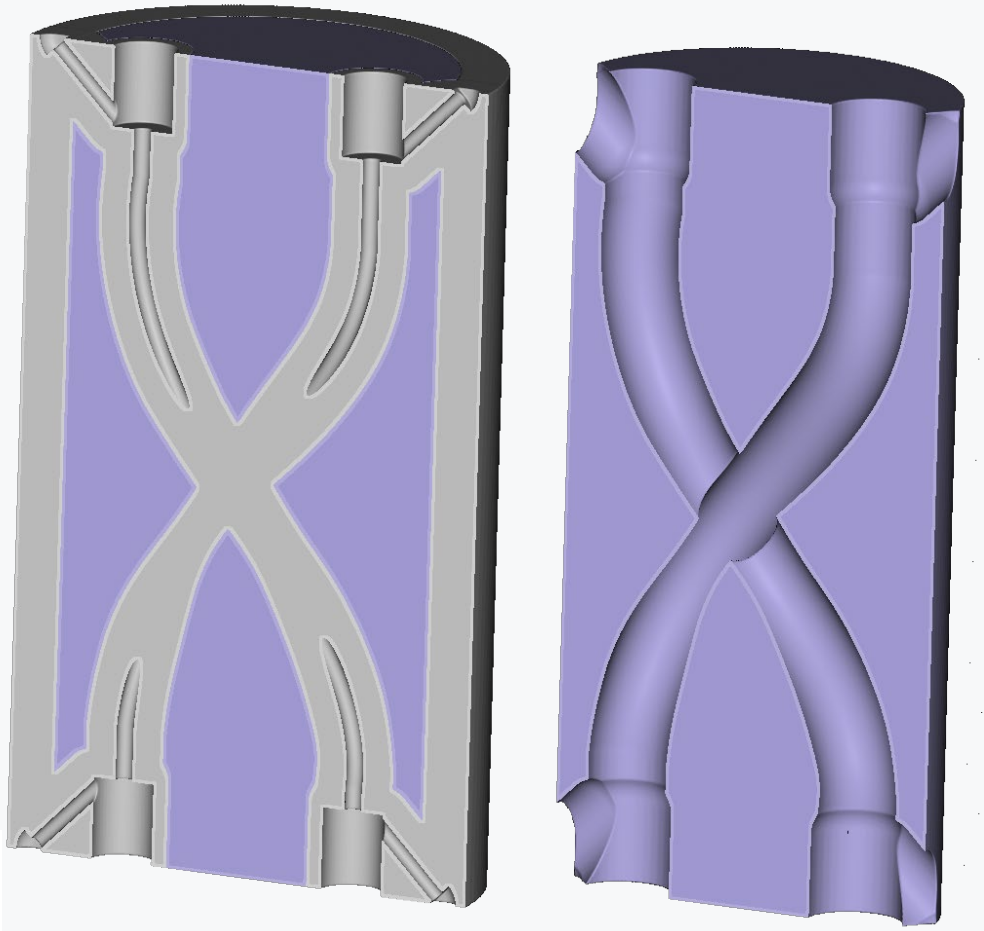
Olaf et al. 2019

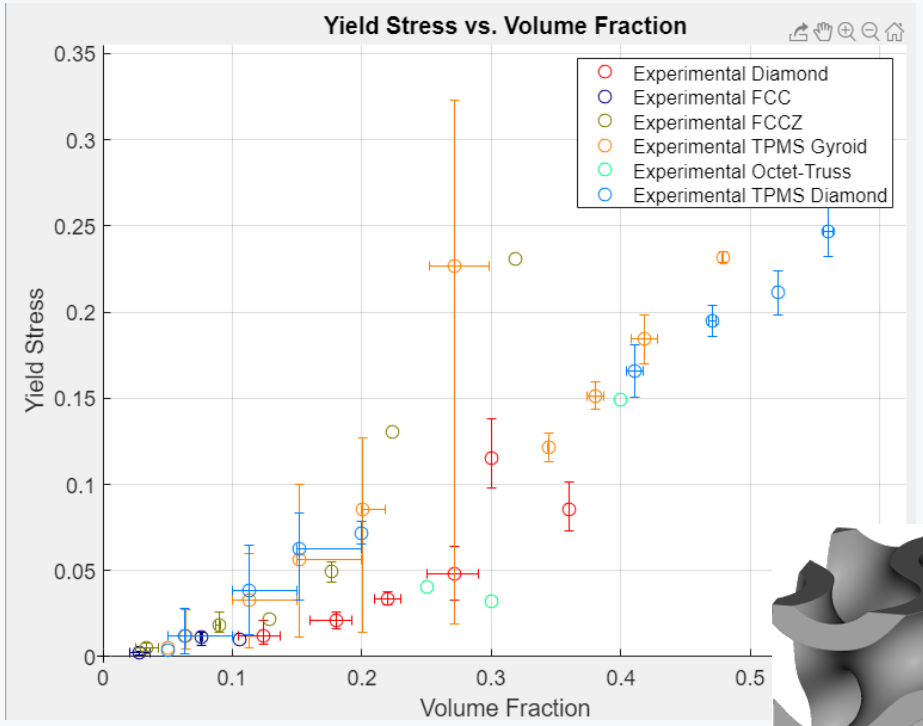
The component requirements are used to define a simulation of the loading, which will inform the lattice level requirements

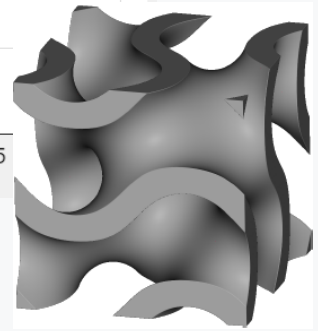




Based on the component requirements the domain of the lattice was defined and a suitable lattice topology was chosen

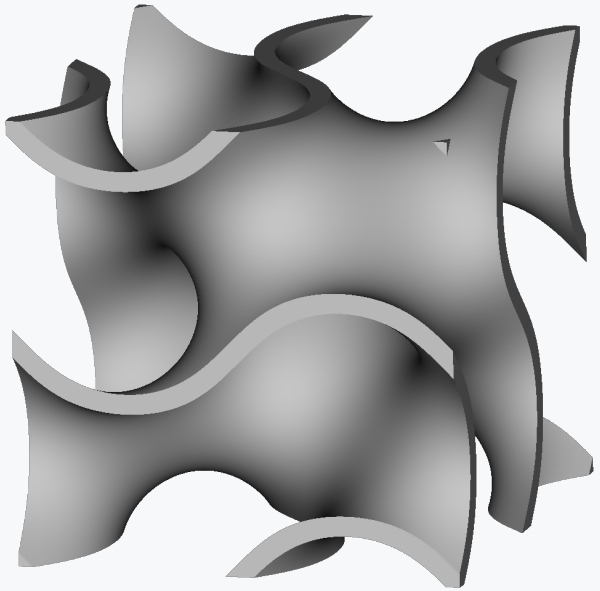




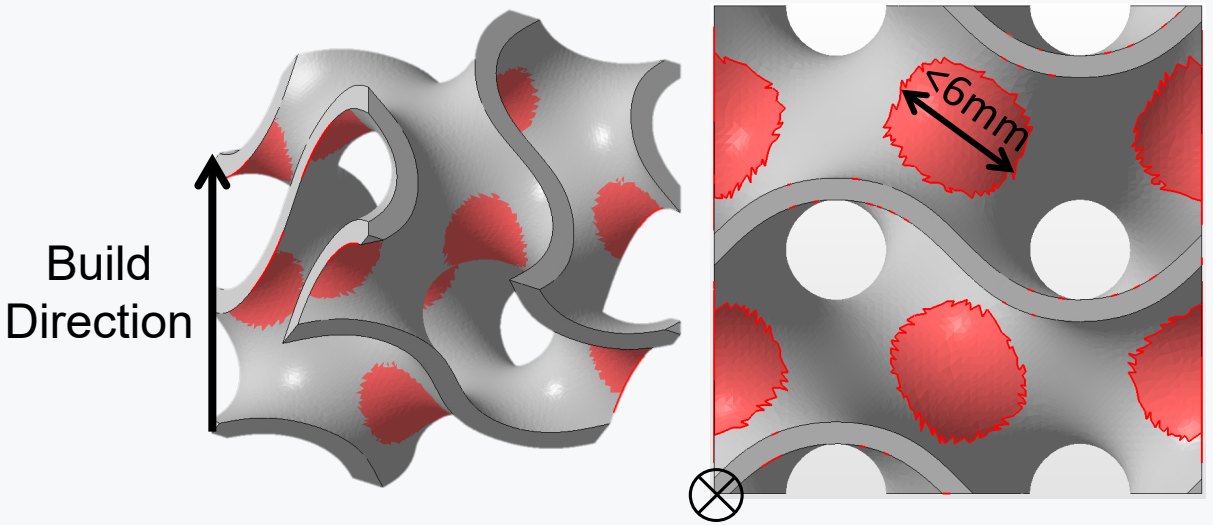


We choose a volume fraction of 12.8% based on the localized requirements, and checked the manufacturability of the lattice

Minimum feature size ~0.774 mm ✓

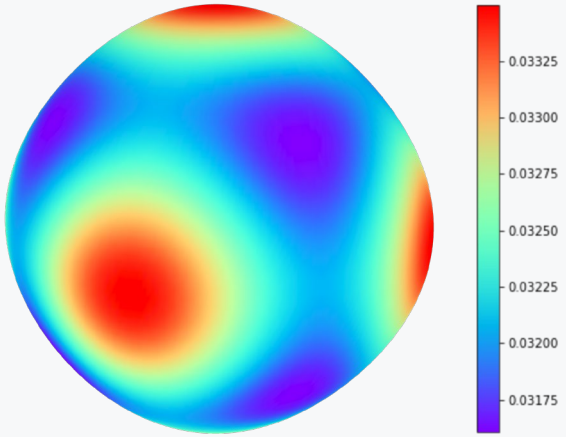


Gyroid unit cell at 12.8% VF

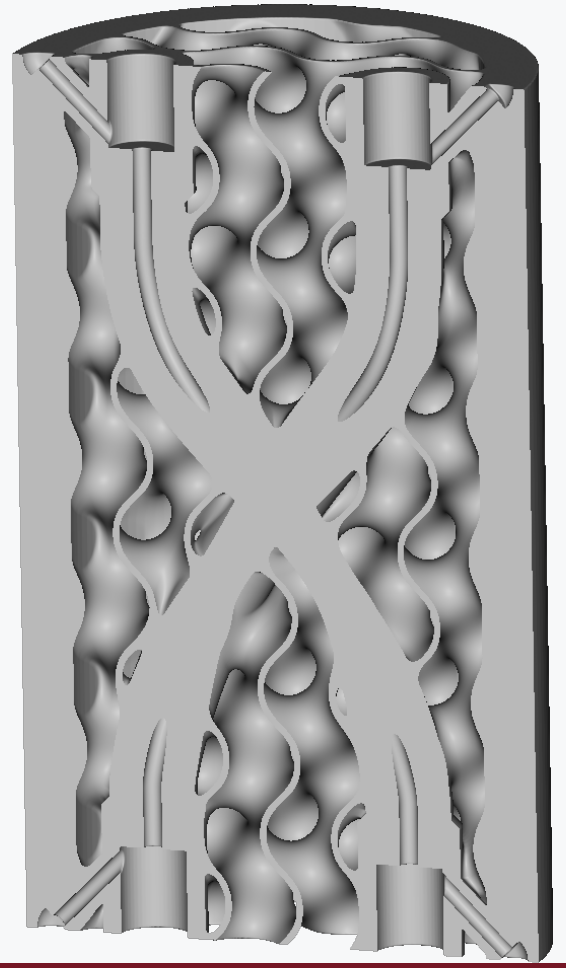


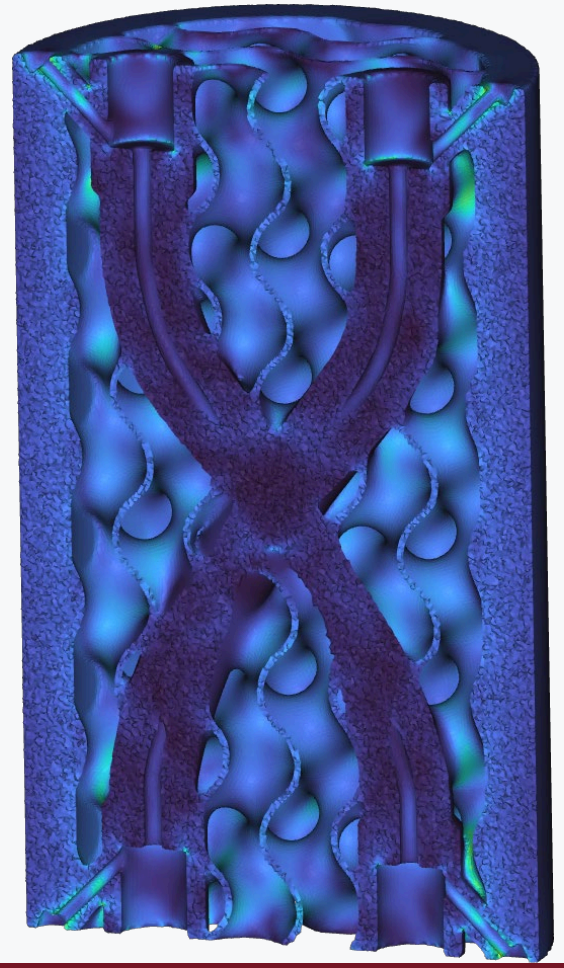
Gyroid has arches with <45 overhang highlighted ✓

The lattice cell was homogenized, and the result was verified against the localized requirements, then the lattice was integrated, and the component analyzed



Young's modulus response surface normalized to bulk





The LVF provides an extensible framework for bridging system engineering design methodology and lattice design/optimization

- Fits within existing engineering design methodology
- Balances prescription and extensibility

Ongoing and future work

- Generation of lattice database through experimentation and FEA for decision making
- Developing of a toolchain demonstration for the LVF
- Applying the LVF to additional case studies

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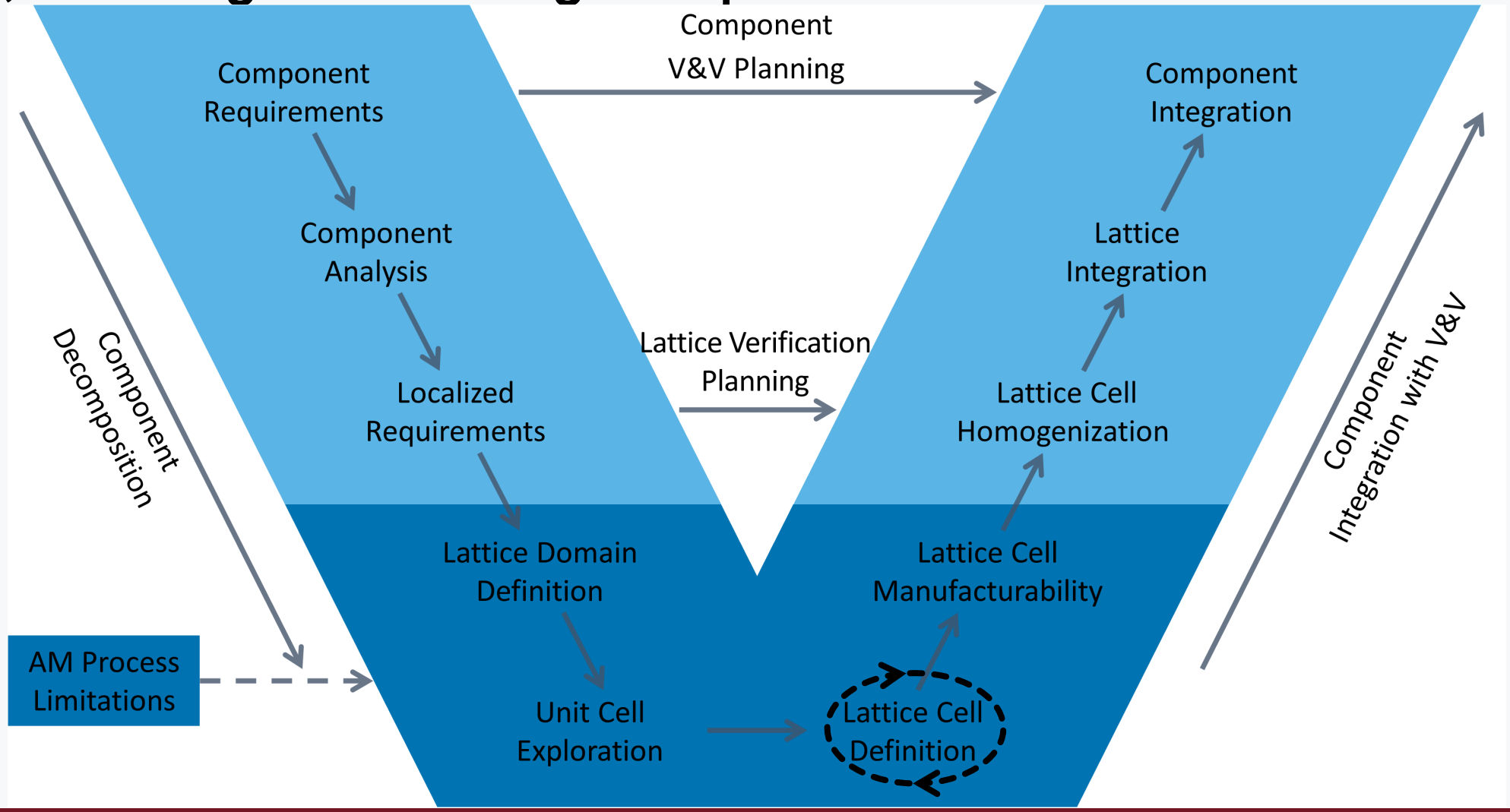
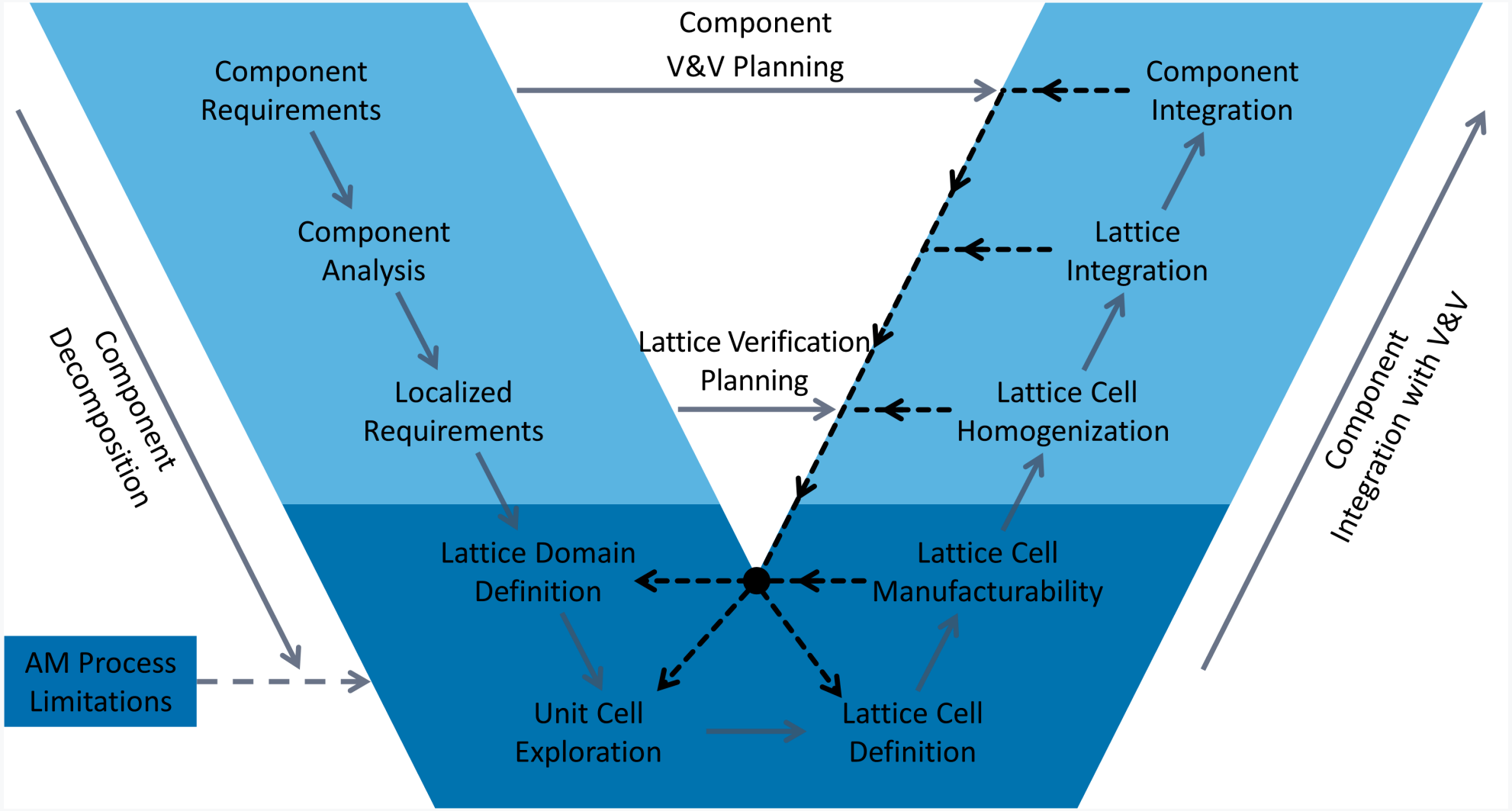
Three different levels of iteration can occur when implementing the LVF, including within a single step

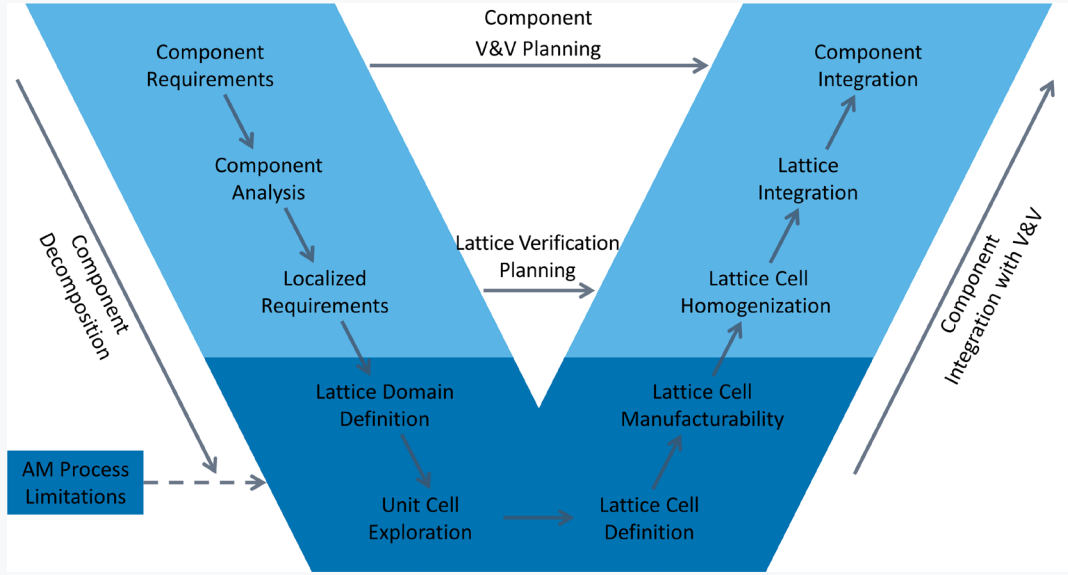


Iteration within the LVF can force revisiting steps as far back as Lattice Domain Definition

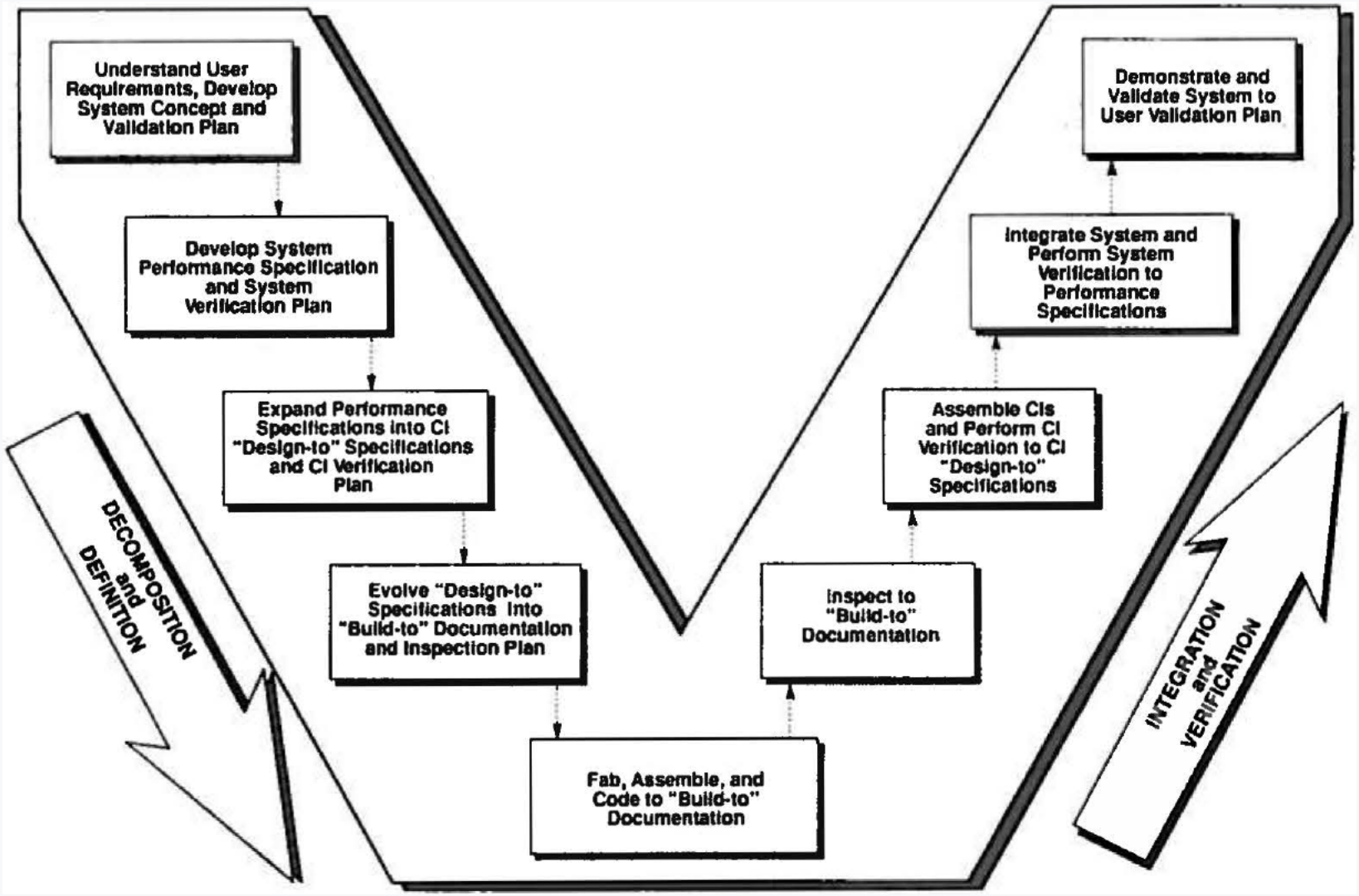


System level iteration is needed when no valid solution based on the component requirements can be found

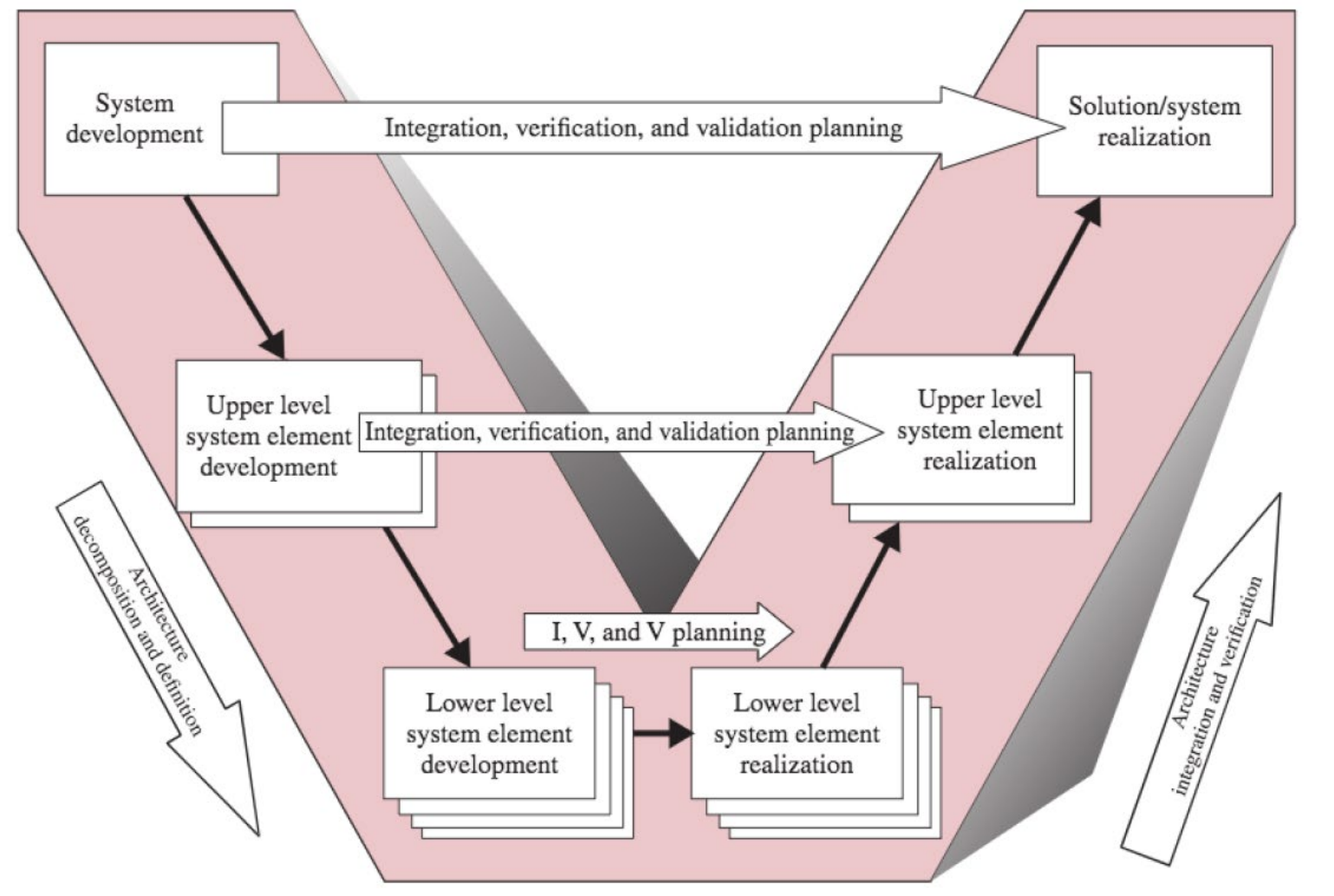
System Level Requirements/Design



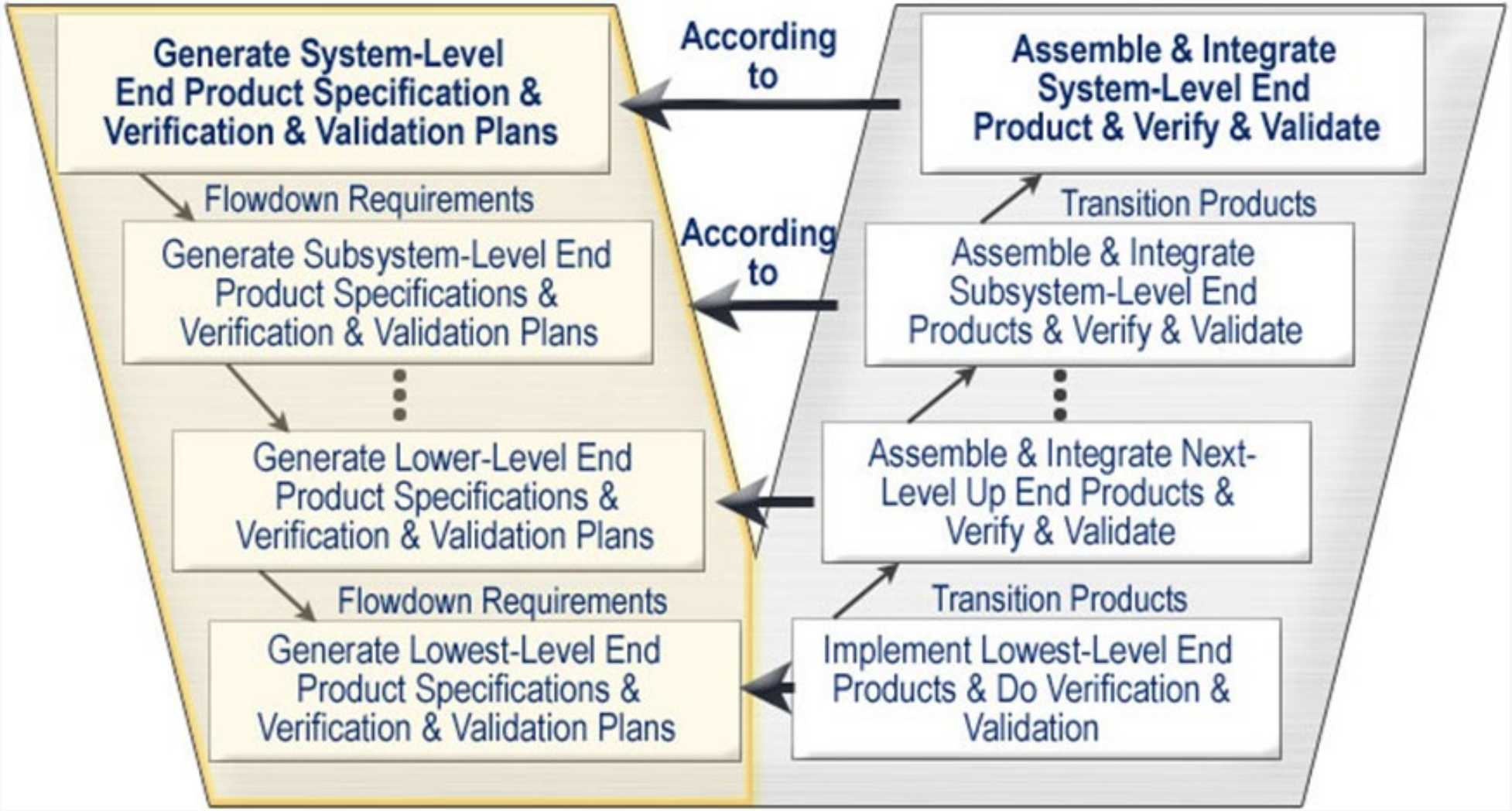
Forsberg's System Vee from Forsberg and Mooz 1992



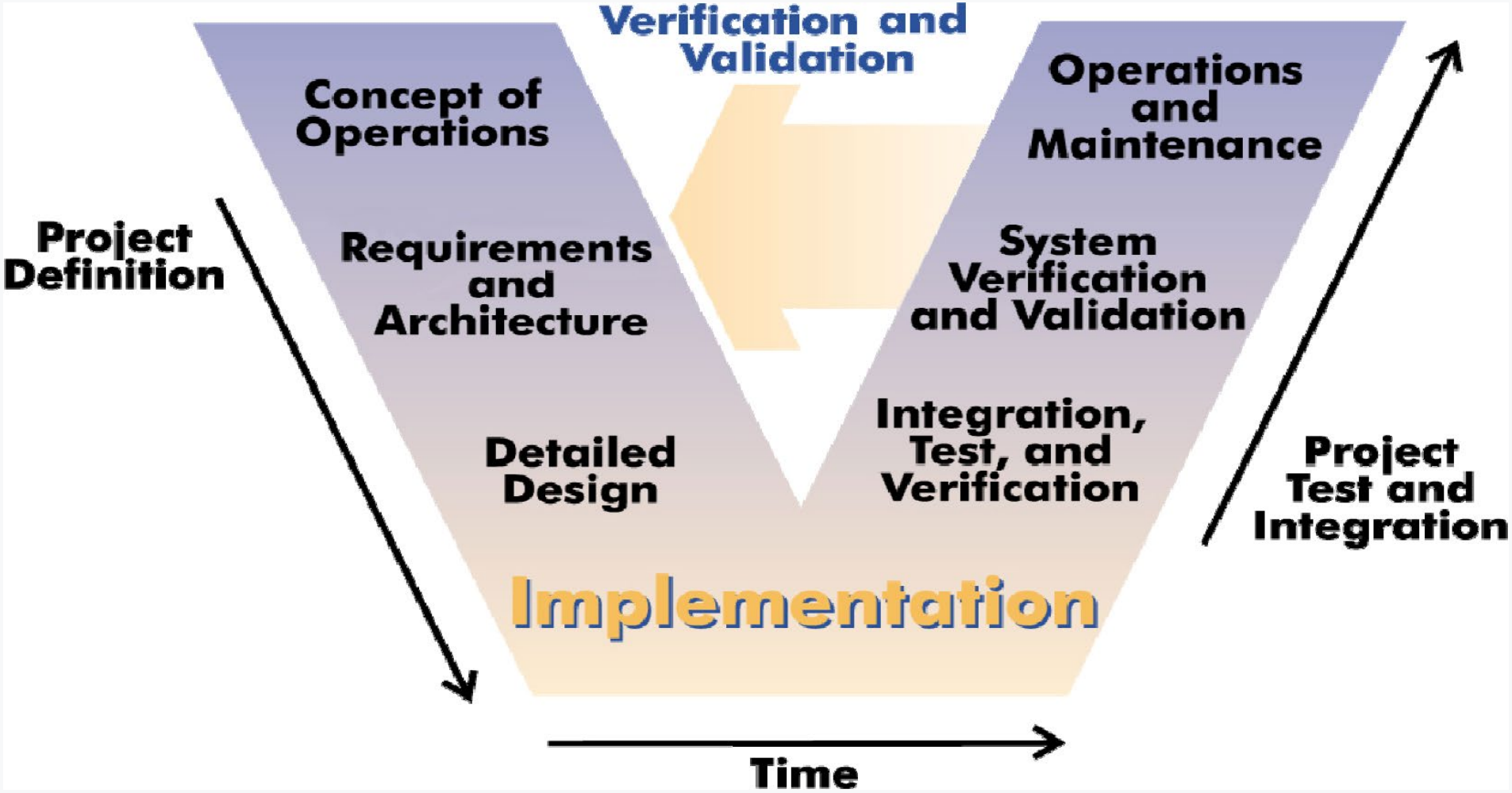
INCOSE System Vee, from *INCOSE Systems Engineering Handbook* adapted from Forsberg 2005



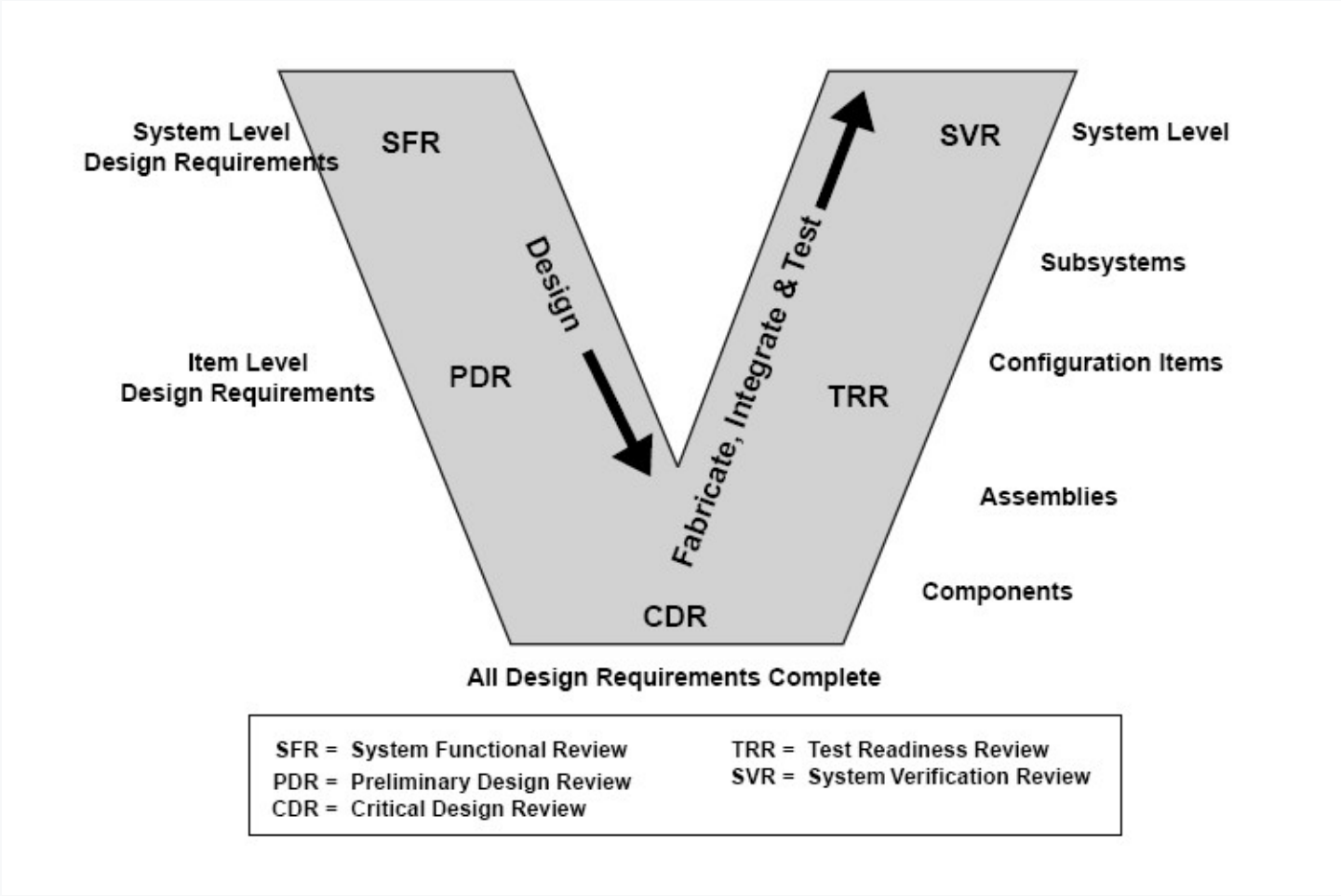
System Vee model from Defense Acquisition University [Prosnik2010]



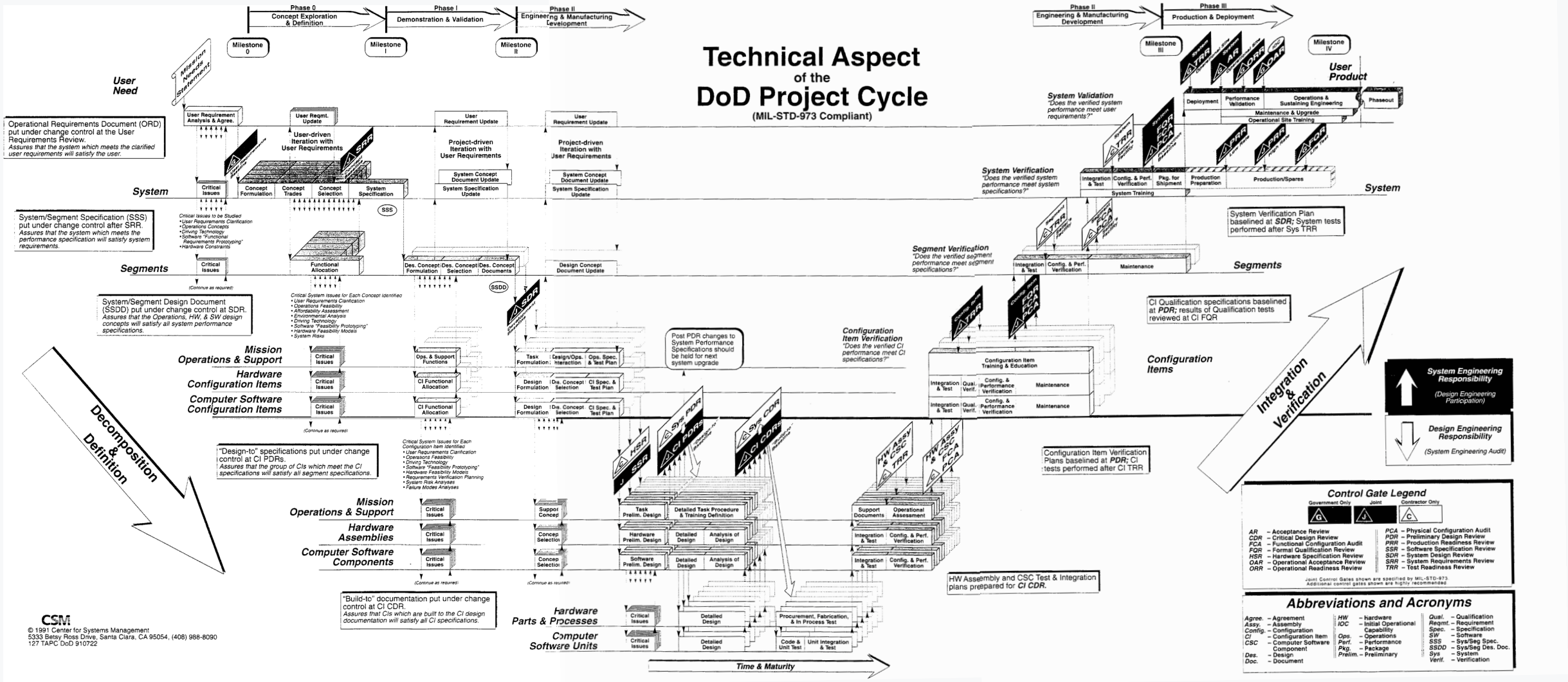
System Vee model from the Federal Highway Authority [Osborne 2005]



The stage gates commonly used for project management fit within the System Vee from Defense Acquisition University [Lightsey 2001]



Forsberg's full original model from Forsberg and Mooz 1991



Iteration within the System Vee is vertical unlike in the LVF