A VISION FOR GENERATIVE DESIGN

A market report from intrinSIM LLC

Contents

"A Vision for Generative Design" is a software independent intrinSIM market research paper that explores the potential paradigm shift enabled by Generative Design and what is required to enable that design paradigm shift. This market research paper looks at the key capability areas required to support a paradigm shift and proposes a capability assessment model with detailed assessment criteria for each of the key capability areas. The capability assessment model can be used for determining; capabilities of specific Generative Design workflows, requirements for specific applications, suitability of specific Generative Design workflows for specific applications. intrinSIM has also developed a quantitative model of the Generative De4sign Capability Assessment Model outlined in this paper.

intrinSIM has a collaborative working relationship with the ASSESS Initiative and shared research on this topic with the ASSESS Initiative. The ASSESS Initiative has published a Strategic Insight Paper entitled "*Understanding a Generative Design Enabled Design Process Paradigm Shift Generative Design*". The ASSESS Initiative paper was written by Joe Walsh and Keith Meintjes and reviewed by consultants, academic researchers, and software vendors. Many concepts related to Generative Design are shared between this paper and the ASSESS Initiative Strategic Insight Paper.

What is Generative Design?

The first step in establishing a vision for Generative Design is to define what is meant by Generative Design. There have been several attempts to define Generative Design and many of these are from suppliers of technology who then try to define Generative Design in terms of the solutions that they offer. Three independent definitions that stand out are the definition from Professor Kristina Shea of ETH Zurich, the definition by Dr. Keith Meintjes of CIMdata, and the definition agreed upon by the ASSESS Initiative Working Group on Generative Design (Alexander Karl of Rolls Royce, Andreas Vlahinos of AES, Joe Walsh of intrinSIM, Keith Meintjes of CIMdata, and Ted Blacker of Sandia National Labs).

Professor Kristina Shea's definition:

> "Integrated performance-driven generative design systems are aimed at creating new design processes that produce spatially novel yet efficient and buildable designs through exploitation of current computing and manufacturing capabilities."

Dr. Keith Meintjes definition:

> "Generative Design is a collection of tools and techniques that help to create or modify feasible product designs, including geometry, from statements of requirements and constraints."

ASSESS Initiative definition:

> ***"Generative design is the use of algorithmic methods to generate feasible designs or outcomes from a set of performance objectives, performance constraints, and design space for specified use cases."***

The ASSESS Initiative goes on to account for the fact that the requirements, constraints, and uncertainties may account for factors from all areas influencing the design objectives and performance. Generative Design may be driven by any of the influencing areas and a combination of these influences. As Generative Design matures, its ability to deal with factors across a broader range of influences and combinations of influences will increase.

> ***"Performance objectives and constraints may include factors from multiple areas including operational performance, weight/mass, manufacturing, assembly or construction, usability, aesthetics, ergonomics, and cost. It is recommended that the specification of the use cases should incorporate uncertainties related to all inputs used to specify the intended use."***

Generative Design may include geometric shape definition, material distribution (e.g. lattice structures, multi-materials…), configurations, architectures, and a combination of ant design characteristics of interest. Using the ASSESS Initiative definition of Generative Design, we can further explore Generative Design as an algorithm or collection of algorithms that transforms inputs into desired outputs for a specified use case.

The ASSESS definition is gathering broader and broader acceptance as a common definition of Generative Design amongst the Generative Design solution providers.

Generative Design Inputs

- Requirements (performance, cost, …)
- Constraints (connections, design rules, manufacturability, …)
- Available design space (available or unavailable space along with reserved areas)
- Uncertainty Information (loads, materials, …)
- Manufacturing information (additive, subtractive, …)
- Objectives (stiffness, stress, durability, vibration, cost)

Generative Design Outputs

- Range of possible designs within the available design space and specified manufacturing processes that address
    - Requirements (performance, cost, …)
    - Constraints (connections, design rules, manufacturability, …)
    - Uncertainty (loads, materials, …)
    - Objectives (stiffness, stress, durability, vibration, cost)
- Probability of possible designs to meet all criteria under all load conditions

<u>Generative Design is not a particular algorithm or an optimization technology</u>, but instead may leverage one or more optimization technologies (topology optimization, shape optimization, parametric optimization,…) and algorithms (lightweighting, form synthesis, force based growth algorithms…) along with artificial intelligence to create/drive viable designs or outcomes for a specific design scenario.

Topology Optimization that accounts for Additive Manufacturing constraints is a solid beginning for Generative Design. But Generative Design is an approach to design that spans broader capabilities and use cases that may include artificial intelligence and multiple forms of design and optimization technologies in a single design process (e.g. topology optimization, growth algorithms, free form shape optimization, conversion to design & and manufacturing data, CAD/Feature recognition, Parametric optimization, …).

The Possibility of a Paradigm Shift

The vision for Generative Design is that it could enable a significant paradigm shift in the design processes used today. Generative Design has the potential to enable a disruptive design paradigm inversion. It proposes in concept that designs can be computer generated by proper specification of rules, requirements, and constraints. This overturns the current practice of design, where designs must first be created so they can be evaluated against their performance requirements. This means that Engineering Simulation tools, developed for design evaluation, become the driver for design creation.

This potential paradigm shift can be easily seen in the following figures developed and presented by Keith Meintjes of CIMdata. Figure 1 illustrates the traditional design process where a proposed design is created, and then evaluated against the product performance requirements, followed by an iterative loop of re-design and re-evaluation.

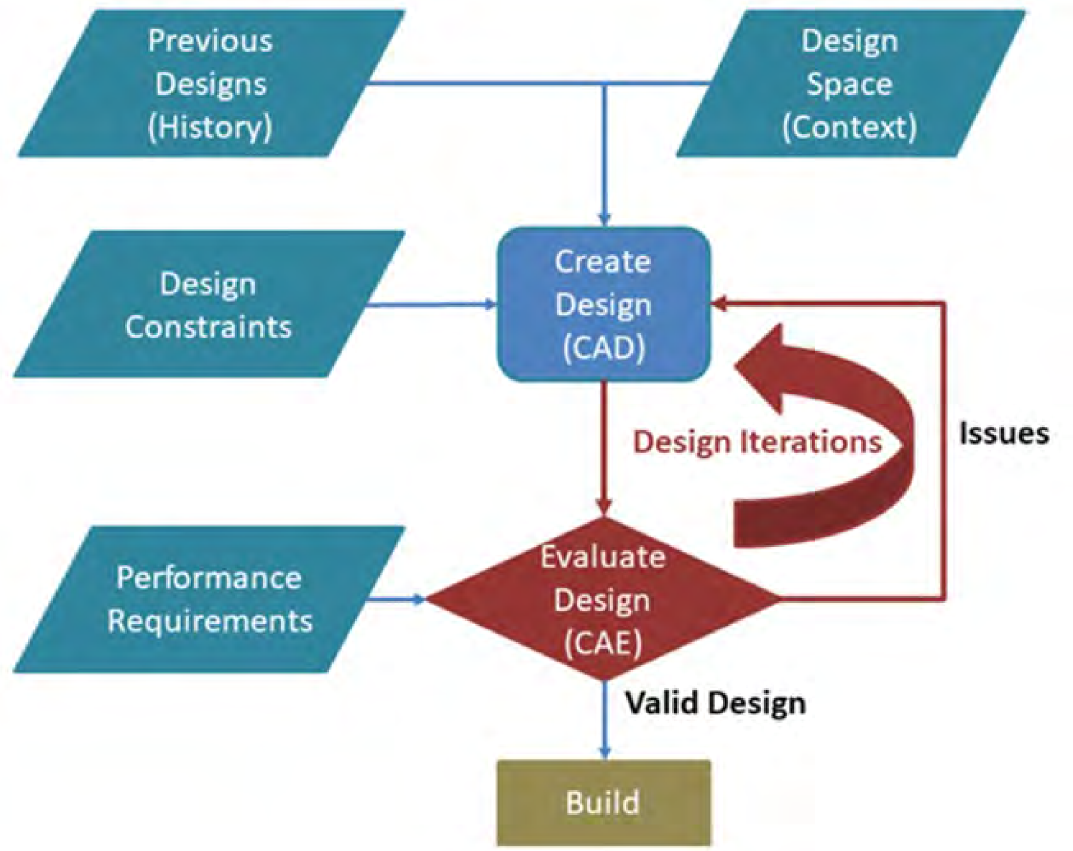

Figure 1 Traditional Design Process

The Generative Design process transforms product requirements into designs (shape, materials, and configurations) that account for the performance requirements. The Generative Design process itself ensures the requirements and constraints have been met or indicates no feasible designs. In the ideal case the manufacturing/assembly/construction processes and uncertainties related to the use case specifications are accounted for. Figure 2 also from Keith Meintjes of CIMdata illustrates a Generative Design process.

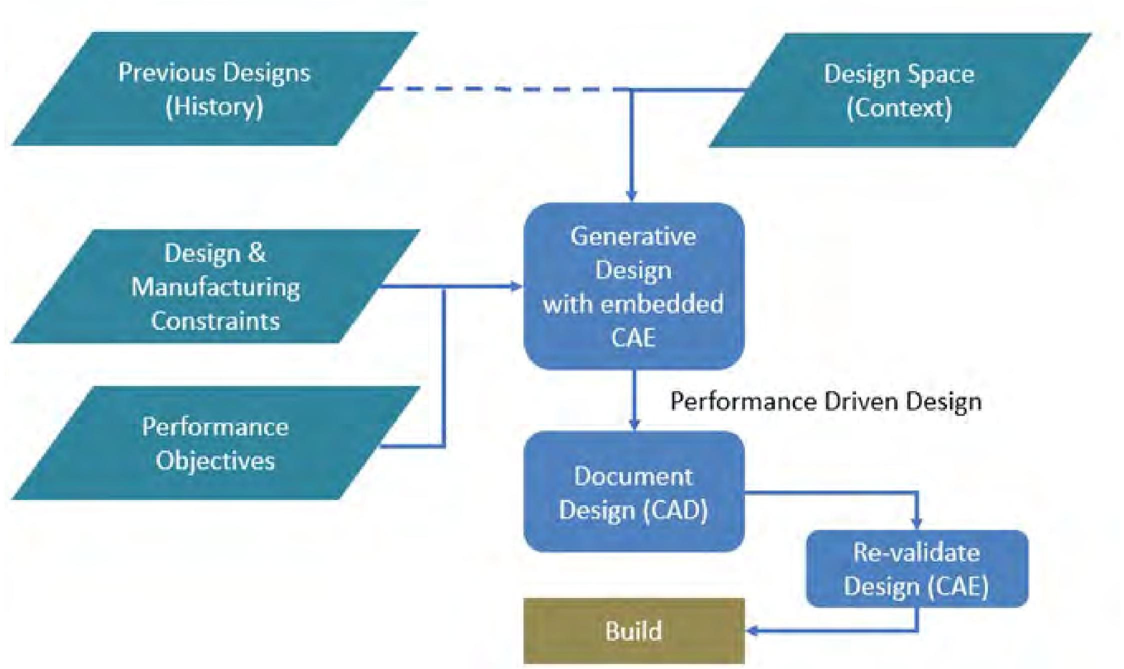

Figure 2 Generative Design Process

Topology Optimization that accounts for Additive Manufacturing constraints is a solid beginning for Generative Design, however, Generative Design is more than this and should include multiple algorithms and support for multiple manufacturing processes.

Generative Design represents the next big Technology Driver in the Engineering Simulation domain and most major Engineering Simulation vendors are actively pursuing some form of Generative Design strategy starting with coupling Topology Optimization with Additive. But this is just the beginning and the vision of Generative Design is not limited to a single form of optimization or a single form of manufacturing. Additional optimization techniques along with artificial intelligence are likely to be required to address all design objectives and constraints in a general case.

Generative Design should not be limited to use by the expert analysts and indeed only achieves its vision if it is used early and often in the design process by those people doing the design. Generative Design has the potential to be a key enabler of Democratization of Engineering Simulation by providing simulation-driven design concepts through enabling the user to define his design scenario and allow a Generative Design tool to explore the design space for feasible design options.

Enabling a Paradigm Shift

Conceptually the benefits of the possible paradigm shift are quite clear with better designs faster enabled for a broader impact on design decision. This conceptual benefit, however, is illusive in real-world practice due to the state of the current offerings for Generative Design. Several specific cases have been cited by Generative Design technology providers that illustrate the success their users have had using their Generative Design tools. Typically, these involve a limitation on the problem definition to their current capabilities.

The vision of Generative Design, as stated earlier, is to enable a fundamental paradigm shift of the design process. Therefore, to achieve this paradigm shift the Generative Design process must support and enable more efficient design exploration in the context and terminology of the design scenario/problem at hand and provide support for the current set of design requirements, constraints, and uncertainties that the designer faces every day. The ability for Generative Design to enable a Paradigm shift is predicated on Generative Design being able to handle the same range of inputs and design concerns that Design Engineers and/or Designers handles today in their design process.

Generative needs to enable the exploration and selection of "robust design" alternatives for as wide a range of design scenarios as possible to enable the possible paradigm shift in the design process. The following illustrates 15 key capability areas outlined by the ASSESS Initiative to be addressed for Generative Design to enable a paradigm shift.

1. Handling all appropriate objectives and constraints
2. Handling multiple operational (load) conditions
3. Handling multi-physics
4. Handling complex materials
5. Handling transitions from solid to lattice structures
6. Handling uncertainties
7. Handling multiple manufacturing processes
8. Handling manufacturing process dependent materials
9. Handling cost as an objective or constraint
10. Handling Generative Design in an assembly/system context
11. Enabling informed, comprehensive and efficient exploration of viable design alternatives
12. Enabling efficient & effective transformation to detailed design analysis
13. Enabling efficient selection guidance of generated design concepts
14. Enabling Generative Design within the designer's process, context & terminology
15. Enabling broad accessibility to Generative Design

These key capability areas are organized into two concepts. The first concept is related to "handling" specific capabilities related to the use case scenario definition. The second "concept" is related to "enabling" user related activities and workflows. The essence of the key capability areas outlined is to provide effective coverage and meaningful information to enable efficient Generative Design and subsequent processes for a broad coverage of use case scenarios that are being handled with the traditional design process.

For the purposes of this paper we are going to organize these 15 key capability areas into two main groups. The first group are those that are currently required for general applicable of Generative Design. The second group are those that currently apply to specialists advancing applications and methods related to Generative Design. It is expected that over time some of the capabilities areas in the second group (specialists) will move to the first group for general applicability.

Key Capability Areas of Generative Design for General Applicability

The following Illustrates a first pass at the key areas of capabilities to meet applicability requirements for general deployment of Generative Design.

1. Handling all appropriate objectives and constraints
2. Handling multiple operational (load) conditions
3. Handling Multi-Physics
4. Handling multiple manufacturing processes
5. Handling cost as an objective or constraint
6. Handling Generative Design in an assembly/system context
7. Enabling informed, comprehensive and efficient exploration of viable design alternatives
8. Enabling efficient & effective transformation to detailed design analysis
9. Enabling efficient selection guidance of generated design concepts
10. Enabling Generative Design within the designer’s process, context & terminology
11. Enabling broad accessibility to Generative Design

Handling all appropriate objectives and constraints

Real-world design scenarios almost always have multiple design objectives and constraints even within a single loading condition. For instance, a structural design problem may include objectives and constraints on stiffness, stress, fatigue life, and cost. Simply performing a topology optimization for a target stiffness does not address the full range of objectives and constraints that a designer is faced with.

To be broadly deployable for general applicability Generative Design workflows need to support a broad range of design objectives and constraints that match to the design criteria being used without Generative Design. Designs generated for an incomplete set of objectives and constraints have limited usage as design inspiration and cannot be used directly as the start of the design process.

Different combinations of design objectives and constraints for the same design space and use cases should result in different design options.

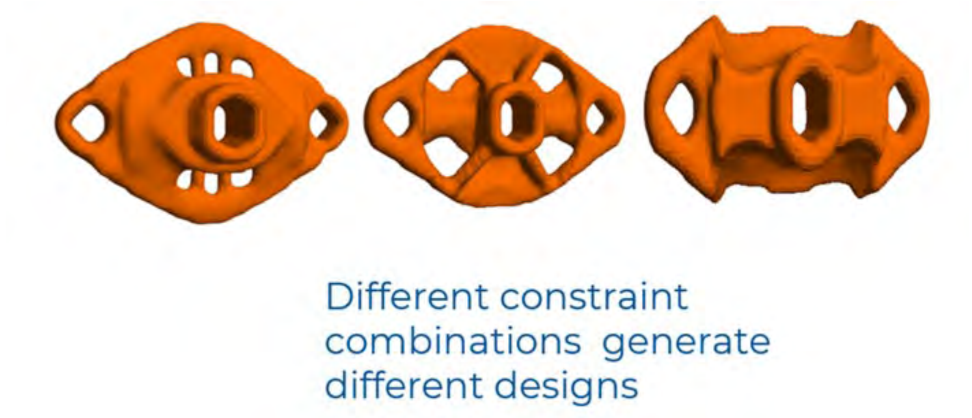

Figure 3 Differing Results for Different Constraints

It is further anticipated that to achieve support for multiple design objectives and constraints for a broad range of design scenarios that Generative Design tools will be required to deploy a combination of optimization technologies, shape modifications, and possibly artificial intelligence to enable proper support of all required objectives and constraints.

A potential workflow for a single load case structural design problem is illustrated below.

1. Topology optimization to develop initial design concepts (driven by stiffness or displacement)
2. Material distribution optimization
3. Free form shape optimization to "adjust" design concepts (driven by stress and fatigue life)
4. Conversion to a CAD consumable model
5. Feature recognition and feature driven adjustment of CAD consumable model
6. Adjustments to "standard" feature sizes as appropriate
7. Parametric shape optimization for current design objectives and to enable families of parts

Handling multiple operational (load) conditions

Real-world design scenarios rarely involve a single use case or operational (loading) condition and indeed usually must deal with multiple operational conditions (load cases). For instance, building and bridge designs have multiple conditions for dead loads, live loads, wind loads, seismic loads, and various combinations of these loads. Mechanical components need to address start up conditions, multiple operating conditions, and shut down.

To be broadly deployable for general applicability Generative Design workflows need to support multiple load (operational) conditions (use cases) that match to the full range of use cases being used in the traditional design process without Generative Design. Generative Design needs to intelligently work with design scenarios that include multiple load conditions to have a significant impact on the design process. These multiple load conditions are not encountered simultaneously but are represent different operational conditions. Different load cases will result in different material distribution and just combining all material from all load cases is fundamentally sub-optimal resulting in dramatic overdesign.

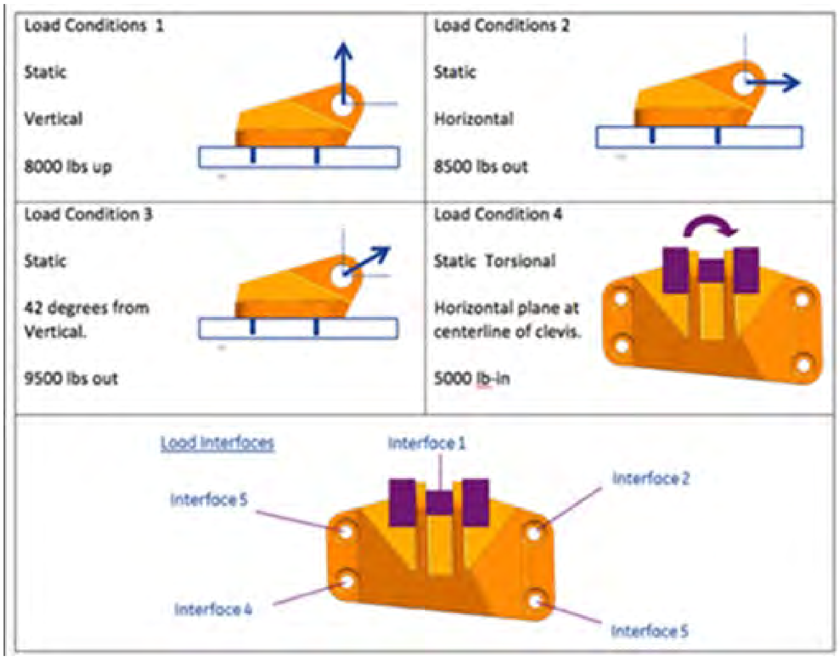

Figure 4 Multiple Load Case Example

Intelligent combination of load cases requires coming up with designs that are appropriate across all usage scenarios and associated loading conditions. This will probably require an iterative interaction between load cases and a potential use of artificial intelligence to find designs that efficiently work for all use cases and loading conditions.

The following illustration from Tony Abbey, FEA Trainer & Consultant shows the challenge of dealing with multiple load cases.

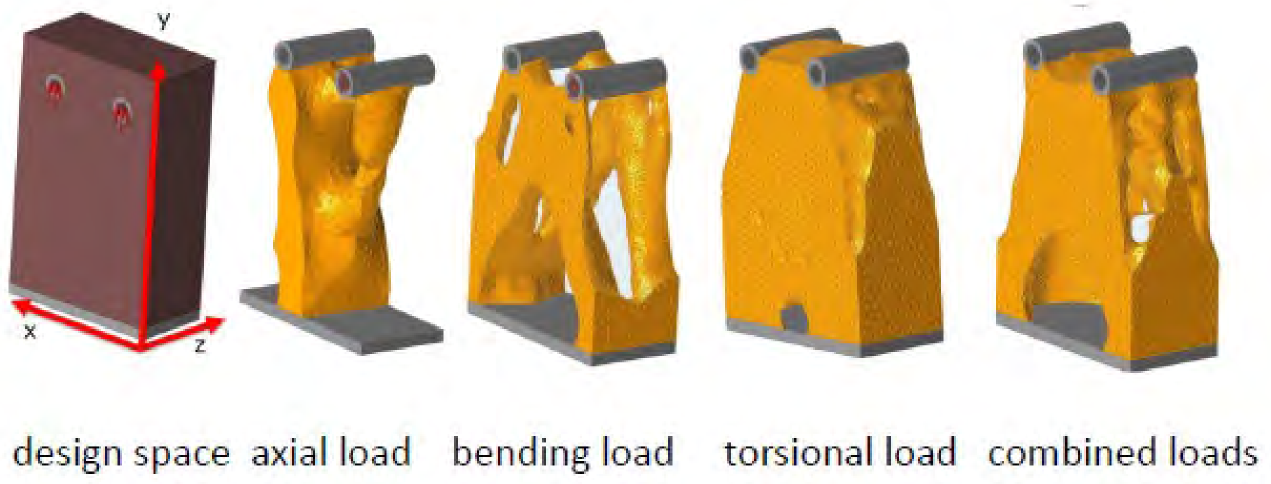

Figure 5 Different Results for Different Loads

Handling multi-physics

Real-world design scenarios often also involve multiple physics (structural, vibration, fluids, electromagnetics, …) phenomena either in a single load condition or as different load conditions. Generative Design needs to deal appropriately with the physics of interest for the design scenario under investigation.

To be broadly deployable for general applicability Generative Design workflows need to support a reasonable set of combinations of different physics with their unique design objectives and constraints such as structural, thermal, and vibration that match to the use cases being used without Generative Design. These multiple physics can usually be unlinked or loosely coupled but need to be accounted for simultaneously in the design generation.

Current tools for Generative Design are limited in the range of physics supported and their combinations. The user has to be careful that the physics supported adequately represents their design scenario and constraints.

Handling multiple manufacturing processes

One of the key considerations in a design process is evaluating the available manufacturing processes. Each manufacturing process will have its own set of design constraints for manufacturability. Real-world design choices have to cover multiple manufacturing options. Generative Design needs to address the design constraints of a wide range of manufacturing processes including both additive and subtractive processes that result in viable design alternatives for each manufacturing process.

To enable a paradigm shift, the Generative Design process should support evaluation of all the manufacturing processes under consideration for a specific design in the traditional design process along with enabling investigation of additional manufacturing processes. To be broadly deployable for general applicability Generative Design workflows need to support a broad range of manufacturing processes that match to the manufacturing processes being used without Generative Design. Additive Manufacturing will drive Generative Design applications in the short term; however, other manufacturing processes also need to be supported to allow for larger volumes of production and existing manufacturing capabilities.

The ultimate goal for Generative Design is to enable different designs for different manufacturing plants and processes that offer similar performance and reliability. The functions, performance, and reliability are similar, but the designs may vary significantly. A small run production may be better for Additive Manufacturing while Subtractive Manufacturing may be more effective for large run production. This introduces a paradigm shift in perspective that the design is not about a specific geometry but a family of geometries to provide the desired functions, performance, and reliability. The interesting side effect is that as adoption and production increases a "replacement" part geometry may be significantly different than the "replaced" part while the connections and performance remain constant (or improve).

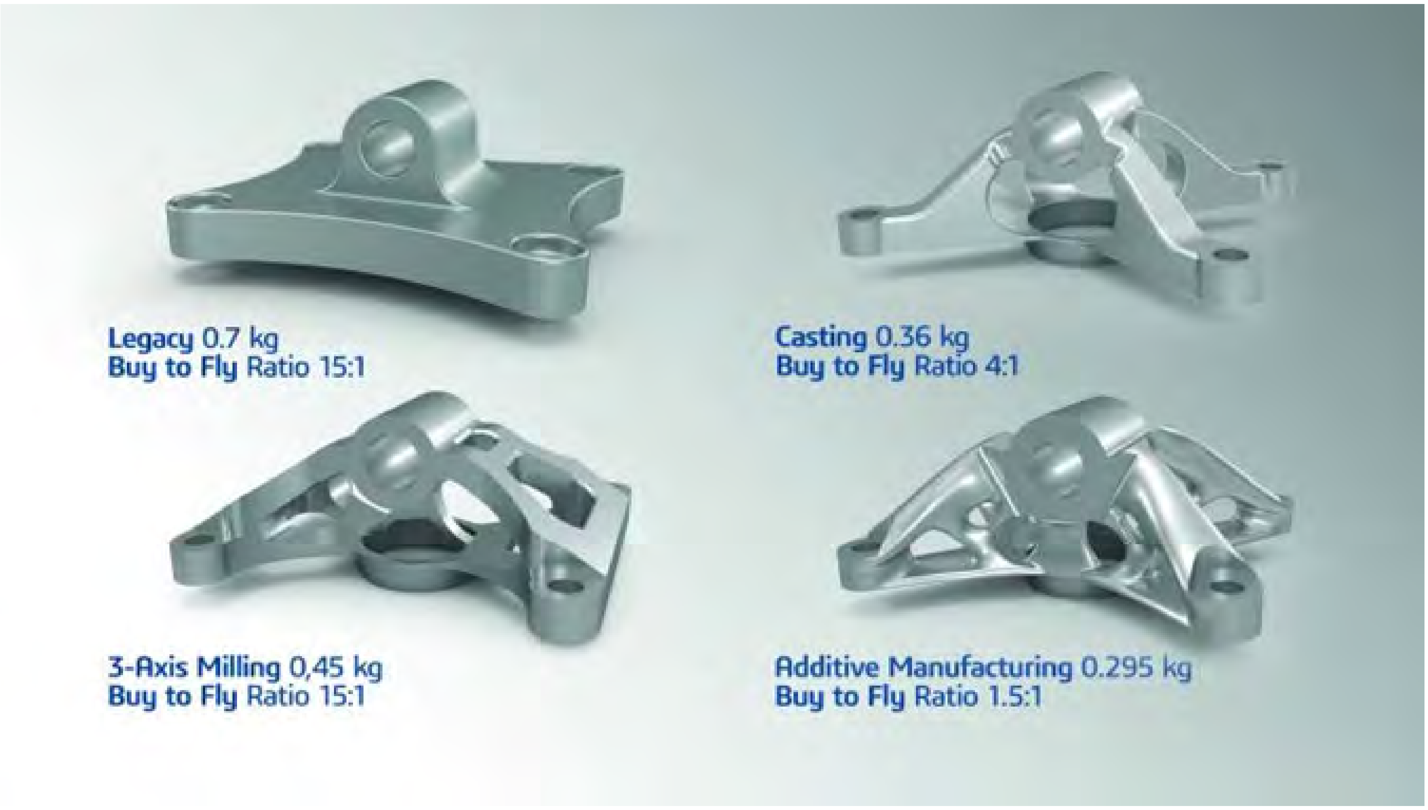

Figure 6 Different Results for Different Manufacturing Processes

The constraints related to a specific manufacturing process may also go all the way down to the specific machine or 3D printer being used. The variation by machine is quite prominent in additive manufacturing as each 3D printer has specific constraints. Generative Design tools need to enable a means to capture enterprise wide manufacturing process constraints as well as provide a reasonable set of default manufacturing processes and constraints.

Coupling Topology Optimization with additive manufacturing and its process constraints is just the beginning for Generative Design. Broader support of manufacturing processes is needed that may also require alternative approaches to geometry definition.

Handling cost as an objective or constraint

Real-world design scenarios should include cost of production as either a design objective (minimization) or as a constraint. Omitting cost as a consideration results in design options that are not feasible to manufacture. Generative Design tools rarely account for manufacturing cost today. Cost should be available to be defined either as an optimization objective or a constraint at the user's discretion. The incorporation of cost models and resulting cost estimates is key to the Generative Design process and should significantly reduce the number of design options to consider.

To be broadly deployable for general applicability Generative Design workflows need to support cost estimations since cost is always a factor in design criteria currently being performed without Generative Design. Without the ability to account for production costs the danger is that designs can be generated that are not economically feasible with the user having little to no capability to assess their costs and economic feasibility. **The ability to account for cost as a filter on designs generated is a key minimum requirement to enable broader use of Generative Designs.**

The other interesting side effect will be that the selection of "best" manufacturing processes could be determined based on the available manufacturing processes, the cost objectives/constraints, and the desired run rate. This could mean that as production ramps up that the "best" manufacturing process could change, and the resulting geometry could change significantly while retaining the function and performance within acceptable variability. In other words, a replacement part may not resemble the shape of the part it is replacing but it will provide the same function and performance.

In this approach, the geometry is not the design, but the function and performance are the design, and the geometry is just an instance to provide the design function and performance.

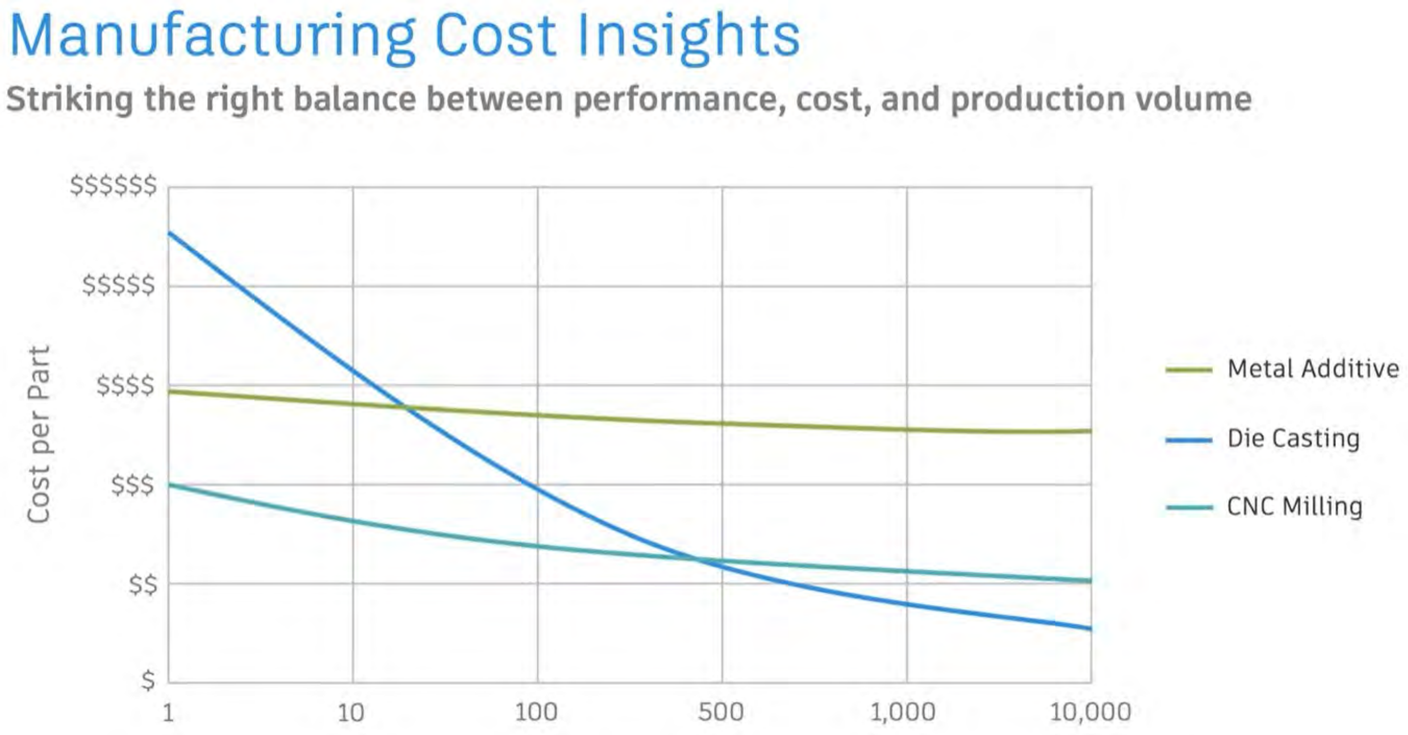

Figure 7 Manufacturing Cost Insights

Handling Generative Design in an assembly/system context

To be broadly deployable for general applicability Generative Design workflows need to support working in assembly context to enable more accurate definition of loads and to generate designs for multiple components in and assembly to maximize the efficiency of the assembly when not all parts in the assembly can be consolidated into one.

Generative Design tools typically work on a component by component basis. This approach has three inherent issues as follows:

1. The load distribution in an assembly context is usually a function of the properties (e.g. stiffness) of the component and changing properties of a component results in a different load path.
2. It may be difficult to define realistic loads and boundary conditions that the component sees as these are a function of the full assembly context (especially for someone who is not a simulation expert).
    a. This prevents effective us of Generative Design without bringing in the simulation expert.
3. The loading complexity issue is exacerbated if the goal is to apply Generative Design to multiple (or all) of the components in an assembly.
    a. Performing part by part Generative Design assumes properties of the other components that may change.

The first approach used to address these issues is to specify a key property such as stiffness. This is straightforward for structural performance by using stiffness but not as straightforward for other physics. The result of specifying a material property as a constraint may also result in designs with non-optimal performance to material based on the constrained property.

The second approach is to replace multiple parts in an assembly with a single part. This is a very good design practice that is enabled by Generative Design, however, not all assemblies can be reduced to a single component and maintain their function (e.g. a linkage mechanism). This approach can offer the benefit of simplifying designs but does not remove the need to handle multiple parts in an assembly context

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PART CONSOLIDATION

Consolidate multiple components into solid parts to maximize the potential of additive manufacturing.

Figure 8 Part Consolidation

The ultimate goal is for Generative Design to support simultaneous design of multiple components in an assembly context driven to the assembly objectives and constraints that account for the changing load distributions. The desired result is not a set of component designs but a set of assembly designs with different component geometries that when combined meet the performance objectives and constraints of the assembly.

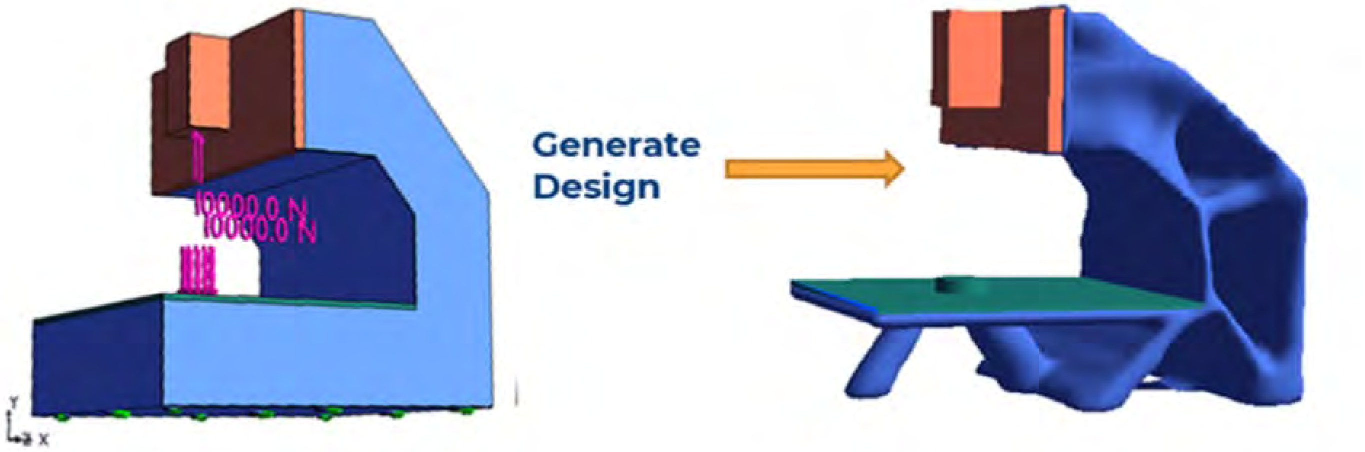


Figure 9 Assembly Based Loading

Figure 10 Generative Design of Multiple Parts in an Assembly

Enabling informed, comprehensive and efficient exploration of viable design alternatives

To be broadly deployable for general applicability Generative Design workflows need to support design exploration that is broader and more comprehensive than what is possible to do without Generative Design.

Generative Design should enable the ability to explore a wider range of design options than the human designer. A comprehensive exploration of design concepts that would otherwise not be considered. This should include variations on material properties, manufacturing processes, as well as various lattice structures types or solid material. The efficient exploration should enable exploration of all the feasible designs that meet the specified constraints with single and multiple design objectives. This is best done with a single Generative Design scenario but can be accomplished with multiple Generative Design scenarios. For multi-objective optimization the ability to understand trade-offs between objectives is critical.

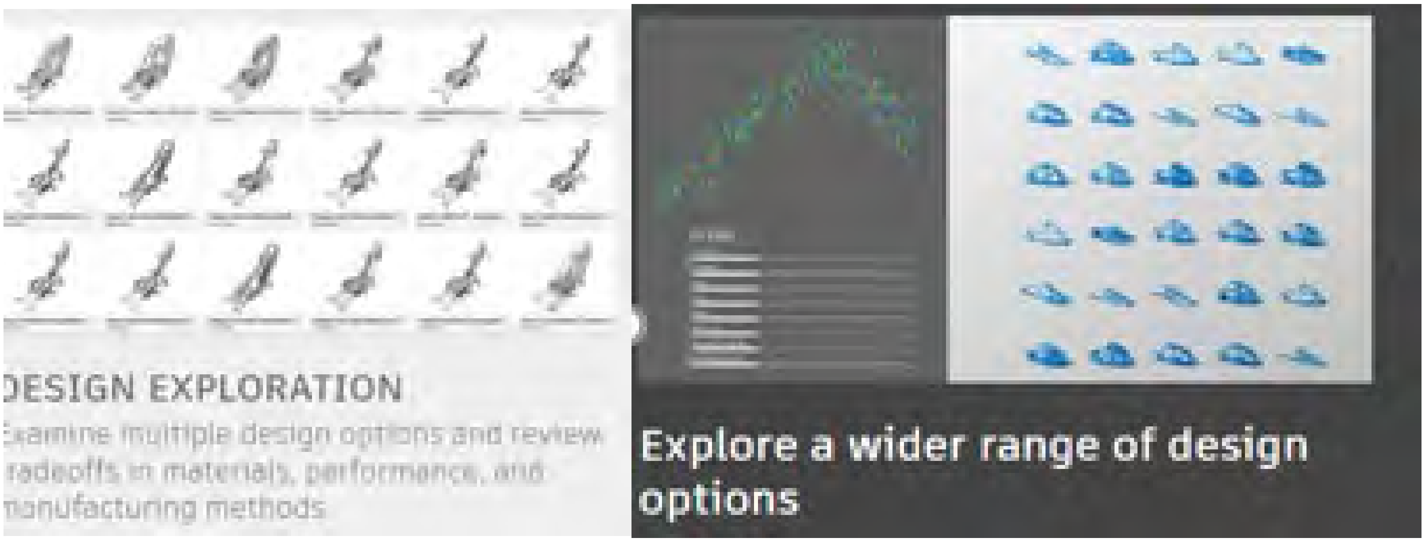


Figure 11 Design Exploration

Enabling efficient selection guidance of generated design concepts

One of the benefits and disadvantages of Generative Design is that it should enable a comprehensive exploration of the design space which may result in thousands and thousands of viable design options. No designer or engineer has the inclination, time or ability to review thousands of design options or even hundreds. Most designers and engineers are interested in a “Top Ten” list or less.

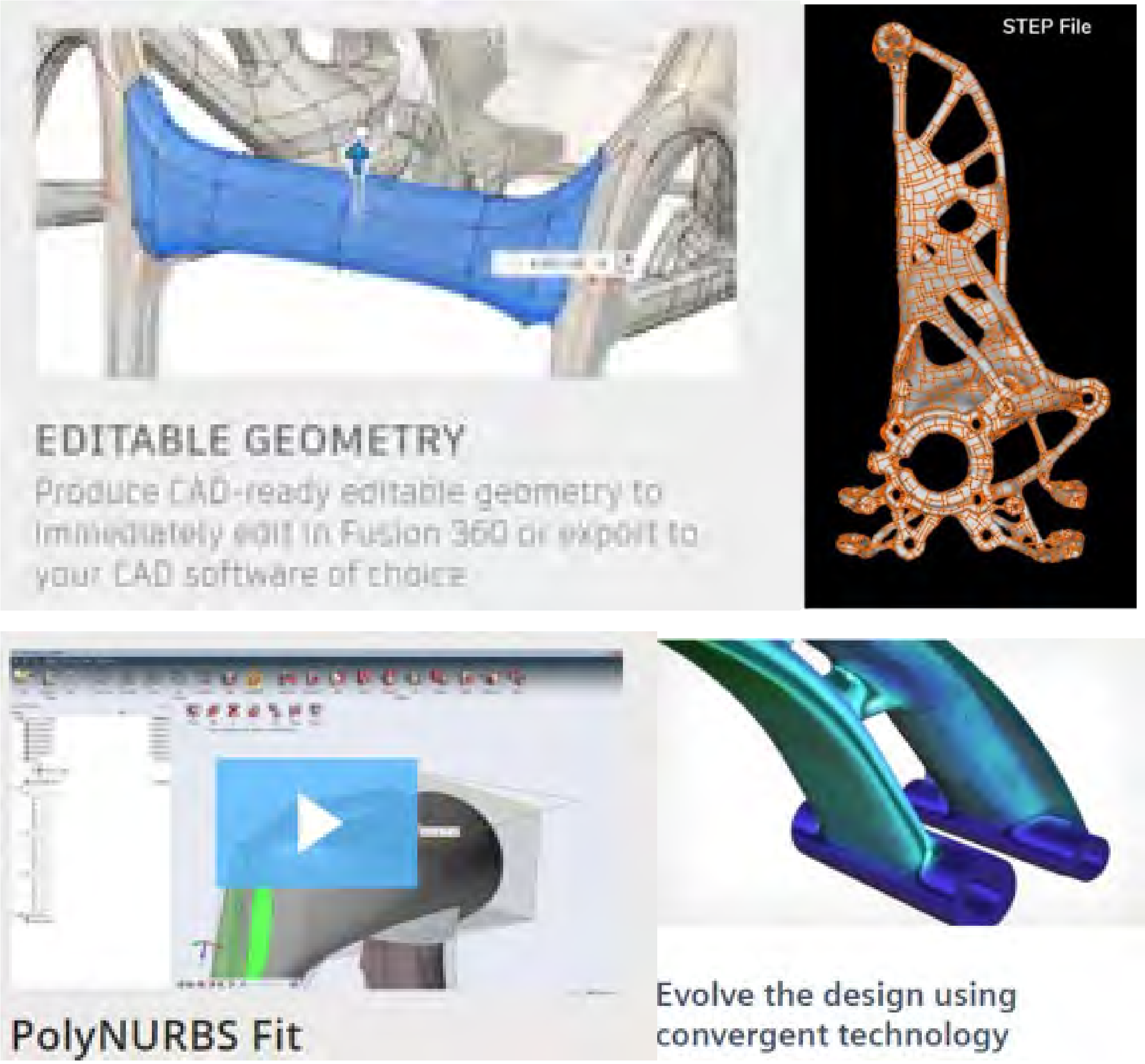
To be broadly deployable for general applicability Generative Design workflows need to enable efficient refinement to the feasible designs of interest. Without this efficient selection of key design options, the design engineer’s time is not saved but merely moved to the task of reviewing design alternatives. Ensuring that all of the objectives and criteria are properly specified is a first step in reducing options. However, many well-defined Generative Design options can result in a large number of feasible design options with similar rankings on the design criteria.

It is anticipated that adding cost may reduce the options significantly and enable better ranking of design alternatives. Combining proper problem definition, cost information and detailed validation would significantly reduce the design options and provide better ranking of options. However, even with these additional steps many Generative Design options can result in too large number of viable design options for consumption by the user. **This problem opens an excellent opportunity for leveraging artificial intelligence to reduce the viable design options to the “Top Ten” options to make the Generative Design results consumable.**

Enabling efficient & effective transformation to detailed design analysis

Generative Design needs to enable a smooth transition to detailed design analysis using traditional simulation methodologies. This seems obvious at first, however, what this smooth transition requires is automated creation of detailed simulation models with a transformation of the problem definition, material distribution, and any uncertainties in the use case definition to these detailed simulation models. This is further complicated with Lattice structures which may need a different geometric representation for detailed design validation within reasonable time and resources.

Manual creation of detailed simulation models is at best inefficient (requires a simulation expert) and at worst confusing as it may result in apples to oranges comparisons casting doubt on the validity of the Generative Design process. The ultimate goal is for Generative Design to support automated creation and solution of detailed simulation models as part of the Generative Design process to enable refinement of viable designs.



Produce CAD-ready editable geometry to immediately edit in Fusion 360 or export to your CAD software of choice

Evolve the design using convergent technology

Figure 12 Transitions to Detailed Design Analysis

A comprehensive design process incorporating Generative Design should look like the following:

1. Perform Generative Design exploration
2. Select key designs for further study
3. For each key design
    a. Perform automated detailed design validation
    b. Refine key designs of interest based on detailed design validation

Generative Design does not replace or remove the need for more detailed validation of the design. The intent of Generative Design is to provide feasible design concepts that are significantly more likely to pass more detailed performance validations. This should result in a major reduction in the design/validate iteration cycles and thereby significantly reduce the amount of design validation analysis that needs to be run.

Enabling Generative Design within the designer's process, context & terminology

The earlier in the design process that this can be explored, the higher the potential benefit. The use of Generative Design early in the design process means that the target user is not the simulation expert but the engineers and designers responsible for early design concepts and for maturation of the design. For Generative Design to be effective it must be well integrated into the designer's workflow and the definition of the Generative Design problem must be in context of their understanding and information available at that time as well as terminology that is consistent with their design requirements, methodologies, and objectives.

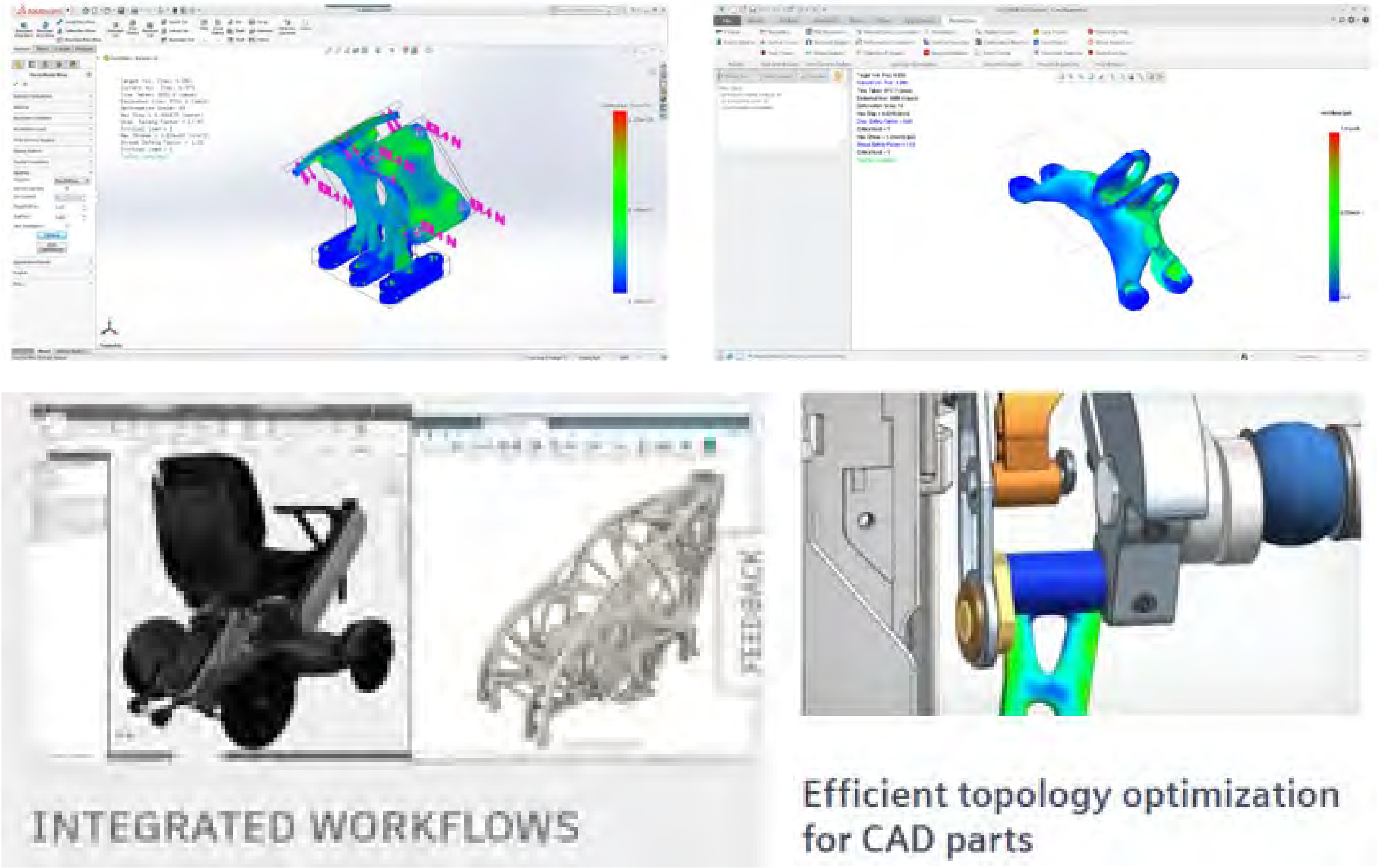


Figure 13 Generative Design in the Design Process

"Smart" defaults and industry specific terminology can go a long way to address the context and terminology issue, however, it is expected that this is another opportunity for leveraging artificial intelligence.

Enabling broad accessibility to Generative Design

For Generative Design to enable a paradigm shift related to the design process it must be readily available and usable by all of those who would be involved in the paradigm shift. Enabling broad accessibility to Generative Design is key to enabling the envisioned paradigm shift.

Enabling broad accessibility to Generative Design includes two major factors:

1. Making Generative Design technology broadly available to the appropriate potential users outside of simulation experts
    a. Commercial / Government Usage = Design Engineers and possibly designers as the primary users
    b. Academic Usage = Researchers, teachers, and students
2. Making Generative Design technology usable by the appropriate potential users outside of simulation experts

Specialist user requirements for Generative Design

The following Illustrates a first pass at the key areas of capabilities to meet specialist user. These are in addition to ongoing advancements to the key areas called out as necessary for specialist users.

1. Handling complex materials
2. Handling transitions from solid to lattice structures
3. Handling uncertainties
4. Handling manufacturing process dependent materials

Handling complex materials

Generative Design should allow the user to determine required material distribution and material properties as well as geometry. One approach commonly used is to leverage varying lattice structures to achieve different behavior with the same base material.

Additive manufacturing is maturing to allow for multiple materials to be printed for a single object. The initial design concepts are usually developed based on a uniform material and then need to be revisited for multi-material conditions. Although there is research focusing on multi-material selection simultaneous with geometry development, almost all commercial Generative Design tools start with an assumed uniform material distribution. Advanced materials that are anisotropic in nature and composites should also be supported as the application of Generative Design expands.

The need for broader understanding of manufacturing processes related to lattice structures and multiple materials needs to advance before this capability can be leveraged in a broader sense. For those not involved in research or bleeding edge applications of Generative Design this is a requirement allowing for further improvement from the single material per part approach. There will be an increasing number of users requiring this capability over time.

Handling transitions from solid to lattice structures

Generative Design has introduced the concept of designing varying lattice structures and the ability of some sections of the design to be solid while others are lattice. This is an excellent way to distribute material as needed, however, abrupt changes in stiffness at the junction of solids and lattice structures lead to stress concentrations and fatigue issues as well as transition issues for other physics.

The need for broader understanding of manufacturing processes and data transfer related to lattice structures needs to advance before this capability can be leveraged in a broader sense. This is considered a specialist user requirement allowing for further improvement from the solid single material per part approach. There will be an increasing number of users requiring this capability over time but a broad base of users is not expected to require non-uniform materials until the methodologies and processes are further refined.

Effective use of lattice structures with solid portions of the design requires smooth transitioning from the solid regions to the lattice structures (gradual transformation zones).

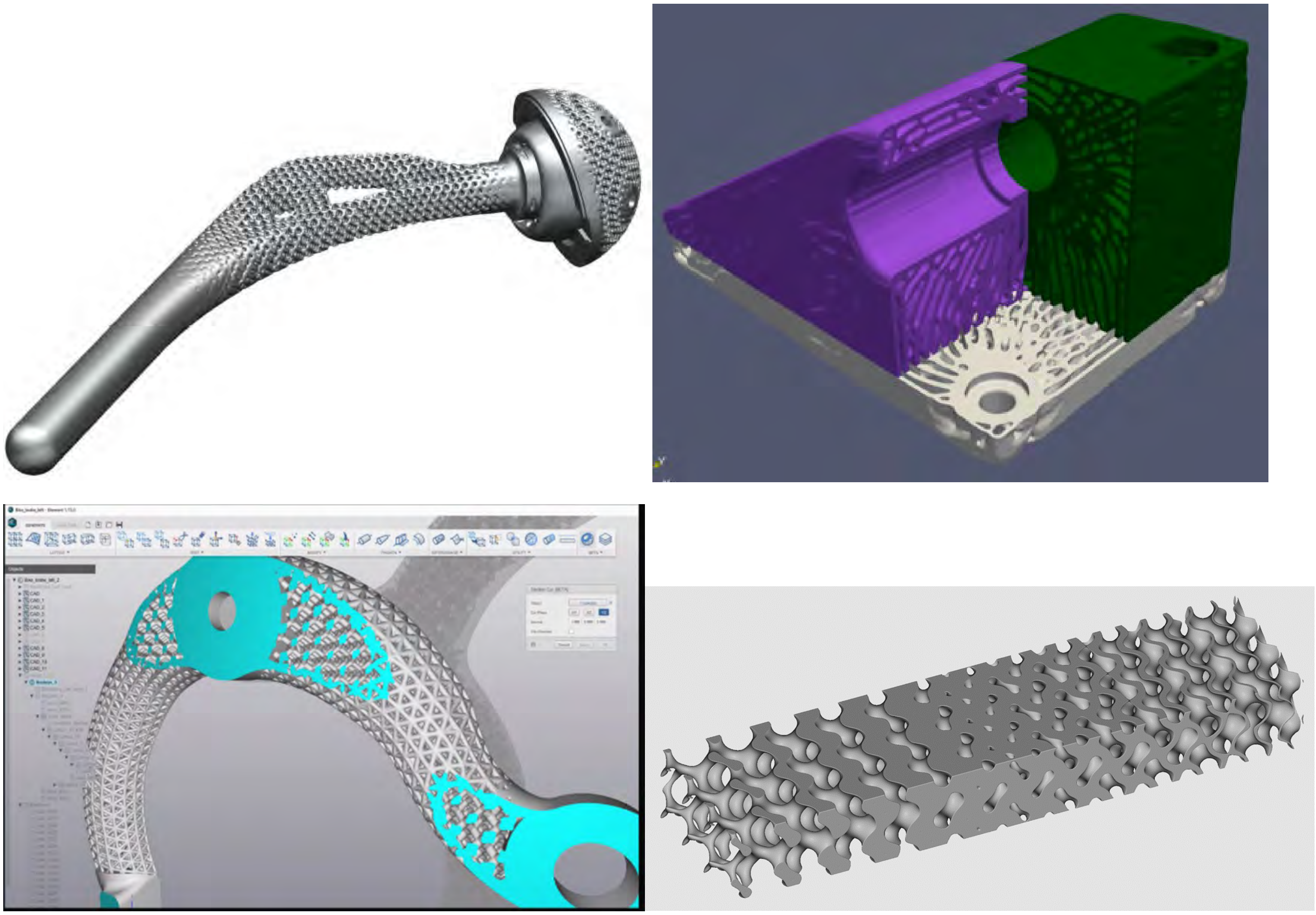


Figure 14 Transitions from Solid to Lattice

Handling uncertainties

If Generative Design is to be a key enabler of Democratization of Engineering Simulation, robust design approaches accounting for uncertainties are a fundamental requirement. Generative Design needs to address uncertainty of inputs and statistical probability of a design to meet objectives and constraints.

The ASSESS Initiative clearly calls out the strong recommendations to support uncertainties. This need to support uncertainties becomes more and more critical as we approach designs being generated where either: 1. The margin of safety can be less than the potential variability, or 2. The sensitivity of performance to variability can result in infeasible designs within the potential variability.

> "It is recommended that the specification of the use cases should incorporate uncertainties related to all inputs used to specify the intended use."

Like "Handling of multiple load cases" the challenge is not to keep adding material but to come up with design alternatives that meet the desired statistical probability of success accounting for the uncertainty of inputs. Terms like "statistical probability of success" and "uncertainty of data" are not commonly understood today by the design community.

It is anticipated that in the short term that this uncertainty will be handled by constraints on Factor of Safety and other design criteria that account for and exceed the uncertainty. As designs from Generative Design approach more optimal solutions uncertainty becomes critical for robustness under all operating conditions. Accounting for uncertainty will enable less restrictive constraints on the design and more efficient designs being generated.

Handling manufacturing process dependent materials

The fundamental assumption of geometric shape generation algorithms, such as Topology Optimization, is that the materials are uniform and homogeneous. It is only recently that research advances have been made to enable consideration of multiple materials rather than a single material. Manufacturing processes rarely result in homogeneous materials.

Dr. Andreas Vlahinos of AES has suggested that we need to introduce two key aspects into the Generative Design process to account for the resulting material variability. The first key aspect that Dr. Vlahinos suggested is to incorporate multi-physics simulation for characterization of the resulting properties. The second key aspect is to develop a "Material Property Field" as a result of the material characterization that could be used as input to the geometric shape generation algorithms rather than homogeneous material distribution.

This "Material Property Field" approach opens the following potential scenarios for application.

1. Perform Generative Design based on an estimated Material Property Field
    a. Similar manufacturing process and design
    b. Experience based
    c. With no known data or experience the default field degenerates to a homogeneous material
2. Select key designs for further study
3. For each key design
    a. Perform multi-physics simulation for characterization of the resulting properties
        i. Preferably automated based on manufacturing process information
        ii. Currently limited to experts only due to the complexities involved
    b. Extract a "Material Property Field" and uncertainties from the characterization
    c. Rerun the Generative Design Process based on Material Property Field
    d. Refine key designs of interest and iterate until resulting materials are within the uncertainty range of the Material Property Field

There are some inherent challenges with this approach. The following illustrates just a few of these challenges.

1. Automation of the multi-physics simulation for characterization of the resulting properties such that a simulation expert does not need to be called in for this step.
   a. The manufacturing process simulation needs to use the available information on the manufacturing process being used and may require additional data
   b. The manufacturing process information will be sparse in the early design stages resulting in higher uncertainties
2. Characterization of the uncertainty of the material properties in the "Material Property Field"
   a. The likely results are a range of material property values of interest at various points in space
3. Accounting for Lattice structures in the process flow
4. Application of the "Material Property Field in subsequent Generative Design runs
5. Defining/achieving convergence of the "Material Property Field"

The Need for a Generative Design Capability Assessment Model

The vision for Generative Design is that it could enable a significant paradigm shift in the design processes used today. Generative Design has the potential to enable a disruptive design paradigm inversion. It proposes in concept that designs can be computer generated by proper specification of rules, requirements, and constraints. This overturns the current practice of design, where designs must first be created so they can be evaluated against their performance requirements. This means that Engineering Simulation tools, developed for design evaluation, become the driver for design creation.

End User Benefits from the Use of a Generative Design Capability Assessment Model

Organizations that are considering investing significantly in Generative Design can use the Generative Design Capability Assessment model for three distinct purposes:

1. Understand their current and future capability requirements
2. Understand the capabilities available, strengths and weaknesses related to different Generative Design workflows
3. Understand the suitability of different Generative Design workflows to their current and future requirements

Understand their current and future capability requirements

Broader support of the capability areas enables a broader range of a end user applications that can be supported. It was mentioned earlier, that there is no Generative Design provider who meets the desired state of capabilities across the full range of the required capabilities listed above to enable the desired paradigm shift. It is also true that each potential application of Generative Design will not require the full capability in all of the areas outlined.

The first step for an organization considering investing significantly in Generative Design should be to use the Generative Design Capability Assessment model to understand their capability requirements for successful deployment. This can be accomplished by using the Generative Design Capability Assessment Model proposed in this document to rate what capabilities need to be supported to enable success. This evaluation of the organization's requirements should be done by the organization and/or through independent consultants knowledgeable in the use and application of Generative Design.

Understand the capabilities available, strengths and weaknesses for different Generative Design workflows

The second step for an organization considering investing significantly in Generative Design should be to review Generative Design Capability Assessments of candidate Generative Design solution workflows from various providers. These Generative Design solution workflow assessments should be performed by independent consultants with interaction with providers and not by the providers themselves.

Understand the suitability of different Generative Design workflows to their current and future requirements

The third step for an organization considering investing significantly in Generative Design should be to evaluate the suitability of candidate Generative Design solution workflows from various providers. A proposed approach for this suitability assessment is based on a quantifiable "Suitability Index." A Suitability Index can be calculated for each Generative Design capability area by dividing the Generative Design workflow capability assessment value by the corresponding requirements value from step 1 outlined above. A Suitability Index of less than 1.0 indicates that the workflow evaluated is not suitable to support the intended application.

The approach outlined will results in multiple suitability qualifications (one for each capability area). By determination of the minimum and mean Sustainability Indices it is possible to support further qualification of the proposed workflows may be performed as follows:

- Clearly suitable
    - Minimum Suitability Index is equal to or greater than 1.0
- Possibly appropriate and needs further investigation
    - Mean Suitability Index is equal to or greater than 1.0
    - Minimum Suitability Index is less than 1.0
- Clearly not appropriate
    - Mean Suitability Index is less than 1.0

Generative Design provider Benefits from the Use of a Generative Design Capability Assessment Model

Organizations that are provide Generative Design can use the Generative Design Capability Assessment model for three distinct purposes:

1. Understand which applications best fit their workflows
2. Understand competitive positioning
3. Support future capability planning
4. Enable potential end users to better understand their capabilities

These benefits for Generative Design solution providers are best accomplished through Generative Design solution workflow assessments performed by independent consultants. It is imagined that there would be two types of assessments as follows:

1. Internally only to establish strengths & weaknesses and future plans
2. External to enable positioning for specific applications and/or leadership positioning

Proposed Capability Assessment Criteria

To achieve this paradigm shift, the Generative Design process must support and enable more efficient design exploration in the context and terminology of the design scenario/problem at hand and provide support for the current set of design requirements, constraints, and uncertainties that the designer faces every day. Generative Design needs to enable the exploration and selection of “robust design” alternatives for as wide a range of design scenarios as possible to enable the possible paradigm shift in the design process. The following illustrates the fifteen (15) key areas of capability as defined by the ASSESS Initiative that need to be addressed for Generative Design to enable a paradigm shift for a significant portion of today’s design efforts that are described in more detail earlier in this paper.

1. Handling all appropriate objectives and constraints
2. Handling multiple operational (load) conditions
3. Handling multi-physics
4. Handling complex materials
5. Handling transitions from solid to lattice structures
6. Handling uncertainty
7. Handling multiple manufacturing processes
8. Handling manufacturing process dependent materials
9. Handling cost as an objective or constraint
10. Handling Generative Design in an assembly/system context

11. Enabling informed, comprehensive and efficient exploration of viable design alternatives
12. Enabling efficient & effective transformation to detailed design analysis
13. Enabling efficient refinement and selection guidance of design concepts generated
14. Enabling Generative Design within the designer's process, context & terminology
15. Enabling broad accessibility to Generative Design

There is no Generative Design provider who meets the desired state of capabilities across the full range of the required capabilities listed above to enable the desired paradigm shift. Therefore, it is recommended that a Generative Design Capability Assessment Model based on the areas outlined in this report would be beneficial to better understand the current state and near future of any Generative Design offering and its competitive positioning.

General Applicability Capability Assessment Criteria

The following outlines the Capability Assessment Criteria for key capability areas associated with the general applicability of Generative Design. The criteria are outlined are based on the ASSESS Initiative Generative Design Strategic Insight Paper (Understanding the Path to a Generative Design Enabled Design Process Paradigm Shift). Any criterion in addition to the criteria outlined by the ASSESS Initiative are highlighted in red text.

Handling all appropriate objectives and constraints

Assessment Level	**Assessment Criteria**
1 limited	Supports stiffness/displacement as an objective
	Supports Volume or Volume Fraction as a constraint
	Supports one objective at a time
	Supports basic Additive Manufacturing constraints
	Supports one design constraint at a time
2 basic	Supports weight/mass/volume as an objective
	Supports stress or safety factor as a constraint
	Supports frequency as a constraint
	Supports temperature or heat xfer as a constraint
	Supports displacement as a constraint
	Supports strain as a constraint
	Supports advanced Additive Manufacturing constraints
	Supports basic Subtractive Manufacturing constraints
	Supports basic assembly/construction constraints
	Supports Symmetry constraints
	Supports multiple design constraints

Handling all appropriate objectives and constraints	
Assessment Level	**Assessment Criteria**
3 functional	Supports weight/mass as a constraint
	Supports stress or safety factor as an objective
	Supports frequency as an objective
	Supports temperature or heat xfer as an objective
	Supports displacement or stiffness as an objective
	Supports strain as an objective
	Supports Fatigue Life as a constraint
	Supports Velocity as a constraint
	Supports Acceleration as a constraint
	Supports Pressure as a constraint
	Supports standard Subtractive Manufacturing constraints
	Supports standard assembly/construction constraints
	Supports manufacturing processes specific materials
4 advanced	Supports cost as a constraint
	Supports Multiple objectives
	Supports Fatigue life as an objective
	Supports Velocity as an objective
	Supports Acceleration as an objective
	Supports Pressure as an objective
	Supports stamping related constraints
	Supports multi-physics interactions as objectives
	Supports time between required maintenance as a constraint
	Supports machine specific Additive Manufacturing constraints
	Supports advanced Subtractive Manufacturing constraints
	Supports advanced assembly/construction constraints
	Supports robustness of design options as a criteria
	Supports Hybrid Manufacturing constraints
	Supports Printer Specific Constraints
5 comprehensive	Supports assembly/construction related objectives
	Supports maintainability related constraints and objectives
	Supports any physics based performance criteria as constraints & objectives
	Supports multi-physics interactions as objectives
	Supports time between required maintenance as an objective
	Supports usability, ergonomics and aesthetics as constraints & objectives
	Supports cost as an objective
	Supports factory specific Manufacturing constraints
	Supports comprehensive Subtractive Manufacturing constraints
	Supports comprehensive assembly/construction constraints
	Supports robustness of design options as an objective
	Supports manufacturing process dependent material properties as a constraint

Handling multiple load conditions	
Assessment Level	**Assessment Criteria**
1 limited	Supports only a single load condition
	Supports component level loading
2 basic	Supports a limited number of multiple load conditions for a single physics problem
3 functional	Supports a limited number of multiple load conditions for 2-3 physics
	Supports an unlimited number of multiple load conditions for single physics problems
	Supports Assembly level loading
4 advanced	Supports a limited number of multiple load conditions for a broad range of physics
	Supports an unlimited number of multiple load conditions for 2-3 physics
	Supports xfer of Assembly loads from MBD analysis
5 comprehensive	Supports an unlimited number of multiple load conditions for a broad range of physics
	Supports an unlimited number of multiple load conditions for all physics

Handling multi-physics	
Assessment Level	**Assessment Criteria**
1 limited	Supports only one physics solution
2 basic	Supports 2-3 uncoupled physics simultaneously
3 functional	Supports a broad range of uncoupled physics simultaneously
4 advanced	Supports coupled multi-physics problems for a broad range of physics
	Supports contact analysis
	Supports joint/connector loads
	Supports coupled multi-physics problems for some combinations of physics
5 comprehensive	Supports uncoupled multi-physics problems for all physics
	Supports coupled multi-physics problems for all physics
	Supports automated joint/connector loads

Handling multiple manufacturing/assembly/construction processes	
Assessment Level	**Assessment Criteria**
1 limited	Supports Additive Manufacturing overhang/repose angle as a constraint
	Supports Additive Manufacturing minimum thickness as a constraint
2 basic	Supports extrusion related constraints
	Supports Symmetry constraints
	Supports Additive Manufacturing support design as a constraint
	Supports Additive Manufacturing print direction as a constraint
	Supports basic assembly/construction constraints
3 functional	Supports stamping related constraints
	Supports extrusion related constraints
	Supports casting related constraints
	Supports forging related constraints
	Supports 2 axis cutting related constraints
	Supports 3 axis milling related constraints
	Supports standard assembly/construction related constraints
	Supports generation preliminary manufacturing/assembly process plans
	Supports Printer Specific Constraints
	Supports manufacturing processes specific materials
4 advanced	Supports fixture Jig related constraints
	Supports manufacturability related constraints
	Supports Additive Manufacturing constraints for de-powdering & support removal
	Supports 5 axis milling related constraints
	Supports 2.5 axis milling related constraints
	Supports Manufacturing Process Simulation
	Supports Multiple materials for Additive Manufacturing
	Supports machine specific Additive Manufacturing constraints
	Supports advanced Subtractive Manufacturing constraints
	Supports advanced assembly/construction constraints
	Supports Hybrid Manufacturing Constraints
	Supports generation of "near final" manufacturing/assembly process plans
5 comprehensive	Supports full range of Subtractive Manufacturing related constraints
	Supports assembly/construction related objectives
	Supports manufacturability related objectives
	Supports process planning related constraints
	Supports factory specific manufacturing constraints
	Supports comprehensive Subtractive Manufacturing constraints
	Supports comprehensive assembly/construction constraints
	Supports generation of recommend manufacturing/ Assembly processes

Handling cost as an objective or constraint	
Assessment Level	**Assessment Criteria**
1 limited	Does not support cost as an objective or constraint
2 basic	Supports cost simulation for specified design options
	Supports cost simulation of a single part (ignoring setup cost)
	Supports cost simulation of setup cost
	Supports Additive Manufacturing cost simulation
	Supports cost as a filter for feasibility of designs
3 functional	Supports cost simulation of all design options
	Supports cost as a constraint
	Supports cost simulation based on expected volume
	Supports some Subtractive Manufacturing cost simulations
	Supports some assembly & construction cost simulations
4 advanced	Supports cost as an objective
	Supports machine specific Additive Manufacturing cost simulation
	Supports most Subtractive Manufacturing cost simulations
	Supports process specific Subtractive Manufacturing cost simulations
	Supports broad assembly & construction cost simulations
	Supports Hybrid Manufacturing cost simulations
5 comprehensive	Supports integrated simulation of cost as part of the generative process
	Supports factory specific Subtractive Manufacturing cost simulations
	Supports site specific assembly & construction cost simulations

Handling Generative Design in an assembly/system context	
Assessment Level	**Assessment Criteria**
1 limited	Supports Generative Design of components only
	Supports design scenario defined on components only
2 basic	Supports Generative Design of components in an assembly context
	Supports design scenario defined in an assembly/system level
	Supports bonded contact of components
3 functional	Supports Generative Design of multiple components in an assembly
	Supports linear contact analysis as appropriate
	Supports loading from an MBD solution
4 advanced	Supports definition of joint types & behavior
	Supports non-linear contact
	Supports dynamically varying contact
	Supports Assembly/construction loading
5 comprehensive	Supports generation of assembly /system structure as part of Generative Design

Enabling informed, comprehensive and efficient exploration of viable design alternatives	
Assessment Level	**Assessment Criteria**
1 limited	Supports a single Optimal design for a single Objective and a single material/process design scenario
	Supports Additive Manufacturing process only
	Supports a single material
2 basic	Supports explorations of design options for a multiple Objectives in multiple design scenarios
	Supports one selected Manufacturing/assembly/construction process (not limited to Additive)
	Supports non-lattice structures
	Supports a different material per component
	Supports explorations of design options for a multiple materials and a single design scenario
	Supports default filtering out of infeasible design options
3 functional	Supports explorations of design options for a multiple Objectives and multiple design scenarios
	Supports multiple Manufacturing / assembly/ construction processes
	Supports choice of lattice or non-lattice structures
	Supports explorations of design options for a multiple manufacturing processes and a single design scenario
4 advanced	Supports all available Manufacturing process
	Supports mixed structures (lattice and non-lattice structures areas)
	Supports selection of material for each component as part of the Generative Design Process
	Supports explorations of design options for a multiple manufacturing processes and multiple materials in a single design scenario
5 comprehensive	Supports all combinations of objectives, scenarios, materials, manufacturing/assembly/construction processes
	Supports definition of material as part of the Generative Design process

Enabling efficient and effective transformation to detailed design analysis	
Assessment Level	**Assessment Criteria**
1 limited	Supports export of Generated Design in facet format
2 basic	Supports export of Generated Design in geometric format (Subd or NURBS) or use of facet data in modeling
	Supports semi-automatic generation of geometric format (Subd or NURBS) or use of facet data in modeling
3 functional	Supports efficient representation of lattice structures for downstream use
	Support transfer of the design scenario definition (loads, boundary conditions, materials, etc..)
	Supports automatic generation of geometric format (Subd or NURBS) or use of facet data in modeling
	Support transfer of the design scenario definition to major CAE solutions
4 advanced	Supports transfer of contact and joint information
	Supports transfer of optimization constraints & objectives
	Supports transfer of uncertainties
	Supports associativity of usage scenario to geometry used for definition
	Supports semi-automatic Feature Recognition
5 comprehensive	Supports seamless transfer of all information related to the design
	Supports automatic Feature Recognition

Enabling efficient selection guidance of generated design concepts	
Assessment Level	**Assessment Criteria**
1 limited	Supports generation of a large number of design options
	Supports methods of limiting design options to be considered to less than 1000
2 basic	Supports filtering by feasibility
	Supports methods of limiting design options to be considered to less than 100
3 functional	Supports only generating feasible designs
	Supports methods of limiting design options to be considered to less than 25
	Supports ranking by cost of Manufacture/assembly/construction
4 advanced	Supports filtering of designs by probability of feasibility based on uncertainty of inputs
	Supports methods of limiting design options to be considered to less than 10
	Supports filtering by cost of Manufacture/assembly/construction
5 comprehensive	Supports methods of limiting design options to be considered to less than 5
	Supports cost of Manufacture/assembly/construction as a constraint
	Supports cost of Manufacture/assembly/construction as an objective

Enabling Generative Design within the designer's process, context & terminology

Assessment Level	Assessment Criteria
1 limited	Supports Generative Design in a standalone application with input as a facetted model (or integrated with CAD)
	Supports definition of design scenarios independent of CAD
2 basic	Supports Generative Design in a standalone application with input as a geometry model (or integrated with CAD)
	Supports Generative Design generations on the cloud (or local)
3 functional	Supports initial design concept as a guide
	Supports generation of designs consumable by the CAD system
	Supports generation of Generative Design templates by simulation experts for use by non-experts
4 advanced	Supports Generative Design integrated within the designer's CAD application
	Supports Generative Design generations local (no need for cloud)
	Supports CAD system based definition of design scenarios
	Supports generation of designs as CAD system entities
5 comprehensive	Supports seamless integration of Generative Design at any stage of the design process

Enabling broad accessibility to Generative Design

Assessment Level	Assessment Criteria
1 limited	Supports use by optimization specialist
	Supports commercial licensing
2 basic	Supports use by simulation specialist
	Supports an academic licensing program
	Supports simple execution
3 functional	Supports use by Design Engineers
	Supports research licenses and graduate level student access
	Supports simple setup & execution
4 advanced	Supports use by designers
	Supports a broad and proactive academic access program
	Supports teaching and student versions for Universities
	Supports almost "transparent" simulation and execution
5 comprehensive	Supports use by anyone capable of running the CAD system
	Supports teaching and student versions for High Schools
	Supports unlimited access to FIRST program
	Supports fully "transparent" simulation and execution

Specialist User Capability Assessment Criteria

The following outlines the Capability Assessment Criteria for key capability areas associated with the specialist user of Generative Design. The criteria are outlined are based on the ASSESS Initiative Generative Design Strategic Insight Paper (Understanding the Path to a Generative Design Enabled Design Process Paradigm Shift).

Handling complex materials	
Assessment Level	**Assessment Criteria**
1 limited	Supports one linear material
2 basic	Supports different linear materials in different components in an assembly
	Supports different single material options in a scenario
3 functional	Supports different linear materials within a component
	Supports one non-linear material within a component
	Supports manufacturing processes specific materials
4 advanced	Supports varying linear materials within a component
	Supports homogenization approaches for material distribution
	Supports material distribution as a design outcome
	Supports anisotropic materials
	Supports definition of desired material property distribution
	Supports different non-linear materials in different components in an assembly
5 comprehensive	Supports varying linear materials in different components in an assembly
	Supports composite material definitions
	Supports material distribution as an objective & constraint

Handling transitions from solid to lattice structures	
Assessment Level	**Assessment Criteria**
1 limited	Does not support lattice generation
2 basic	Supports uniform lattice generation in a component
	Supports lattice templates
	Supports a basic representation of lattice structures
3 functional	Supports lattice generation in specified regions of parts
	Supports lattice generation in multiple components of an assembly
	Supports transitions from lattice to solid structures
	Supports Homogenization of lattice structures
	Supports varying lattice properties
	Support Density fields for lattice structure sizing
4 advanced	Supports smooth transitions to solids
	Supports smooth transitions to solids
	Supports generation of Mesostructural lattice structures
	Supports varying Homogenization of varying lattice structures
5 comprehensive	Supports automated generation of solids / lattice transition based on objectives & constraints
	Supports automated selection of lattice templates or Mesostructural lattice
	Supports material distribution as an objective & constraint
	Supports automated generations of multiple lattice types

Handling uncertainties	
Assessment Level	**Assessment Criteria**
1 limited	Supports only single values for inputs with no variation or uncertainty
2 basic	Supports uncertainty of input magnitudes
	Supports uncertainty of material property values
3 functional	Supports uncertainty of input locations & orientations
	Supports uncertainty of material distribution
	Supports feasibility evaluation under variation
	Supports probabilistic distribution of all variability
	Supports impact of variation of feasibility based on uncertainty
4 advanced	Supports treating numerical accuracy for each criterion as an uncertainty
	Supports probability of feasibility (or failure) in each load case as an output
	Supports sensitivity of variation of feasibility based on uncertainty
	Supports robustness of design options as a criteria
5 comprehensive	Supports treating numerical accuracy for each criterion & objective as probabilistic uncertainties
	Supports probability of feasibility (or failure) across all load cases
	Supports robustness of design options as an Objective

Handling manufacturing process dependent materials	
Assessment Level	**Assessment Criteria**
1 limited	Does not support process dependent materials
2 basic	Supports calculation of Additive Manufacturing properties of selected designs
3 functional	Supports spatially varying material properties from Additive Manufacturing as input for a redesign
	Supports calculation of Subtractive Manufacturing characteristics and properties of selected designs
	Supports impact of Additive Manufacturing on constraints & objectives
4 advanced	Supports spatially varying material properties from Additive Manufacturing as part of the process
	Supports impact of material properties from Subtractive Manufacturing as input for a redesign
	Supports impact of Subtractive Manufacturing on constraints & objectives
5 comprehensive	Supports full integration of manufacturing effects on materials in the generation process
	Supports manufacturing process dependent material properties as a constraint

Making the Generative Design Capability Assessment Model Meaningful

intrinSIM has developed a methodology to quantify the requirements of a potential Generative Design application or to quantify the capabilities of a specific Generative Design workflow based on the Capability Assessment Model criteria outlined above. Determination of both the requirenents of a potential application and the capabilities of a specific workflow enables the determination of suitability indices for the specific application and the Generative Design workflow(s).

intrinSIM anticipates working wth Generative Design providers to provide general applicability Capability Assessment for commercially available (or planned) Genereative Design workflows.