Generative Theme Strategic Insight 2019

ASSESS

Understanding a Generative Design Enabled Design Process Paradigm Shift

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The vision for Generative Design is to enable a significant paradigm shift in the current design processes via the creation of computer-generated designs as early as the concept stage by Design Engineers.

THE VISION FOR GENERATIVE DESIGN

The vision for Generative Design is to enable a significant paradigm shift in the current design processes via the creation of computer-generated designs as early as the concept stage by Design Engineers. These generated designs are based on proper specifications of the intended use case, design space, performance objectives, and design constraints that account for the desired performance and manufacturing/assembly/fabrication of the design. This approach overturns the current practice where designs must first be created so they can be evaluated against their performance requirements.

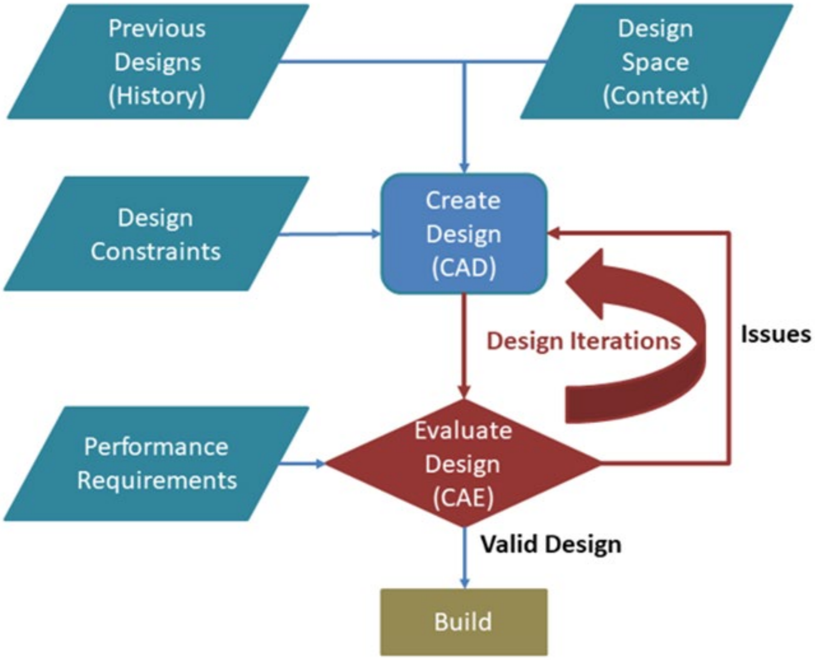
Generative Design techniques also have the potential of being a key enabler for Democratization of Engineering Simulation by providing simulation-driven design concepts that allow a user to define a design scenario as input to a Generative Design tool to explore the design space for feasible design options. Driving Generative Design up front to the "early stages" of the development process will change the nature of the work that is performed throughout the design process. The significant paradigm shift in the design process that could be enabled by Generative Design is the ability for Design Engineers to use automated design processes that are performance driven and manufacturing/assembly/fabrication "aware."

Generative Design is a form of design space exploration that is generally underpinned by physics-based simulations. A typical problem may have the statement, "give me designs for my use case that meet my stiffness and stress requirements and with minimum weight." Generative Design should be employed as early as possible, before the design space becomes overly constrained. However, this does not negate the vision that optimization and validation be applied repeatedly as the product design is developed.

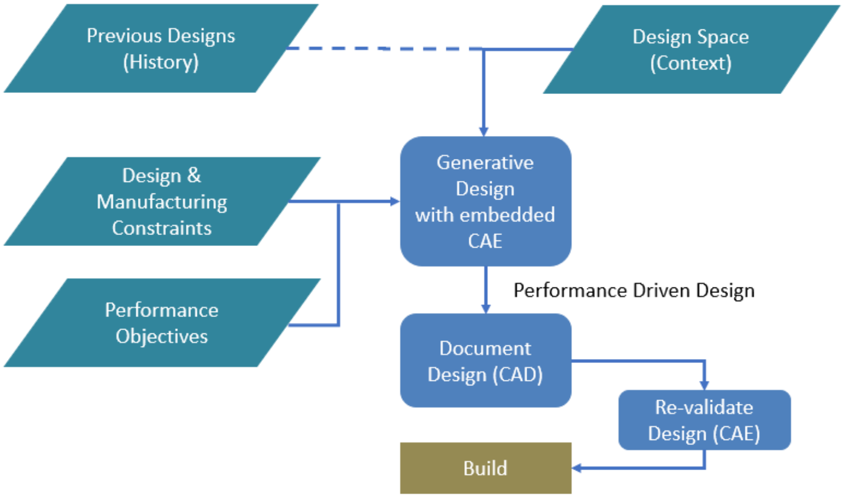
In the traditional development process, CAE or simulation is predominantly applied after there is CAD available to analyze but there is not enough decision space remaining to exploit the innovation that is enabled via Generative Design methods. The figure below illustrates the traditional design process where a proposed design is first created, and then it is evaluated against the product performance requirements, followed by iterative cycles of evaluation against the performance requirements and subsequent redesign. When design evaluation including testing shows that all the requirements are met, the design can be passed on to production manufacturing. The traditional design

In the traditional development process, CAE or simulation is predominantly applied after there is CAD available to analyze but there is not enough decision space remaining to exploit the innovation that is enabled via Generative Design methods.

process usually rests heavily on previous designs as a starting point.



The Generative Design process opens up the possibility of thoroughly exploring the design space and exploring design concepts outside of previously accumulated proprietary knowledge. Design always starts with requirements. For the purposes of this paper we are going to focus on the actual Generative Design process which is driven by the definition of objectives and constraints as a function of the design requirements. The figure below illustrates the Generative Design process with a reduced dependence on historical designs as shown by the dashed line.



The Generative Design process opens up the possibility thoroughly exploring the design space and discovering design concepts outside of previously accumulated proprietary knowledge.

The Generative Design process does not rely heavily on an initial design concept and is usually independent of an organization's accumulated experience or tribal knowledge. The advantage is that it is not limited by previous efforts/knowledge but also has the disadvantage that is it is not transferring previous knowledge. Some Generative Design workflows can start with historical designs as initial design concepts. One idea for consideration is to leverage Machine Learning (a form of Artificial Intelligence) to develop the definition of the available design space from previous designs.

WHAT IS GENERATIVE DESIGN

There have been numerous attempts to define Generative Design where many of these are from suppliers of technology who define Generative Design in terms of the solutions that they offer. Through efforts of the ASSESS Generative Theme working group and multiple ASSESS Congress working sessions, the ASSESS Initiative has developed the following definition of Generative Design and highly recommends that end users, software vendors, industry analysts, and research organizations adopt this definition to enable a common understanding.

> ***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.***

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 operation conditions should incorporate uncertainties related to all inputs used to specify the intended use. Based on the ASSESS Initiative definition of Generative Design, it is clear that Generative Design is based on an algorithm or collection of algorithms that transforms inputs into desired outputs for a specified use case or design scenario.

Generative Design inputs could Include:

- Requirements (use case performance, cost, longevity. …)
- 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 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.

Generative Design outputs could include:

- Numerous viable designs within the available design space and specified manufacturing processes that address the specified Requirements, Constraints, Objectives, Uncertainties, etc.
- Probabilities of viable designs to meet all criteria under all operational conditions

Stated simply, Generative Design is the use of a set of tools that transforms statements of a combination of use cases, objectives, constraints, and design space into feasible designs. For millennia, the only way to evaluate an idea was to create a design, then build, and then test it. That usually led to cycles of redesign and re-testing.

Generative Design methods cannot guarantee that a feasible design can be created for the specified set of Generative Design inputs. The inability to generate feasible designs may be due to improperly defined inputs or inadequate design space to meet the requirements. It is important that the Generative Design workflows filter out and/or highlight infeasible designs but also allow investigation of the infeasible designs if no feasible designs are found.

Generative Design is not a particular algorithm or an optimization technology, 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 application scenario.

THE POSSIBILITY OF A PARADIGM SHIFT

Generative Design has the potential of creating a disruptive design paradigm inversion. It proposes that viable designs can be computer generated merely based on proper specifications of use cases, design space, performance objectives, and design constraints that account for the desired performance and manufacturing/assembly/fabrication of the design. This means that when a Generative Design process is used, the Engineering Simulation process becomes the driver in creating viable design options. This overturns the current practice of design, where design options must first be created so they can then be evaluated against their performance requirements.

Generative Design is not a particular algorithm or an optimization technology, 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 application scenario.

For Generative Design to be successful, the engineering simulations need to reflect reality and capture the key physics phenomena associated with the design problem. The ability to reflect and capture the key physics phenomena with good engineering rigor for a desired application may require the ability to incorporate AI techniques such as machine learning.

The Generative Design process transforms product requirements into viable designs (shape, materials, and configurations) that account for the specified performance objectives and constraints. The Generative Design process itself ensures that the specified objectives and constraints have been met or it will indicate that no feasible viable designs can meet the required design scenario.

Generative Design methods have the potential of being a key enabler for Democratization of Engineering Simulation by providing simulation-driven design concepts that allow a user to define a design scenario and allow a Generative Design tool to explore the design space for feasible design options. The user can then explore the generated design alternatives. It is anticipated that Generative Design best achieves its vision if it is used early and often in the design process by those people developing a design.

Generative Design represents the next big technology driver in the Engineering Simulation domain with the potential to enable a significant paradigm shift in how products, buildings, and infrastructures are designed via computer -generated algorithms based on proper specification of use cases, design space, performance objectives, and design constraints. As the application of Generative Design is just starting to mature, there are numerous challenges; however, the advances in the next decade are expected to be rapid, exciting, and transformative to design processes.

Making the potential paradigm shift enabled by Generative Design a reality will require both organizational/cultural changes and a broadening of available software capabilities to cover a broader range of design scenarios with Generative Design.

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WHAT SOFTWARE CAPABILITIES ARE REQUIRED TO ENABLE A PARADIGM SHIFT

The Generative Design enabled paradigm will result in better viable designs that are created faster. These benefits are 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 that their users have had using their Generative Design tools. Typically, these specific examples are based on limitations on the problem definitions so that they match the current software capabilities.

To enable a paradigm shift, the Generative Design process must support and enable more efficient design explorations in the context and terminology of the design scenario specified for the problem at hand. Support is required for the current set of design requirements, constraints, and uncertainties that the designer faces every day for as wide a range of design scenarios as possible.

Generative Design will also need to evolve over time to enable the exploration and selection of "robust designs" so that the resulting design options are closer to being optimum. The alternative for not accounting for uncertainty and robustness is to use either loads or safety factors that are increased over standard requirements to account for uncertainties. Generative Design processes that account for uncertainty and "robust design" concepts have the potential of generating more efficient designs.

One fundamental requirement for Generative Design is for the underlying simulation algorithms and technologies to be verified for the use cases that they are meant to address. Incorrect or highly inaccurate simulation results in the underlying technologies can result in the Generative Design algorithms pursuing and defining meaningless design options. If the Generative Design technology provider does not provide verification information, it is then imperative that the user compares results of the embedded simulation technologies with standard Engineering Simulation tools for key results of interest in the design scenario being considered.

The alternative to verifying the underlying technology prior to generating Design Alternatives is to run a more comprehensive analysis for every design option of interest with standard Engineering Simulation tools to validate that the designs are indeed feasible or infeasible and then adjust the designs accordingly. This results in a very cumbersome process that severely limits the effectiveness of using Generative Design early in the design process.

One fundamental requirement for Generative Design is for the underlying simulation algorithms and technologies to be verified for the use cases that they are meant to address

Once the underlying simulation technology has been verified, the next step is to evaluate the capabilities necessary to enable the envisioned paradigm shift. The ASSESS Initiative has outlined the following fifteen (15) key areas of capability that can be used to define a Generative Capability Assessment Model for manufacturing applications.

1. Handling all appropriate objectives and constraints
2. Handling multiple operational 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 or system context
11. Enabling informed, comprehensive and efficient exploration of the viable design alternatives
12. Enabling efficient & effective transformation to detailed analysis
13. Enabling efficient selection guidance of design concepts generated
14. Enabling Generative Design within the designer's process, context & terminology
15. Enabling broad accessibility to Generative Design.

Items 7 & 8 are unique to manufacturing applications and do not apply to AEC applications. For AEC applications these items should be replaced with something along the lines of "Handling multiple construction, fabrication, and assembly processes.

1. Handling all appropriate objectives and constraints

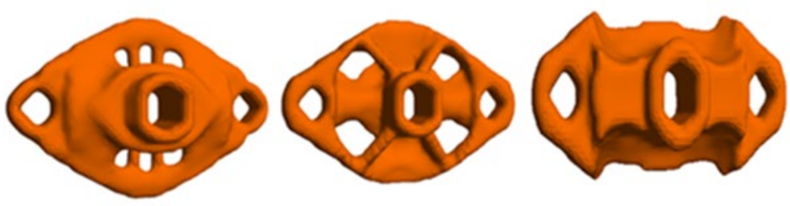
Real-world design scenarios almost always have multiple design objectives and constraints even within a single operational environment. For instance, a structural design problem may include objectives and constraints on stiffness, stress, fatigue life, and cost. Simply performing a topology optimization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

For a given design scenario, it is important that the Generative Design process supports the same objectives and constraints that the design engineer or designer is currently dealing with to make design decisions.

For a given design scenario, it is important that the Generative Design process supports the same objectives and constraints that the design engineer or designer is currently dealing with to make design decisions. The performance related items, for example, include stiffness, stress, fatigue life, temperatures, flow characteristics, dynamic behavior, and more. The manufacturing related items include geometry constraints for all the potential manufacturing processes being considered for the specific design scenario. Cost consideration is always an issue in the traditional design process and needs to be accounted for in the Generative Design process as well.

Real-world design scenarios rarely involve a single operational condition and almost always have to deal with multiple operational conditions.

The illustration below highlights the fact that different Generative Design constraint combinations should result in different design options being generated.



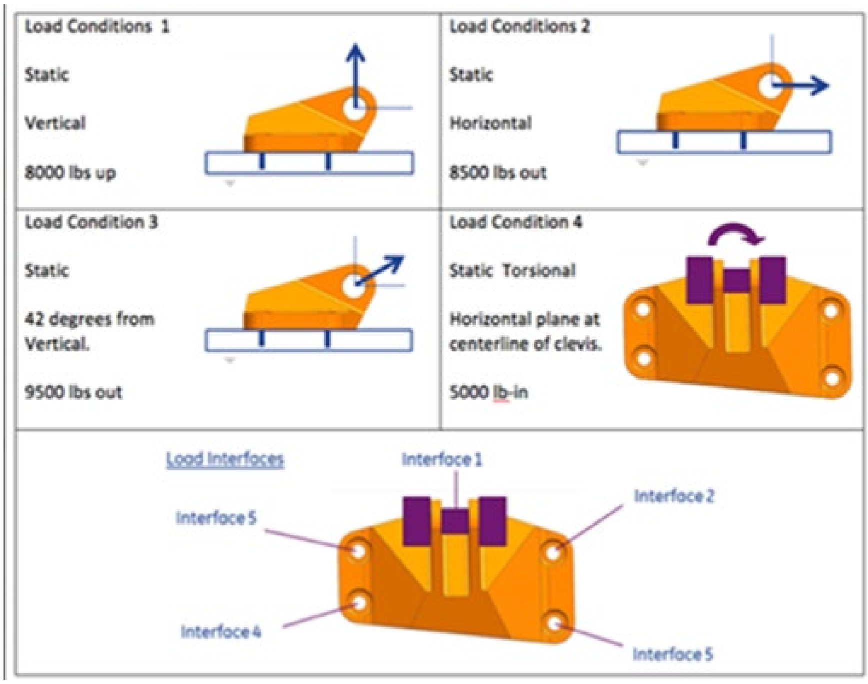
Different constraint combinations generate different designs

It is 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 Machine Learning. 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

2. Handling multiple operational conditions

Real-world design scenarios rarely involve a single operational condition and almost always have to deal with multiple operational conditions. 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.



Generative Design needs to 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 represent different use cases. Different load cases will result in different material distribution. Merely combining all material from all load cases would be fundamentally sub-optimal and would result in dramatic overdesigns. The following illustrates the challenge of dealing with multiple load cases.

design space axial load bending load torsional load combined loads

Generative Design needs to 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 represent different use cases.

Intelligent combinations of load cases in Generative Design requires coming up with designs that are appropriate across all resulting load conditions. This will probably require an iterative interaction between load cases and a potential use of Machine Learning to find designs that efficiently work for all use cases and loading conditions.

3. Handling multi-physics

Real-world design scenarios often also involve multiple physics (structural, vibration, fluids, electromagnetics, …) phenomena either in a single operational condition or as different operational conditions. Generative Design needs to deal appropriately with the physics of interest for the design scenario under investigation. The use of Generative Design with lattice structures may be a very effective way to handle multi-physics objectives such as structural strength and heat dissipation.

Another common engineering scenario is the ability to decrease the pressure drop of a fluidic component while respecting a mechanical performance requirement.

Current tools for Generative Design are limited in the range of physics supported and their combinations. The user has to be careful that the supported physics adequately represent the required design scenario and constraints. In addition, the involved engineering simulations need to reflect accurately the physics and reality.

4. Handling complex materials

Generative Design should allow the designer to determine the required material distribution and material properties as well as geometry.

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 simultaneous multi-material conditions. Although there is research focusing on multi-material selection with geometry development, almost all commercial Generative Design tools start with an assumed uniform material distribution.

Lattice structures off an interesting approach to obtaining effective non-uniform material properties by leveraging varying lattice structures shapes and sizes to achieve different behavior. Lattice structures that vary allow for non-uniform material behaviors with the same base material.

Advanced materials that are anisotropic in nature and composites should also be supported as the application of Generative Design expands.

Real-world design scenarios often also involve multiple physics (structural, vibration, fluids, electromagnetics, …) phenomena either in a single operational condition or as different operational conditions.

5. Handling transitions from solid to lattice structures

Generative Design has also 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. 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).

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6. Handling uncertainties

If Generative Design is going to enable a paradigm shift for simulation-driven design to be used early and often in the design process, it needs to consider the exploration and selection of “robust design” alternatives. This means accounting for uncertainties in all the design scenario specifications including loads, boundary conditions, materials, and more.

If Generative Design is to be a key enabler for Democratization of Engineering Simulation, robust design approaches accounting for uncertainties are key elements. The alternative used in Generative Design today is to ether increase the loading or increase the safety factor to cover the potential variation in loading and material properties which results in less efficient designs.

Support of uncertainties becomes more and more critical as we approach optimal 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.

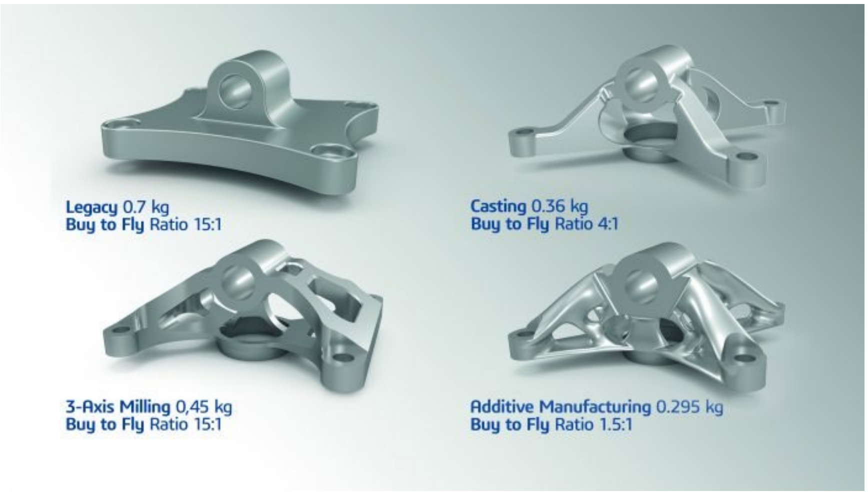
> "It is recommended that the specification of the use cases should incorporate uncertainties related to all inputs used to specify the intended use."

Similar to "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.

7. 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 must cover multiple manufacturing options.

Generative Design needs to address the design constraints for a wide range of manufacturing processes including both additive and subtractive processes that result in viable design alternatives for each manufacturing process. The following illustration shows different designs generated on the premise of using different manufacturing processes.



The equivalent to manufacturing processes in AEC applications is construction, fabrication, and assembly processes.

Generative Design needs to address the design constraints for a wide range of manufacturing processes including both additive and subtractive processes that result in viable design alternatives for each manufacturing process.

The 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. 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 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 may be significantly different from the "replaced" part.

The constraints related to a specific manufacturing process may need to consider the specific machine or 3D printer being used. The variations between machines is quite prominent in additive manufacturing as each 3D printer has its own 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.

The goal for Generative Design is to enable different designs for different manufacturing plants and processes that offer similar performance and reliability.

8. 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 and varying materials rather than a single material. Manufacturing processes such as plastic injection molding, die casting, stamping, and additive manufacturing rarely result in homogeneous materials.

Future Generative Design methods should consider the resulting material variability as a function of the manufacturing processed used. The first part to incorporate multi-physics simulation for characterization of the resulting properties. The second part 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.

9. Handling cost as an objective or constraint

Real-world design scenarios should include cost of production/construction/assembly as either a design objective (minimization) or as a constraint. Omitting cost as a consideration results in design options that may be functionally feasible but are not feasible to manufacture or to market.

Using estimated cost as a ranking or filter is a good start for Generative Design offerings. However, one should be able to define cost either as an optimization objective or a constraint at the user's discretion to eliminate generation of design options that are too expensive to make. The incorporation of cost models and resulting cost estimates is key to the Generative Design process and should significantly reduce the number of viable design options to be considered by the designer.

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, the "best" manufacturing process might 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 the recommended approach of accounting for function and cost, the geometry is not the design, but the function and performance with known cost characteristics represent the design; the geometry is just an instance to provide the design function and performance.

The concept that the geometry is not the design but just an instance to provide the design function and performance is revolutionary in nature and will result in massive ramifications related to product validation. The implications related to certification on regulated industries have not yet been explored.

10. Handling Generative Design in an assembly/system context

Current Generative Design tools often work on a component by component basis. This approach has the following three inherent issues:

1. It may be difficult to define realistic operational loads and boundary conditions subjected to a component because they might be influenced by the full assembly environment
2. The load distribution in an assembly context is usually a function of the properties (e.g., stiffness) of the components; changing properties of a component results in different load paths
3. The second issue is exacerbated if the goal is to apply Generative Design methods to multiple (or all) of the components in an assembly.

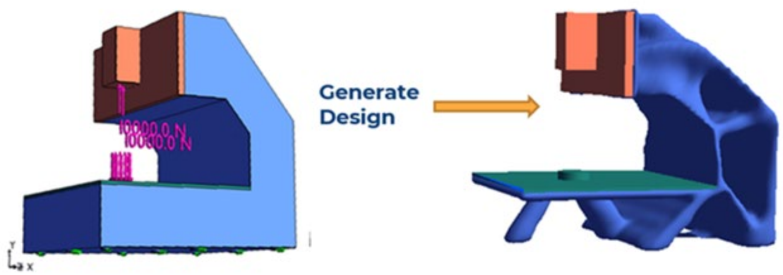
In the recommended approach of accounting for function and cost, the geometry is not the design, but the function and performance with known cost characteristics represent the design; the geometry is just an instance to provide the design function and performance.

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 is not as straightforward for other types of 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.

Another 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 so that their function is maintained (e.g., a linkage mechanism). This approach can simplify designs but does not remove the need to handle multiple parts in an assembly context.

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

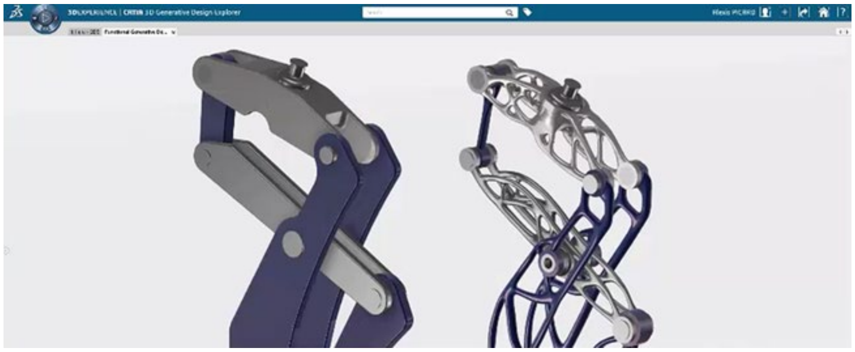
The first step toward the goal is enabling Generative Design of a component within an assembly context where loading is on the assembly and the loads are transferred through the assembly to the component. The illustration below shows loads applied in an assembly context for Generative Design of one component of the assembly.



The second step toward the goal is enabling Generative Design of a multiple components simultaneously within an assembly context. The illustration below shows Generative Design of multiple components of the assembly performed simultaneously.

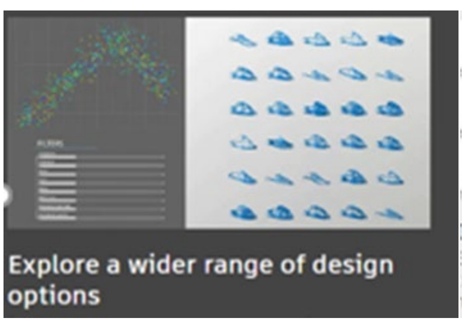
The goal for Generative Design is to support simultaneous design of multiple components in an assembly context driven by the assembly objectives and constraints that account for the changing load distributions throughout the assembly.

Generative Design should enable the ability to explore a wider range of viable design options than humanly possible by enabling a comprehensive exploration of design concepts that would otherwise not be considered.



11. Enabling informed, comprehensive and efficient exploration of the viable design alternatives

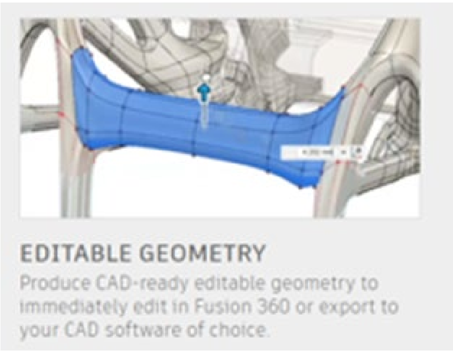
Generative Design should enable the ability to explore a wider range of viable design options than humanly possible by enabling a comprehensive exploration of design concepts that would otherwise not be considered. This includes variations of material properties, manufacturing processes, as well as various lattice structure types or solid materials. It should be possible to provide efficient exploration of all the feasible viable designs that meet the specified constraints with either single or multiple design objectives. This is best performed with a single Generative Design scenario but can be accomplished with multiple Generative Design scenarios. For multi-objective optimizations, the ability to understand trade-offs between objectives is critical.



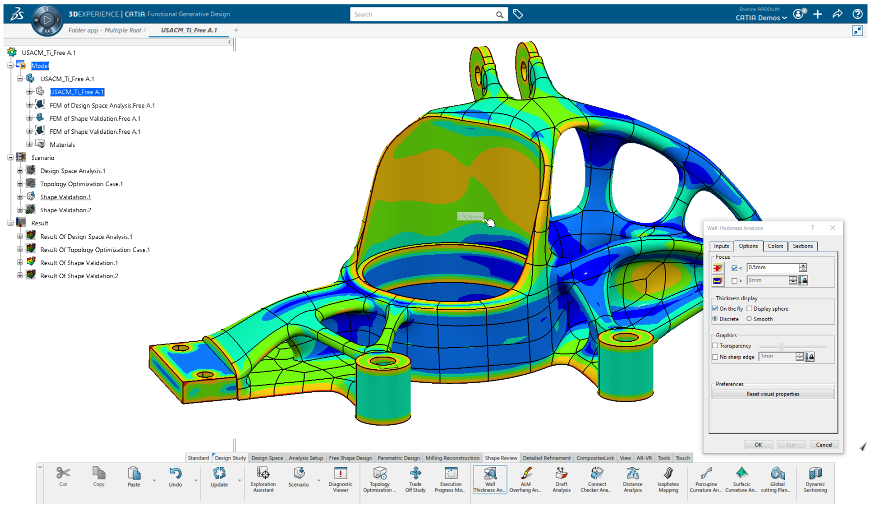
12. Enabling efficient & effective transformation to detailed design analysis

Generative Design should enable a smooth transition to detailed design validation using traditional simulation methodologies. This seems obvious at first; however, this smooth transition requires an automated creation of detailed simulation models with a transformation of the problem definition, material distribution, and uncertainties 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.

The following illustration represents two approaches to enabling a smooth transition to detailed design validation. The first approach is to convert the Generative Design to CAD-ready editable geometry. The second approach is to upgrade the CAD system to support the ability to evolve the design with design operations on facetted and hybrid geometries.



Additionally, the mechanical interfaces of a component should be transferred into the new detailed design and manufacturing/production planning tools to assist the engineer to ensure the component can be actualized with the chosen manufacturing/assembly/fabrication processes. The following illustrates manufacturing process information calculated by a manufacturing planning tool for a design geometry generated by Generative Design.



Manual creations of detailed simulation models is at best inefficient (requires a simulation expert) and at worst confusing, as they may result in “apples to oranges” comparisons that might cast doubt on the validity of the Generative Design process. A goal for Generative Design is to support the automated creation and solution of detailed simulation models as part of the Generative Design process to enable refinement of viable designs.

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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 performed. However, because not all of the generated designs will pass the detailed design validation, subsequent design refinements and modifications may be needed.

13, Enabling efficient selection guidance of generated design concepts

One of the benefits of Generative Design is that it should enable a comprehensive exploration of the design space which may result in a large number of viable design options. However, this can also result in a limitation to the application of Generative Design. No designer or engineer has the inclination, time or ability to review a large number of viable design options. Most designers and engineers are interested in a "Top Ten" list or less.

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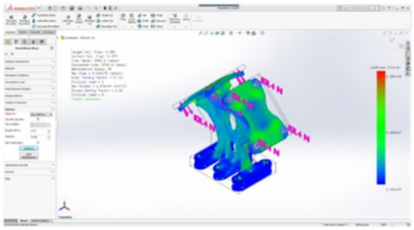
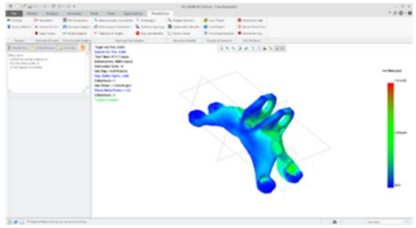
It was recommended earlier in this report that cost should be added as either an objective or constraint. It is anticipated that adding cost may reduce the number of options significantly and enable a better ranking of the resulting design alternatives. However, many Generative Design options can result in too many viable design options for practical consumption by the user. This problem opens up an excellent opportunity for leveraging Machine Learning to reduce the number of viable design options to the "Top Ten" options and/or intelligent navigation of trade-offers to enable rapid review of design options of interest.

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

Generative Design enables in-depth exploration of viable design options that previously could not be performed. 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, with the definition of the Generative Design problem being in context of their understanding and information available at that time, and by using terminology that is consistent with their design requirements, methodologies, and objectives.





“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 methodologies.

15. 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 personnel who are involved in the design process. Enabling broad accessibility to Generative Design methods is a key element 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 and 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

A CAPABILITIES ASSESSMENT MODEL

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 use cases, design space, performance objectives, and design constraints. This overturns the current practice of design, where designs are first be created so they can be evaluated subsequently against their performance requirements. This means that Engineering Simulation tools, developed for design evaluation, become the driver for design creation.

To achieve the envisioned 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 a designer faces every day for a wide range of design scenarios.

For Generative Design to be effective it must be well integrated into the designer’s workflow, with the definition of the Generative Design problem being in context of their understanding and information available at that time, and by using terminology that is consistent with their design requirements, methodologies, and objectives.

Currently, there is no Generative Design provider with capabilities that meet the desired state and full range of the desired capabilities outlined in this paper, especially over a wide range of design scenarios that is necessary to enable the desired paradigm shift. Therefore, it is recommended that a Generative Design Capability Assessment Model based on the fifteen (15) key capability areas outlined in this paper should be developed for assessing what is needed to enable a paradigm shift in the design process by leveraging Generative Design. Such an assessment model will also be beneficial to better understand:

1. The required Generative Design capabilities for the planned application scenario(s).
2. The current state of available Generative Design capabilities related to specific Generative Design Workflows
3. Determination of "Suitability" for potential Generative Design Workflows to provide the required capabilities for the planned application scenario(s).

The Generative Design Capability Assessment Model should provide a rating of capabilities or capability requirements across all of the fifteen (15) capability areas outlined previously in this paper. An initial pass at recommended criteria for ratings for each capability area is outlined in Appendix 1 of this paper. The criteria are designed to provide rating values from one (1) to five (5) based on the following scale.

1. Limited Capability
2. Basic Capability
3. Functional Capability
4. Advanced Capability
5. Comprehensive Capability

It is expected that the capabilities of a Generative Design Workflow and the requirements of a given application scenario may not meet or require all of the criteria at a specific rating level and may meet/require some capabilities at higher rating levels. The recommendation is that partial credit should be given for criterion that are meet/required and that a cumulative non-integer rating should be determined for each capability.

The Generative Design Capability Assessment Model could be used to understand and define the planned Generative Design application scenario specific capability requirements. The same Generative Design Capability Assessment Model could also be used to understand and evaluate the capabilities of one or more Generative Design Workflows.

To achieve the envisioned 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 a designer faces every day for a wide range of design scenarios.

Capabilities needed for the planned Generative Design application scenario

A paradigm shift requires a broad applicability over a wide range of Generative Design application scenarios. However, the ability to enable a significant process change and improvement for a specific application scenario only requires effective Generative Design support for that application scenario. The overall industry wide paradigm shift will occur when the process change to Generative Design is applicable for a wide range of application scenarios.

The process of implementing Generative Design starts with specific design scenarios. Using the Generative Design Capability Assessment Model to capture requirements allows the potential user of Generative Design to understand what capabilities are required to support their planned application scenario(s) and to compare those requirements to available capabilities from available Generative Design workflows.

The following illustrates two example applications of Generative Design.

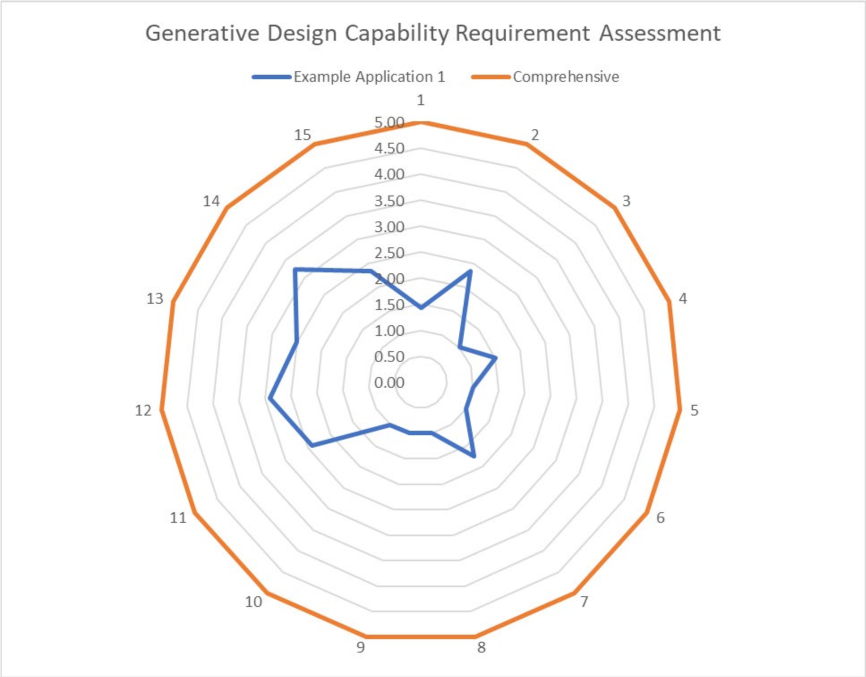
<u>Example Application 1</u>

Requirement: Design structural component concepts
Design objectives, assumptions and constraints:

- Response assumed to be static and linear
- Multiple possible materials
- Multiple possible manufacturing processes
- Planned User: Design Engineer
- Objectives of interest:
    - Minimize weight/mass
- Constraints of interest:
    - Stress or Safety Factor
    - Max displacement
    - Cost
    - Appropriate manufacturing constraints
- Uncertainties handled through increased Safety Factor
- No interest in Lattice options
- Integration with CAD is not important

Using the criteria outlined in Appendix 1 of this paper the following radar chart illustrates an example Generative Design Requirements Assessment for example application 1.

The overall industry wide paradigm shift will occur when the process change to Generative Design is applicable for a wide range of application scenarios.



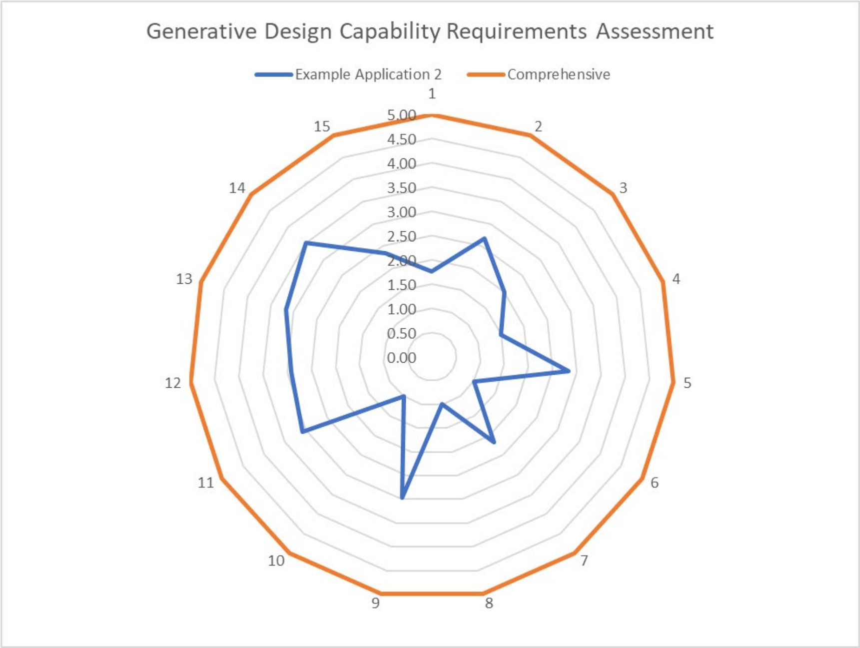
<u>Example Application 2</u>

Requirement: Design structural component concepts with temperature and vibration concerns
Design objectives, assumptions and constraints:

- Response assumed to be static and linear
- Multiple possible materials
- Multiple possible manufacturing processes
- Planned User: Design Engineer
- Objectives of interest:
  - Minimize weight/mass
- Constraints of interest:
  - Stress or Safety Factor
  - Max displacement
  - Max temperature
  - Min first natural frequency
  - Cost
  - Appropriate manufacturing constraints
- Uncertainties handled through increased Safety Factor
- Interest in Lattice options
- Integration with CAD is not important

Using the criteria outlined in Appendix 1 of this paper the following radar chart illustrates an example Generative Design Requirements Assessment for example application 2.

Using the Generative Design Capability Assessment Model to capture requirements allows the potential user of Generative Design to understand what capabilities are required to support their planned application scenario(s) and to compare those requirements to available capabilities from available Generative Design workflows.



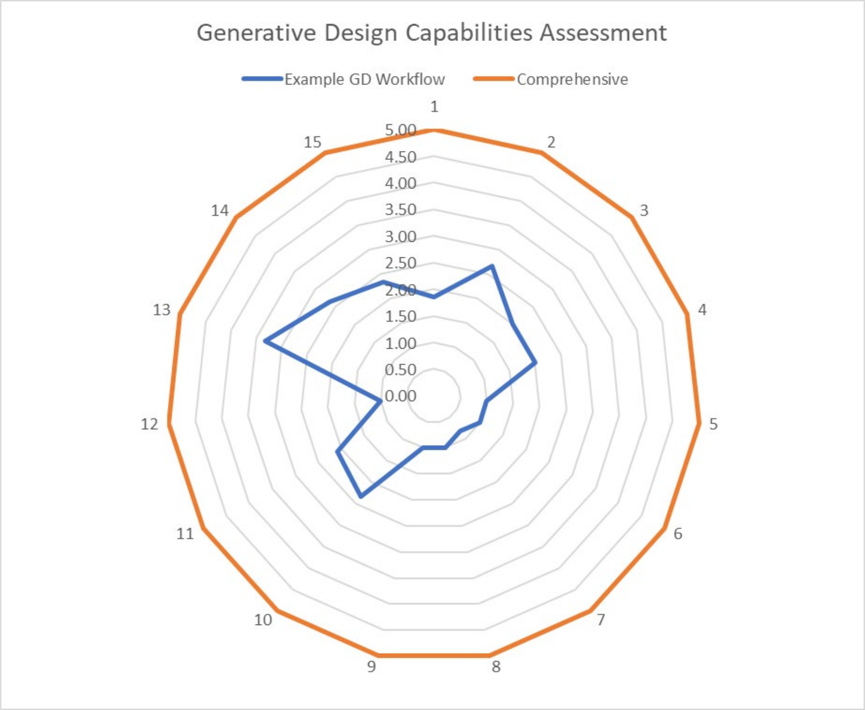
Each Generative Design provider currently offers capabilities that they believe are important to the overall community and that make their offerings unique.

Capabilities available from Generative Design workflows

The Generative Design workflows suggested by various software vendors may include one or more pieces of software and a piece of software may offer more than one Generative Design workflow. Using the Generative Design Capability Assessment Model to capture capabilities of different Generative Design workflows allows an understanding of; 1. The capabilities of different workflows, their competitive strengths and weaknesses, and suitability for potential Generative Design application scenarios.

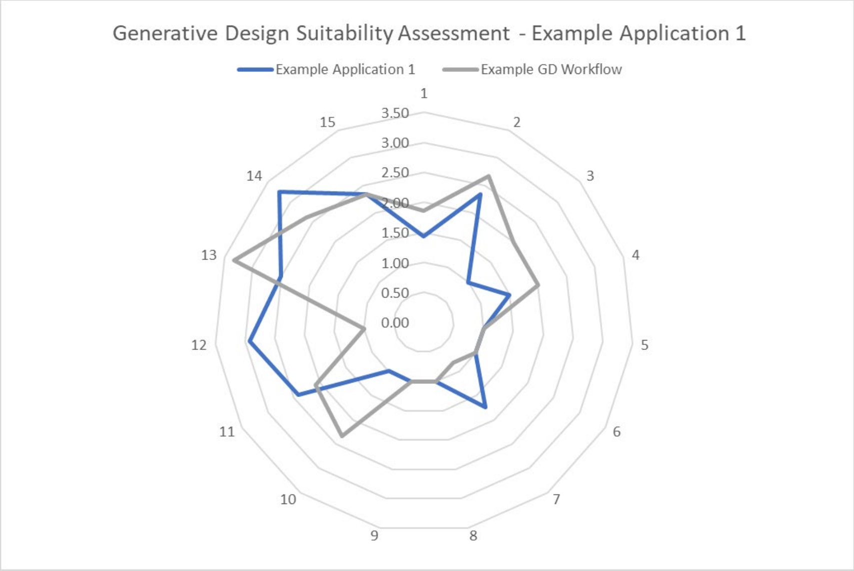
There is no Generative Design provider who currently meets the desired state of capabilities across the full range of the required capabilities outlined previously in this paper over a wide range of design scenarios necessary to enable the desired paradigm shift. Each Generative Design provider currently offers capabilities that they believe are important to the overall community and that make their offerings unique.

Using the criteria outlined in Appendix 1 of this paper the following radar chart illustrates an example Generative Design Capabilities Assessment for a sample Generative Design workflow.

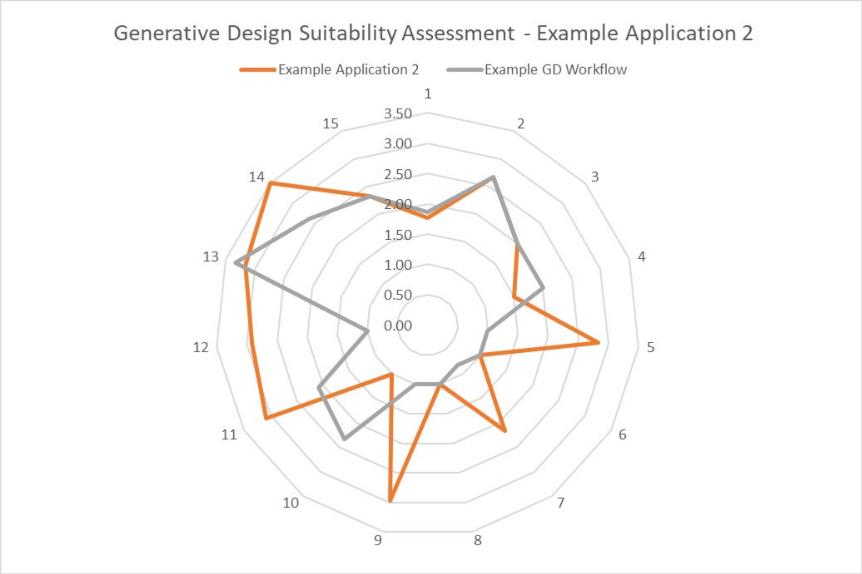


Generative Design Suitability Index

A Suitability Assessment can be performed by comparing the capability requirements assessment for a planned Generative Design application scenario with the capability assessment of potential Generative Design workflows. The purpose is to determine the suitability of the potential Generative Design workflow for the planned Generative Design application scenario. The following radar charts illustrates a comparison of the sample Generative Design workflow capabilities to the required capabilities in the example applications.



A Suitability Index can be calculated for each Generative Design category of capability by dividing each applicable workflow capability rating by the corresponding application scenario requirements value.



One possible approach for the Suitability Assessment is based on a quantifiable "Suitability Index." A Suitability Index can be calculated for each Generative Design category of capability by dividing each applicable workflow capability rating by the corresponding application scenario requirements value.

A Suitability Index of less than 1.0 indicates that the workflow is not appropriate to support the intended application scenarios. This approach results in the following three suitability qualifications for each application scenario:

- Clearly suitable
    - Minimum Suitability Index is equal to or greater than 1.0
- Possibly suitable 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 suitable
    - Mean Suitability Index is less than 1.0

This approach may result in having more careful review of the application capability requirements to ensure that they are not representing desired capabilities rather than required capabilities. Another approach could be to perform a Suitability Assessment separately against application scenario required capabilities and desired capabilities

Suitability Indices calculated for each capability area based on the Generative Design example application scenarios and sample Generative Design workflow previous mentioned in this paper.

A Suitability Index of less than 1.0 indicates that the workflow is not appropriate to support the intended application scenario(s). This approach results in three suitability qualifications as follows for each application scenario:

1. *Clearly suitable*
2. *Possibly suitable and needs further investigation*
3. *Clearly not suitable*

Sample Workflow Suitability Index	Application 1 Suitability	Application 2 Suitability
Handling all appropriate objectives and constraints	1.30	1.05
Handling multiple operational conditions	1.14	1.00
Handling multi-physics	2.00	1.00
Handling complex materials	1.33	1.33
Handling transitions from solid to lattice structures	1.00	0.35
Handling uncertainties	1.00	1.00
Handling multiple manufacturing/assembly/construction processes	0.48	0.38
Handling manufacturing process dependent materials	1.00	1.00
Handling cost as an objective or constraint	1.00	0.34
Handling Generative Design in an assembly / system context	2.33	2.33
Handling informed, comprehensive and efficient exploration of the viable design space alternatives	0.86	0.68
Enabling efficient and effective transformation to detailed validation	0.34	0.34
Enabling efficient selection guidance of design concepts generated	1.33	1.05
Enabling Generative Design within the designer's process, context & terminology	0.81	0.75
Enabling broad accessibility to Generative Design	1.00	1.00
Mean Suitability Index	1.13	0.91
Minimum Suitability Index	0.34	0.34

To be highly effective, Generative Design will require changes in who does the work and when it gets done along with fundamental changes in the product development process and the sequence in which product design decisions are made.

For Application 1, our example Generative Design workflow classification would be "Possibly suitable and needs further investigation."

- Mean Suitability Index (1.13) is equal to or greater than 1.0
- Minimum Suitability Index (0.34) is less than 1.0

For Application 2, our sample Generative Design workflow classification would be "Clearly not suitable."

- Mean Suitability Index (0.91) is less than 1.0

ORGANIZATIONAL AND CULTURAL CHANGES REQUIRED TO ENABLE A PARADIGM SHIFT

In this section the organizational and cultural changes required for implementing Generative Design methods broadly within an organization that involve people and processes are discussed. The shift to Generative Design can easily fail because people become resistant to learning new tools at the same time as implementing new ways (processes) to do their work.

Implementing the Generative Design vision described herein involves change in many dimensions. It will require management understanding and effective change management. To be highly effective, Generative Design will require changes in who does the work and when it gets done along with fundamental changes in the product development process and the sequence in which product design decisions are made.

Generative Design is a tool for design space exploration that can be used to maximum advantage in the early phases of design, where decisions on product packaging, configurations and architecture are being made. However, required resources (CAE expertise) are usually not deployed that early in the design process so a change is needed in the product development process to enable effective and reliable use of Generative Design to enable early phase design support.

As Generative Design matures and is more broadly deployed, it is anticipated that a variety of organizational and cultural issues that need to be overcome to enable a paradigm shift within any company will become apparent. The following outlines three key issues related to the deployment of Generative Design that are currently apparent and need to be addressed to enable a paradigm shift in the design process.

1. **Who will do the work (use the software)?**
   - Over the past two decades, Generative Design has generally been in the domain of CAE (Simulation) experts who thoroughly understand the tools.
   - More recently, Generative Design tools have been created that are aimed at a single user. These tools have enough CAD and CAE capabilities that treat enough manufacturing constraints that a single Generative Design expert, can complete the end-to-end process.

The inclusion of Generative Design in the early phase of design where it delivers the broadest benefit will require organizations to rethink roles, methods and processes which is likely to encroach on existing domains of expertise.

- Solution providers are now delivering Generative Design capabilities that may be standalone or embedded in CAD systems. This is an effort to "democratize" Generative Design and the use of simulation far beyond traditional specialists.
    - At many large corporations, "designers" are not engineers but they are responsible for creating component designs without being aware of the context of the design.
    - At smaller companies, individual engineers are often responsible for the entire process of design and release of a single product. They will require a suite of interconnected applications that allows them to effectively get their work done from initial design concept to detailed design.
- The inclusion of Generative Design in the early phase of design where it delivers the broadest benefit will require organizations to rethink roles, methods and processes which is likely to encroach on existing domains of expertise.
    - Simulation experts are needed initially to verify the underlying technologies and to enable reliable definition of the application scenarios.
    - A collaboration between simulation experts is required to develop confidence in the Generative Design capabilities
    - Once confidence in Generative Design methods has been established, those responsible for design can reliably leverage Generative Design for better design concepts.

2. Knowledge availability

To support a future Generative Design environment, organizations must have, or must have easy access to, expertise in the following areas:

- Simulation (multiple domains and disciplines)
- Design (CAD)
- Manufacturing
- Product requirements
- Statistics and Artificial Intelligence

Methods need to be developed by knowledgeable people to capture the information needed in each of the expertise areas to enable use by those without deep expertise across all the required knowledge areas.

Methods need to be developed by knowledgeable people to capture the information needed in each of the expertise areas to enable use by those without deep expertise across all the required knowledge areas.

- At large companies, resources are scattered across the company. Assembling a team to do a Generative Design project easily becomes a major endeavor, perhaps involving multiple vice-presidents.
    - It is recommended that large organizations should establish a Generative Design center of excellence to bring together the appropriate experts and develop a reliable method that supports broad deployment for Generative Design
- Smaller companies may simply not have experts in all these domains.
    - It is recommended that smaller organizations should leverage outside resources (consultants, software providers, …) to develop a reliable method that supports broad deployment for Generative Design

3. Governance of Generative Design methods and processes
Generative Design should be managed and governed as an integral part of an end-to-end design process from requirements to manufactured product with an emphasis on quality, reliability, and repeatability.

SUMMARY

The ASSESS Initiative has developed the following definition of Generative Design and highly recommends that end users, software vendors, industry analysts, and research organizations adopt this definition to enable a common understanding.

> ***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.***

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

The vision for Generative Design is to enable a significant paradigm shift in the design processes used today via the use of computer generated design options based on proper specification of use cases, design space, performance objectives, and design constraints. This overturns the current practice of design, where designs must first be created so they can be evaluated subsequently against their performance requirements.

The vision for Generative Design is to enable a significant paradigm shift in the design processes used today via the use of computer generated design options based on proper specification of use cases, design space, performance objectives, and design constraints.

Generative Design is not a particular algorithm or an optimization technology, 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 viable designs or outcomes for a specific design scenario.

A Generative Design Capability Assessment Model based on the key capability areas outlined in this paper with an initial pass at recommended criteria was proposed that covers fifteen (15) capability areas to assess what it takes to enable a paradigm shift in the design process by leveraging Generative Design.

Using the Generative Design Capability Assessment Model to capture requirements allows the potential user of Generative Design to understand what capabilities are required to support their planned application scenario(s). A Suitability Index for each Generative Design category of capability can be calculated by dividing each potential Generative Design workflow capability rating by the planned Generative Design application capabilities requirements value.

Making the potential paradigm shift enabled by Generative Design a reality will require both organizational and cultural changes and a broadening of available software capabilities to cover a broader range of design scenarios with Generative Design.

Generative Design represents the next big technology driver in the Engineering Simulation domain with a potential to enable a significant paradigm shift in how products, buildings, and infrastructure are designed via computer generation algorithms based on a proper specifications of use cases, design space, performance objectives, and design constraints. The application of Generative Design is just beginning and there are numerous challenges; however, the advances in the next decade are expected to be rapid, exciting, and transformative to the process of design.

Generative Design represents the next big technology driver in the Engineering Simulation domain with a potential to enable a significant paradigm shift in how products, buildings, and infrastructure are designed where designs are computer generated based on a proper specification of use cases, design space, performance objectives, and design constraints.

APPENDIX 1: RECOMMENDED CRITERIA FOR A CAPABILITIES ASSESSMENT MODEL

The following tables provide an initial pass at recommended criteria for each capability area in a Generative Design Capabilities Model for manufacturing applications. A similar set of tables outlining the criteria for AEC application should be developed.

1. 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
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

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 criterion
	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

2. Handling multiple operational 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

3. 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

4. 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
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

5. 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 design of lattice unit templates
	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 appropriate lattice templates or Mesostructural lattice
	Supports material distribution as an objective & constraint
	Supports automated generations of multiple lattice types

6. 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 criterion
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

7. 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 casting related constraints
	Supports forging related constraints
	Supports 2 axis milling 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
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

8. 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

9. 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

10. 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

11. Enabling informed, comprehensive and efficient exploration of the 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

12. Enabling efficient and effective transformation to detailed validation	
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 facetted data in modeling
	Supports semi-automatic generation of geometric format (Subd or NURBS) or use of facetted 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
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

13. Enabling efficient selection guidance of design concepts generated	
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

14. 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
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

15. 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

