LOCKHEED MARTIN GPS SATELLITE BRACKET – DESING INNOVATION TEAM

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Abstract

With the emergence of Additive Manufacturing (AM), engineers now have an entirely new manufacturing process to consider when developing a new product or redesigning an existing part. Engineers who are well versed in traditional manufacturing techniques will realize that AM is completely different and will need to learn how to design for additive manufacturing (DfAM).

The Design Innovation (DI) team researched scholarly articles to find basic principles about AM and building 3D printed objects. The DI team also directly observed a senior design group as they redesigned a satellite bracket. This was done to gain further insight and information into the AM process. The team's redesigned bracket reduced weight, part count, and fastener count for the Lockheed Martin GPS III Satellite. The DI team was able to extract design and AM principles that relate directly to the additive manufacturing process. These principles were combined with a general design methodology from the U.K. Design Council, called the 4D's, to create a novel design framework to help engineers with DfAM.

The Discover, Define, Develop, and Deliver (4D) process focuses on user centered design work that spurs innovative and creative designing. The Discover phase gathers information through direct contact with stakeholders and users. The Define phase analyzes the information to find root needs for the project through modeling methods. The Develop phase uses creative methods to identify numerous solutions for the project and the Delver phase focuses on prototyping the best solution to create a final product for testing and evaluation. The framework serves as a guide for the entire design process and contains information disseminated through documents, learning modules, and videos. The framework is self-contained and utilizes MindManager software that is easy to follow and navigate. The user was able to quickly view and access all the topics and information. The framework was successful at giving an engineer, familiar with currently used computer aided design (CAD) software, the means to create designs that can be successfully built on a Direct Metal Laser Sintering (DMLS) additive manufacturing machine. The framework was especially helpful in offering engineers a methodology that helped them through all phases of the design process. This framework can be applied to many different types of projects and offers engineers specific information and guidance about designing for additive manufacturing.

Overview

An overall design strategy was needed to help guide the group through the process of redesigning the satellite bracket. With many design strategies to choose from, Design Council's 4D methodology was chosen for its worldwide use over a broad range of disciplines. They also provide excellent documentation on how to best apply their methodology along with feedback from many people who have used the 4D's [1]. In addition to Design Council's methods, other researchers have contributed numerous methods to assist designers in the 4D process. All of this information creates added value to the design process and greatly aids designers including DfAM.

AM principles and practices were garnered from a two-pronged approach. First, they were researched from scholarly papers and articles, which are primarily based on additively manufactured objects from computer aided design (CAD) files [2]. Second, there is direct observation and analysis of both the design and printing processes in creating the satellite bracket. Using both direct and indirect vantage points allowed for a greater examination of the elements needed for DfAM. The AM principles used in the framework are geared more toward the use of a powerful DMLS machine, which uses a powder metal (PM) that is melted by a laser to create the bracket.

To disseminate the acquired information for DfAM, in an easy to understand and user-friendly manner, a tool was created. The tool serves as both the guide and access point for the DfAM information and also helps the designer navigate through the entire design process from start to finish. MindManager software was used as the platform to create the tool because it offers quick accessibility to all of the documentation and instructional information associated with DfAM. The software is also amenable to formatting a flow design for the tool and supports a variety of files that can be accessed directly.

4D Design Method

The design innovation element of this framework is based on, and adapted from, Design Council's Double Diamond and its subsequent 4 steps approach to design. This model offers design teams a strategy to progress through the entire evolution of product development. With millions of references to the Double Diamond on the internet, and testimonials from users, this model has had great success since its inception in 2004 [3]. Using various methods information is gathered, processed, and applied throughout the entire design process. The methods employed come from Design Council and a set of design method cards [2].

The four key phases, known as the 4D's, is a series of focused exploration in particular aspects of the design process. Each phase uses convergent or divergent thinking when exploring a project opportunity. Divergent thinking looks at a broad view and takes into consideration many different ideas, possibilities, sources, formulations, etc. Convergent thinking takes the divergent information and focuses that information into a distinct design, plan, or action [3].

The starting point in this design method is with the Discover phase. The Discover phase helps designers gain understanding and information about a project opportunity. The mindset of the designers during this phase is one of empathy which will help foster communication between designers and stakeholders. Empathy leads to being open minded and in turn aids designers to think in a divergent manner [2]. Divergent thinking allows for better understanding of project opportunities through collaboration with stakeholders [5].

The second phase is the Define phase, which converges information from Discover to formulate defining factors about the opportunity. The defining factors will allow designers to view the opportunity in a new and creative way. A mindfulness mindset will lead the design team into a narrowing focus to get at the heart of what is needed in the project opportunity and why.

The third phase is the Develop phase, which takes the narrowed and focused definitions from the Define phase and produces many ideas and potential designs for the project opportunity. Similar to the Discover phase, divergent thinking is used to gain many possible solutions. Here, a joyful mindset is needed which allows talking with many different people about the ideas and designs. The following action is to select the best possible solutions.

The fourth phase is the Deliver phase, where testing and evaluating prototypes of different solutions from the develop phase is performed. A non-attachment mindset is used to objectively eliminate designs that will not work and continue to iterate designs that are acceptable. Collaborating and co-creating with stakeholders is encouraged to find potential risks and to gather feedback about the solution [5].

The 4D process, shown in Fig. 1, with added mindsets for each phase, illustrates convergent and divergent thinking. Starting at the left divergent thinking begins with discovery where designers explore a project opportunity using many different methods. The Define phase follows, using convergent thinking, to narrow the information and interpret what is needed in the design opportunity. This pattern of divergent and convergent thinking is repeated in the second diamond where the develop phase creates and entertains all possible solutions and the Deliver phase narrows the solutions to a single prototype.

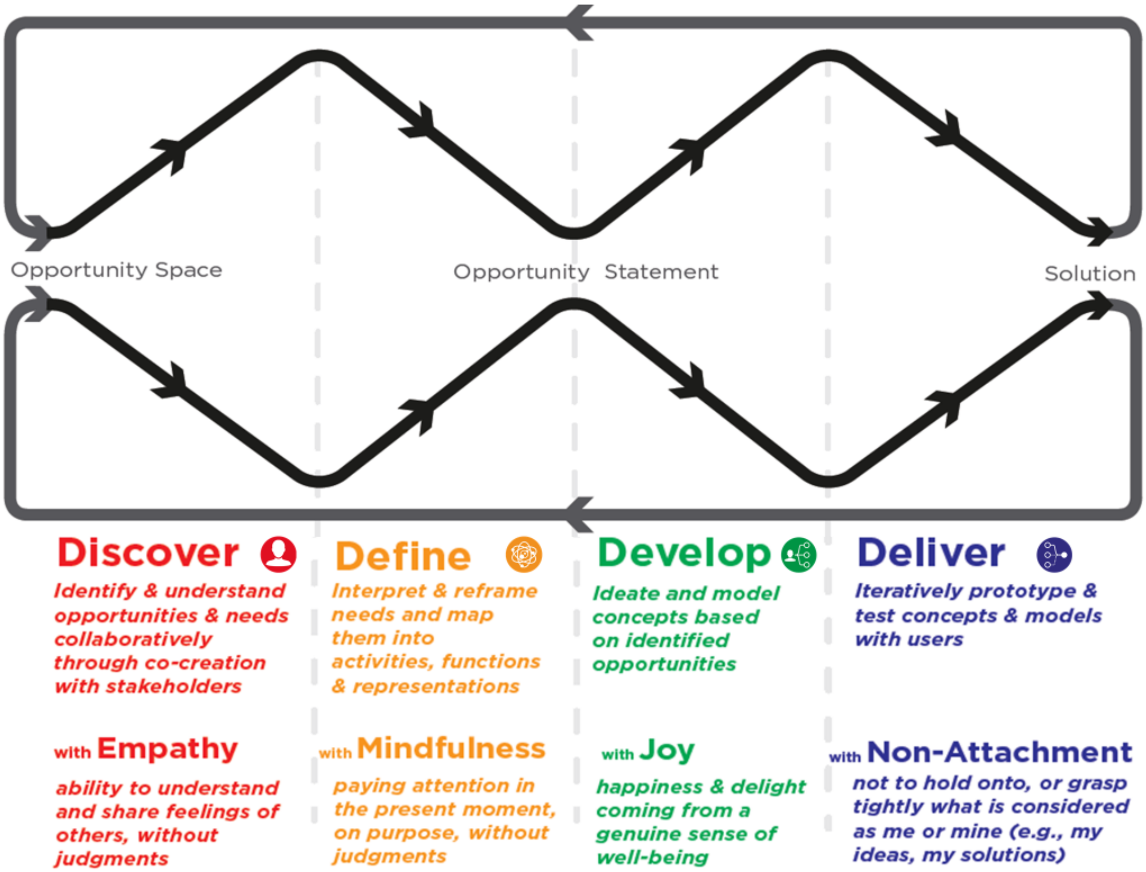


Figure 1: *Modified version of U.K. Design Council's Double Diamond (4D) design method [2].*

AM Principles

Due to recent advances in 3D printing machines, especially with powder metal DMLS machines, there is limited information available about fundamental characteristics of 3D printed parts. With new models of machines coming out continually there is difficulty in evaluating what is truly a fundamental principle and what could be a hurdle that will eventually be overcome with refinement and advances of the 3D printing machines. Combining advances in the machines with continued research into the production of new and superior material for printing, the challenge of finding true AM principles is compounded.

When considering the DMLS process, there are some basic realities that can not be avoided due to the nature of the material and the process of turning a powder metal into a solid metal object. For example, a metal base is needed for the build to begin and is a fundamental part for the build to proceed. The printed part is metallurgically adhered to the build plate and must be removed by some type of mechanical means. This leads to principles based on knowledge that separating or cutting metal requires the removal of material and leaves the part in need of surface finish processes. Orientation of the part, so that delicate features are not adhered to the build plate, is considered an AM principle [2]. Delicate features will be at the mercy of a saw blade, or at the very least some type of material removing machine and could be damaged as a result. There are, however, a few other types of 3D printing machines that do not require a base plate for a build to be adhered to, and therefore would not be restricted by this AM principle. Those machines do not use metal as a material to form the part and would have different applications than the products of DMLS machine. This example describes why it is difficult to state, with absolute certainty, that any AM principle is one that is ubiquitous throughout all AM processes [2].

It is reasonable to expect that AM principles will vary to some degree with different machines and processes but knowing that there are principles guiding each process allows for better designing. A design principle, is that AM centric, is rapid prototyping, which is typically an expensive and time-consuming aspect of the design process. The ability to quickly and effectively produce a part, for testing and evaluating, yields the opportunity to create multiple revisions, or iterations, on the part. This allows a design team to realize potential failure points and offers direction on where further design refinement is necessary.

AM was formerly synonymous with rapid prototyping until recent advances have pushed AM toward a viable and profitable means of production [2]. The fact that AM has multiple functions, reveals the importance of investigating all AM processes for distinct principles. These principles will help direct instruction on the use of AM machines as well as the design work involved with AM.

Framework

The design innovation framework, shown in Fig. 2, is a tool designed to guide engineers through each of the 4D phases. The purpose of the framework is to have structured steps and guidelines that are needed to understand and frame the problem in an approachable way. It provides structure to the entire design innovation process with topics and subtopics arranged in sequence. A process mapping software called MindManager was used to create this framework. This software allows concepts, projects, processes or plans to be placed within structured and interactive visual maps that make information easy to understand, adapt and share.

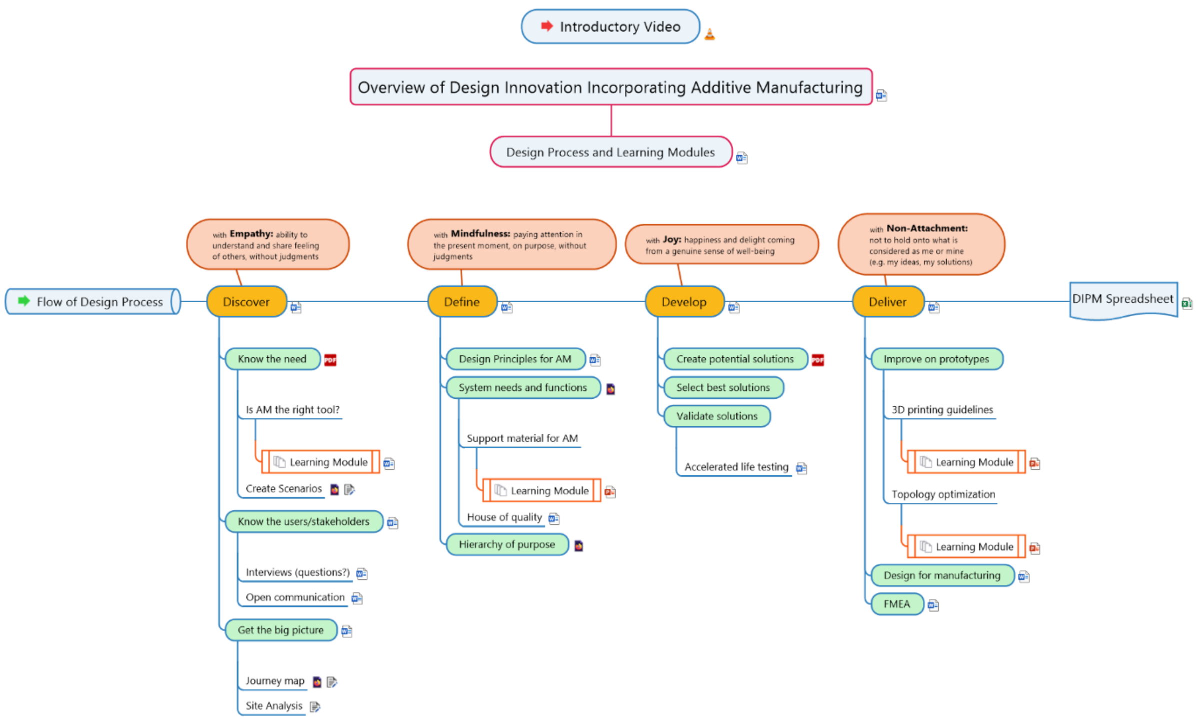


Figure 2: *Design Innovation Framework.*

The framework consists of an overview of the design process, methods, principles and learning modules, associated files and links, in a single user-friendly interface. It starts with an introductory video that provides background information about the framework and instructions on how to use the software. The structure of the framework includes the 4D phases in sequence from left to right as main topics. The information inside the red oval bubbles, above each of the 4D phases, are the recommended mindsets that users need to have during that phase. Each of the 4D topics include subtopics represented by the tree map below it. The subtopics provide details and guidelines on how to execute each of the design phases. The icons, located on the right side of each topic, are links for accompanying documents, online resources and learning modules.

A framework prototype was operated by members of the group and evaluated based on its ease of use and informational quality. Feedback from the members was considered and the framework was enhanced accordingly through iterations until a final product was produced.

Appendix A includes all the documents that can be accessed from the main framework shown in Fig. 2.

Learning Modules

Learning modules cover a key subset of the design methods guiding the user on how to execute them. The learning modules include an overview of the method, procedures, best practices, tool or demo video and examples. The four learning modules included in the framework are as follows:

1) Is AM the right tool?

2) Support Material

3) 3D Printing Guidelines

4) Topology Optimization

The learning module for "Is AM the right tool?" provides information on advantages and disadvantages of AM and guides the user on when to choose additive manufacturing instead of traditional methods. It also contains design parameters to consider for AM along with example pictures for clarity.

The "Support Material" learning module (last page shown in Fig. 3) provides details on why support material is needed in 3D printing and how the supports are oriented within the build structure. It includes a video with several examples of support material structure and the Lockheed Martin Satellite Bracket printing using M290 metal 3D printer that shows how support material is layered during the printing process.

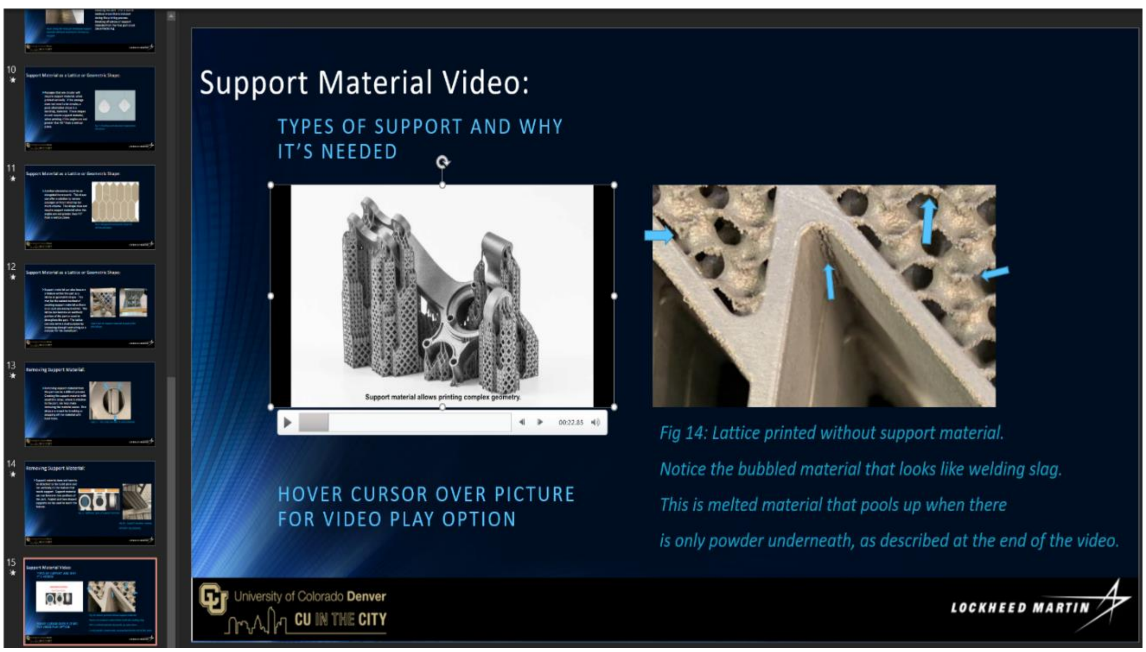


Figure 3: *Snapshot of Learning Module for Support Material showing the embedded video.*

Similarly, the learning module for 3D Printing Guidelines is a fundamental checklist that aids engineers in creating a successful build by avoiding potential failure points which would cause an unsuccessful build. This learning module was created from the direct observation in the production of Lockheed Martin Satellite Bracket prototypes. The topics within the learning module includes build volume, part removal from the build plate, overhangs and support material, part orientation, printing tips for loose powder base fusion machine and build time.

Design Innovation Process Mapping

Apart from the 4D design phases, the framework also includes a design innovation process mapping (DIPM). DIPM is a tool that tracks completed activities and projects it to each 4D category, represented by 4 quadrants, creating a map that shows iterative nature of the design process. This idea was originally developed at the Singapore University of Technology and Design and was labeled "Design Signatures" [6]. The distance from the origin indicates the amount of time spent on a particular activity. Increased distance from the origin represents more time spent on an activity. The four quadrants are represented by each of the four phases of the design process.

Design activities are entered into a excel spreadsheet template which are then linked chronologically, starting at the origin, and plotted into 4 quadrants based on which of the 4Ds that method or activity is associated with. The total number of hours spent on each quadrant are automated which updates as the user inputs the information regarding the activity. It shows when, and how much time, was spent at the different phases of the design process as well as the movements between phases. This provides a visual representation of the entire project which gives meaningful design information and insight that can be extracted and used for future design.

Figure 4 shows the DIPM for Lockheed Martin Satellite Bracket design capstone project. The figure shows that this Lockheed Martin Satellite Bracket capstone project had a heavy focus on Discover and Develop phase totaling 66% of the time spent on the entire project. This is a result of extensive amount of time spent on learning the M290 metal 3D printer to develop the successful build and the several iterations of topology optimization to reduce the weight of the bracket without compromising it's strength that are needed to meet the specification. The figure also shows the activities connected by the curved lines that move from one quadrant to another in a sequence. However, the lines showing chronological sequence are not automated in the excel plot but are drawn manually as the project progresses to various phases. Moreover, the phases (Ds) and activities in general, are almost always repeated and the movement from one phase to another is not entirely sequential. For example, in Fig. 4 there are jumps from Discover to Define as well as to Develop phases. It can also be used to shows how a team might need to shift backwards in the design process, such as going back to the discovery phase when prototype testing showed an undesired effect.

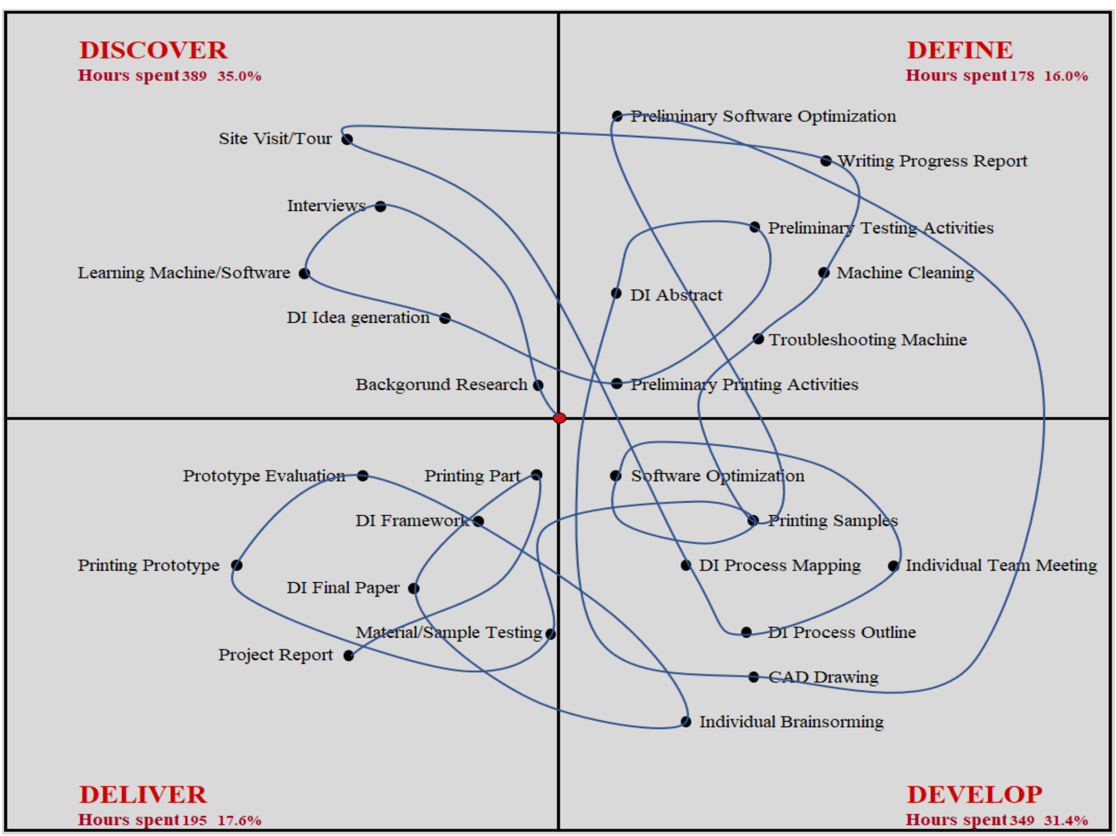


Figure 4: *DIPM – Lockheed Martin Satellite Bracket Design Capstone Project.*

Conclusion

The design innovation framework contains all aspects of the design innovation process and integrates a proven design methodology, the 4D's, with fundamentals of AM principles in a user-friendly interface. Guided by the Lockheed Martin Satellite Bracket design capstone project, this framework includes several documents, videos, pictures, and tools that are useful for designers, researchers and engineers looking to learn and develop skills in design process using additive manufacturing techniques. Assessment of the framework, although somewhat informal, has been very positive. Both faculty and students found the framework to be easy to use and to contain valuable, useful information as they endeavor to add AM capabilities to a design innovation process.

This framework can be further elaborated and simplified using more learning modules. Furthermore, the interactive nature of this framework can only be utilized if the software is available for the users. Looking at the future, once more learning modules are added to the framework, we would like to research using display monitors with touch screens to make the framework more user friendly and easily accessible.

PROJECT CONCLUSION AND ACKNOWLEDGEMENTS

Liz Roshkovskiy

Throughout the last two semesters, our group, composed of four sub-teams, successfully produced two different GPS satellite bracket designs for Lockheed Martin. The final product of our work included the digital bracket designs and a detailed evaluation of the software packages used to create them, physical models of each design and resources for effective design for additive manufacturing, thorough testing of the properties of the material used, and tools and learning modules to assist in the application of design innovation to the additive manufacturing process.

The collaboration between CU Denver and Lockheed Martin resulted in a unique opportunity for our team of students to immerse themselves in a real-world application of the skills they had acquired throughout their academic careers. We were able to interact with professional engineers and gain a better understanding of their methods and practices. The ability to receive direct feedback from our end-users throughout the duration of the project was immensely helpful in allowing us to iterate and improve our work to create two successful bracket systems that met all initial criteria.

We are tremendously thankful to Lockheed Martin for sponsoring our project and providing resources for our success, especially Brian Kaplun, Bob Rauscher, and Joe Block, who assisted us in our progress by continuously offering feedback and suggestions. We are very grateful to the UCD Mechanical Engineering Department, particularly Marty Dunn and Kris Wood for their efforts in facilitating the partnership with Lockheed Martin in order for us to have the opportunity to work on such a unique project. We would also like to express our sincere gratitude for our faculty mentors and advisor, particularly Chris Yakacki and Dan Jensen, who were critical to our success, as they provided guidance and assistance whenever it was needed. Additionally, the campus staff who oversee the mechanical engineering hub and the additive manufacturing lab, including Jac Corless, Tom Thuis, and Nick Diamond, were extremely helpful in teaching us to properly use any necessary tools and assisting us in our efforts.

APPENDICES

Design Innovation Appendix A

All documentation contained in this report is for educational purposes only, and not meant for public distribution or consumption. The pictures and music contained in the report and supporting documentation was gathered via internet access and is considered available for normal use.

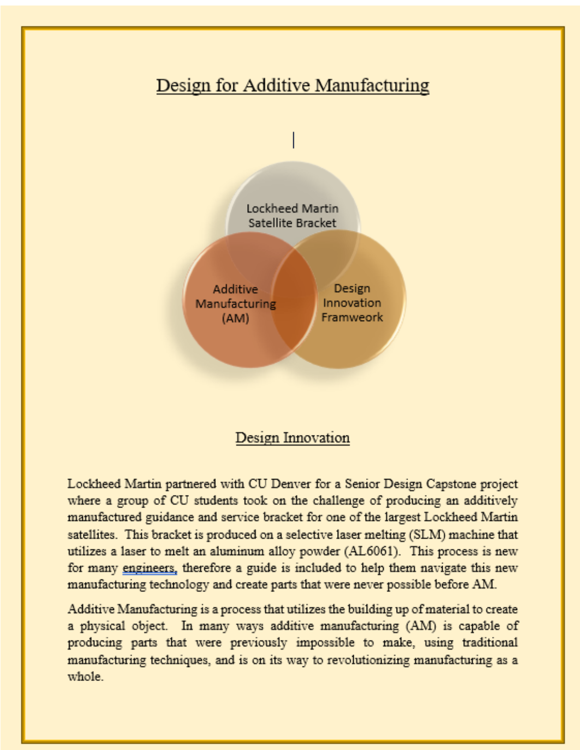
Framework Introduction

Introduction to DI Video

Introduction to DI.mp4

Design Innovation Title

Design Innovation Title.docx



Design for Additive Manufacturing

Design Innovation

Lockheed Martin partnered with CU Denver for a Senior Design Capstone project where a group of CU students took on the challenge of producing an additively manufactured guidance and service bracket for one of the largest Lockheed Martin satellites. This bracket is produced on a selective laser melting (SLM) machine that utilizes a laser to melt an aluminum alloy powder (AL6061). This process is new for many engineers, therefore a guide is included to help them navigate this new manufacturing technology and create parts that were never possible before AM.

Additive Manufacturing is a process that utilizes the building up of material to create a physical object. In many ways additive manufacturing (AM) is capable of producing parts that were previously impossible to make, using traditional manufacturing techniques, and is on its way to revolutionizing manufacturing as a whole.

Design Innovation (DI) is a process and associated methods that assist designers to create innovative products. Design teams follow the overall process, implementing chosen methods during each step. Adhering to the DI process is instrumental in creation of novel designs. The DI aspect utilizes a methodology garnered from the U.K. based Design Council. Their Double Diamond framework for DI contains four phases, Discover, Define, Develop, and Deliver[1] which has been dubbed the 4D's. Within the DI framework, each of the D's in the process is matched with various methods. These four elements are clearly labeled and set the flow pattern for the overall framework. Information about the 4D's is provided independently and in conjunction with AM principles.

This framework is built on the combination of two separate platforms, DI and AM principles, which gives engineers an overall process to follow. Design Innovation for Additive Manufacturing (DIfAM) is the result of this coordinated effort. It is a tool for engineers that facilitates the design process from the initial understanding of a need to a final result. This seemingly linear progression is anything but a simple connect the dots pathway to success.[2] Creating the most optimum design on the first try is a rare thing and in design work it is never heard of. Many iterations are necessary throughout the entire process to come out with an acceptable product.

References:

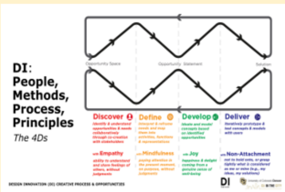
[1]https://www.designcouncil.org.uk/news-opinion/double-diamond-universally-accepted-depiction-design-process

[2]https://www.designcouncil.org.uk/news-opinion/double-diamond-15-years

Design Innovation Process

Design Innovation Process.docx

Design for Additive Manufacturing



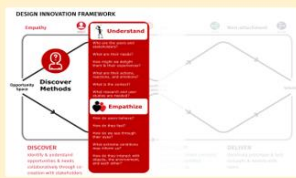
Design Innovation Phases

The design innovation element of this framework is based on Design Council's Double Diamond and its subsequent 4 steps approach to design. This adaptable model offers design teams a strategy to progress through the entire evolution of product development. With millions of references to the Double Diamond on the internet and testimonials from users, this model has had great success since its inception in 2004.

The four key phases, known as the 4D's, is a series of focused exploration in particular aspects of the design process. Each phase uses convergent or divergent thinking when exploring a project opportunity. Divergent thinking looks at a broad view and takes into consideration many different ideas, possibilities, sources, formulations, etc. Convergent thinking takes the divergent information and focuses that information into a distinct design, plan, action, etc.

Discover

Discover phase helps designers gain understanding and information about a project opportunity. Using methods and a work environment that fosters communication and ideation, not only amongst themselves but also with stakeholders, helps designers to think in a divergent manner about a project opportunity.



Define

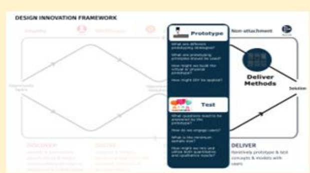
Define phase converges information from discovery to formulate defining factors about the opportunity. This allows designers to visualize the project opportunity in a way that allows for fruitful designs and ideas to take shape.

Develop

Develop phase takes the narrowed and focused definitions of the project opportunity and accumulates many ideas and designs. Talking with many different people about the ideas offers divergent thinking and is critical to gain different viable options.

Deliver

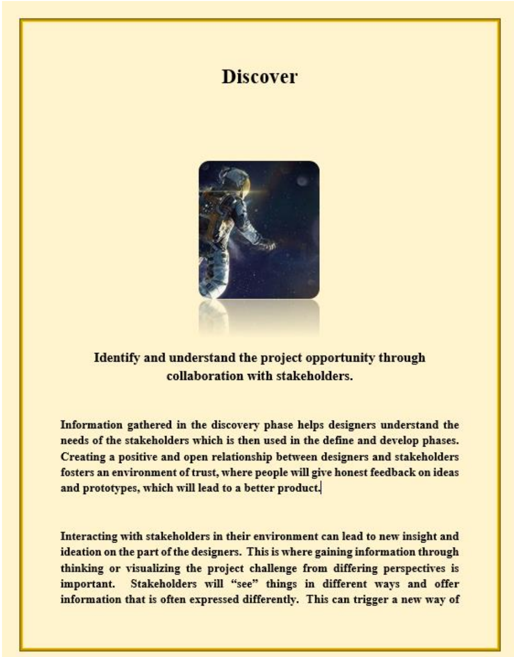
Deliver phase, tests the different solutions from the develop phase. Eliminating designs that will not work and continuing to iterate designs that are potentially acceptable.



Discover

Discover Bubble

Discover Bubble.docx



Discover

Identify and understand the project opportunity through collaboration with stakeholders.

Information gathered in the discovery phase helps designers understand the needs of the stakeholders which is then used in the define and develop phases. Creating a positive and open relationship between designers and stakeholders fosters an environment of trust, where people will give honest feedback on ideas and prototypes, which will lead to a better product.

Interacting with stakeholders in their environment can lead to new insight and ideation on the part of the designers. This is where gaining information through thinking or visualizing the project challenge from differing perspectives is important. Stakeholders will "see" things in different ways and offer information that is often expressed differently. This can trigger a new way of

looking at the challenge which helps designers dispel preconceived notions. Instead of a narrow train of thought, designers should strive to open minded and consider all information as valuable. This can be related to police investigations, where a piece of evidence may be dismissed by investigators because it seems irrelevant and place their focus on other things. When a case goes unsolved for a long period of time, new investigators pick up the file and begin to look at everything with open mindedness. Everything is viewed as important and all information is considered valuable and worthy of investigating.

Designers should get to know their stakeholders and try to develop a good rapport with trust and respect at the center. This is one of the best ways for designers to gain the level understanding of what is needed and why. Information tends to flow more freely where people are in a secure setting and feel comfortable talking to each other.

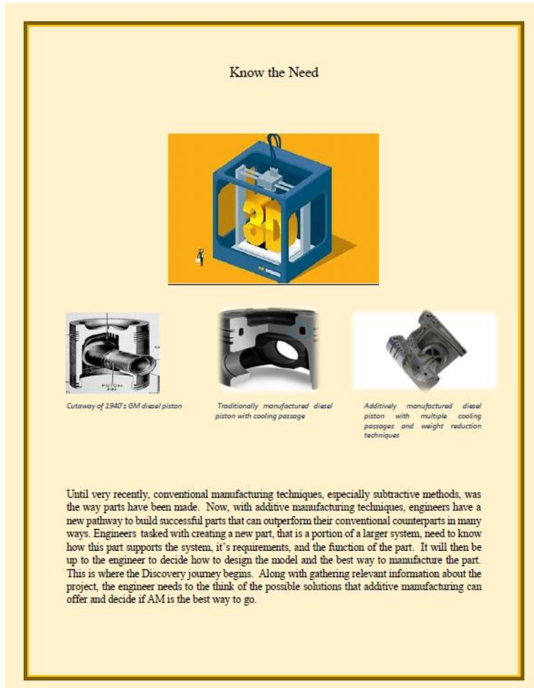
There are many different methods that can be used to help gather and elicit needed information to gain understanding about a project challenge. Some methods are listed on this framework and others can be found on the internet through a general search. Design Council also offers a number of methods used for discovery which can be found on their website:

https://www.designcouncil.org.uk/news-opinion/design-methods-step-1-discover

Another set of methods are printed on a set of handheld cards developed by the fine folks at CU Denver and The Singapore University of Technology and Design. They can be acquired through the department of Mechanical Engineering.

Know the Need

Know the Need.pdf


Know the Need

Cutaway of 1940's GM diesel piston

Traditionally manufactured diesel piston with cooling passage

Additively manufactured diesel piston with multiple cooling passages and weight reduction techniques

Until very recently, conventional manufacturing techniques, especially subtractive methods, was the way parts have been made. Now, with additive manufacturing techniques, engineers have a new pathway to build successful parts that can outperform their conventional counterparts in many ways. Engineers tasked with creating a new part, that is a portion of a larger system, need to know how this part supports the system, it's requirements, and the function of the part. It will then be up to the engineer to decide how to design the model and the best way to manufacture the part. This is where the Discovery journey begins. Along with gathering relevant information about the project, the engineer needs to the think of the possible solutions that additive manufacturing can offer and decide if AM is the best way to go.

Learning Module (Is AM the Right Tool)

Learning Module (Is AM the right Tool).dc


Is AM the Right Tool?

Why? Quality AM machines are sophisticated and expensive. They are designed to create parts that can have internal features and complex geometries that would be impossible, or egregiously time consuming, when made by conventional means. Making simple parts, other than for testing purposes, is not utilizing the machine to its full potential and wastes valuable printing time.

Figure 1: Selective Laser Melting (SLM) machine

What? Avoid making parts using AM simply because they can be made by AM machines. AM is a great option for producing parts, however, it is not always the appropriate machine to use. AM machines tend to have long build times and limited space per build, therefore, any part made by AM should utilize the full capability of the machine. Parts that can be manufactured quickly and cost effectively by traditional methods should not be additively manufactured.

Figure 2: Conventional CNC machine

Procedure:

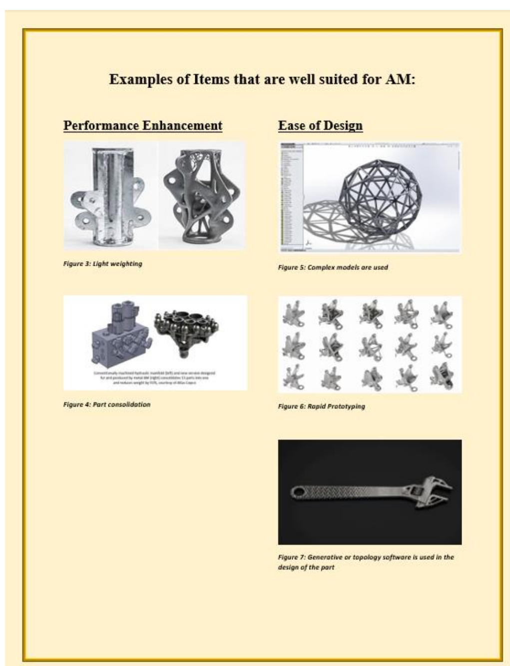
Determine the reason for using AM (use list and flowchart).

Decide if the reasoning is appropriate.

Best Practice:

Avoid using AM just because it can be used.

Explore other options before deciding to use AM, as cost must be considered.


Examples of Items that are well suited for AM:

Performance Enhancement

Figure 3: Light weighting

Figure 4: Part consolidation

Ease of Design

Figure 5: Complex models are used

Figure 6: Rapid Prototyping

Figure 7: Generative or topology software is used in the design of the part

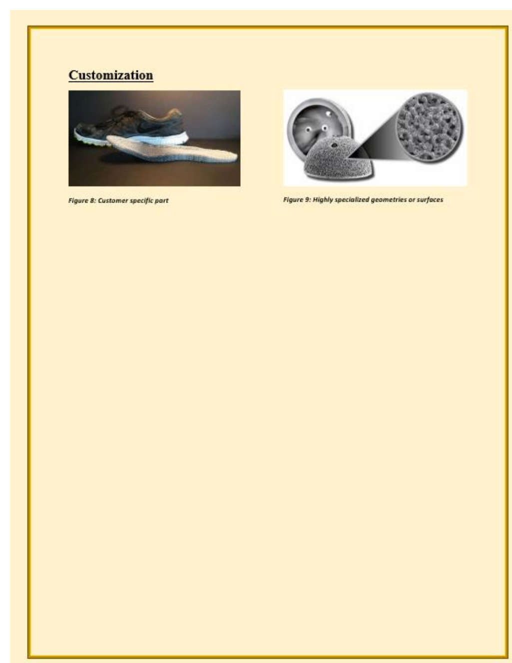

Customization

Figure 8: Customer specific part

Figure 9: Highly specialized geometries or surfaces

Examples of Items that may exclude use of AM:

Easy Conventional Production

Large Parts are needed

Figure 10: Easily machined parts

Figure 13: Large solid volumes are required

Figure 11: Parts can be made quickly and effectively at a low cost

Figure 14: Overall part size exceeds the build volume of the AM machine

Figure 12: Commercially available mass-produced parts

Figure 15: Lead time for machined parts is excessive

Is AM the Right Tool?

Additive manufacturing is very well suited for producing parts that were once impossible to make by conventional means. However, this does not mean that AM can produce anything an engineer can dream up. As with any manufacturing process there are limitations and trade-offs to consider when using AM. Limitations of AM processes could indicate that a different manufacturing process should be used. Creative design work in the CAD model, or part orientation on the print bed, can remedy obstacles that will seem to stymie a print from proceeding. However, there are some situations where there will be a go, or no go, for a part to be produced by AM methods. The categories and pictures above show some of the more typical reasons that AM should or should not be used. Below, are some diagrams of situations that may not readily present themselves at the onset of design work. While some of the criteria can be applied to different AM processes, all of these diagrams can be used for the SLM process.

Design Parameters to Consider for AM using SLM, Powder Bed Fusion Process

Part is required to have an enclosed hollow volume

No

AM

YES

TRADITIONAL

When printing with a powder metal fusion machine, also called selective laser melting, DO NOT leave volumes that appear hollow in the CAD model. Any hollow volume will contain powder when the model is printed on the machine and cannot be removed. A post build machining process may cut into the volume or some unforeseen breach of the volume could occur. Breaching the enclosed volume would result in an abrupt release of the contained powder that can be harmful when inhaled or if it comes in contact with the eyes.

These volumes may be a bubble that can only be seen with "see through views" of the CAD model. Enclosed volumes can occur when adding lattices or other features to a defined surface in the CAD design. The powder filled bubbles could potentially affect part performance, depending on the application. To find and eliminate any enclosed volumes, specialized software, such as Mesh Mixer, can be used on the CAD model. This software is easy to use and can repair imperfections in the model as well as smoothing surfaces of a generative design.

Support material can be removed without part damage

No

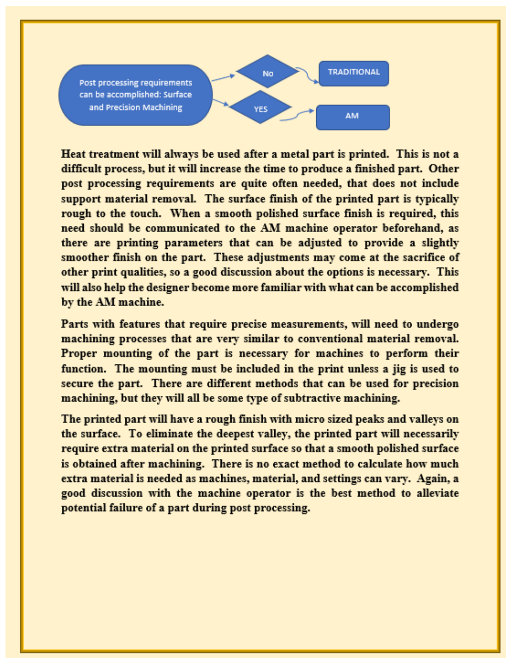
TRADITIONAL

YES

AM

Support material is a very common requirement for a successful build. Removing support material can be a challenge and needs to be considered during the design process. When support material is required, it might be possible to design the part so that the material does not need to be removed. Think about this option, as there are support designs that can be used to increase strength, damping, and aesthetics as well as supporting other features of the part. Lattices are an excellent option, as there are different styles to choose from and each one has its own set of characteristics.

Typically, support material is removed by a conventional subtractive method during post processing of the part. When this option is used, careful attention is needed when developing the CAD model to allow for machine operations. This includes providing proper securement of the part during post processing. A flat surface is often needed along with mounting holes, unless a special jig is to be made to secure the part for machining. Tool paths are also necessary to reach and fully remove support material. Knowing what type of machine can be used in this post process operation is very helpful, so that a design isn't rejected before printing, or worse, after it has been printed and sent off to a machine shop.



Post processing requirements can be accomplished: Surface and Precision Machining

No

TRADITIONAL

YES

AM

Heat treatment will always be used after a metal part is printed. This is not a difficult process, but it will increase the time to produce a finished part. Other post processing requirements are quite often needed, that does not include support material removal. The surface finish of the printed part is typically rough to the touch. When a smooth polished surface finish is required, this need should be communicated to the AM machine operator beforehand, as there are printing parameters that can be adjusted to provide a slightly smoother finish on the part. These adjustments may come at the sacrifice of other print qualities, so a good discussion about the options is necessary. This will also help the designer become more familiar with what can be accomplished by the AM machine.

Parts with features that require precise measurements, will need to undergo machining processes that are very similar to conventional material removal. Proper mounting of the part is necessary for machines to perform their function. The mounting must be included in the print unless a jig is used to secure the part. There are different methods that can be used for precision machining, but they will all be some type of subtractive machining.

The printed part will have a rough finish with micro sized peaks and valleys on the surface. To eliminate the deepest valley, the printed part will necessarily require extra material on the printed surface so that a smooth polished surface is obtained after machining. There is no exact method to calculate how much extra material is needed as machines, material, and settings can vary. Again, a good discussion with the machine operator is the best method to alleviate potential failure of a part during post processing.

Know the Stakeholder

Know the Stakeholders.docx

Know the Stakeholders

With different experiences and backgrounds, engineers will bring perspectives, thoughts, ideas, and a direction about a project. However, everyone should try to avoid taking any preconceived notions or ideas into the project. Try to get at the heart of the project opportunity by getting to know the needs, desires, and wants of the stakeholders. At times the stakeholders will believe they know the best way to proceed with a project; and unwittingly focus on a single direction to proceed and not convey the true need or desired result they really want. It is entirely possible that specific information is intentionally omitted, just to see what the engineers can produce, which leads to some type of innovation in the project. Regardless of the intention of the stakeholders, it is incumbent upon the engineer to ask questions and thoroughly investigate the project before proceeding with creating ideas and solutions.

It is worthwhile to truly understand and co-create with the stakeholders behind the project. In this endeavor, engineers need to be part detective, to help them gain insight into the project opportunity. While a hard-line, interrogation style probe would be excessive, the questioning does need to be specifically targeted to reach far below the superficial layers. Understanding the mindset and feelings of the stakeholders involved, will go a long way to produce a product that is well received. The engineers themselves should take an empathetic approach when engaging with the stakeholders. Engineers also need to be objective in order to understand and implement the entire design process. All of these attributes will help to produce a product that achieves the goals of the stakeholders. Gathering fundamental information at the start of the project will help reduce the number of iterations needed to reach a quality product and shorten the total amount of time invested in a project.

Interview Questions

Interview Questions.docx

Customer Interview

User interviews are used to record customer statements to understand how the products, services or systems (PSS) are used and can be improved, uncovering latent needs. Interviews are held with a single user or a group of users typically in an environment of PSS. Interview questions are developed from how users' approach, use, store or conclude the PSS. The result of several customer interviews leads to the list of customer needs.

Interview Questions

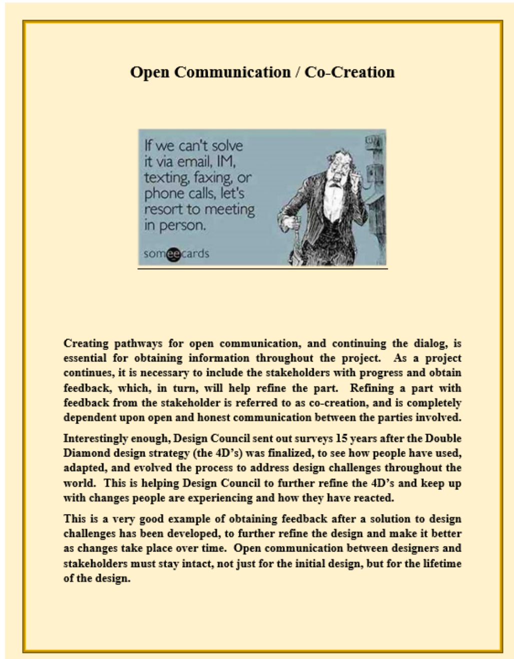
The list of questionnaires below was used by design innovation capstone project team for developing a framework for design innovation incorporating additive manufacturing.

(Look for clarification or questions that supply more info from each main question while interviewing)

1. What process do you use for ideas when developing a new product?
   Start with an end goal? Work backwards from there.
2. Have you used the DI (4-D) process for product development?
   Is this effective?
   Do you see any modifications that could be made to make the process better?
3. What is the overall design process that seems to work best for you? (beginning to end)
4. When developing a new product is it helpful to have a prototype made in the early stages of the design process? (Why)
5. What process do you use for ideas when developing a new product?
6. What is the overall design process that seems to work best for you? (beginning to end)
7. When developing a new product is it helpful to have a prototype made in the early stages of the design process? (Why)
8. What type of AM do you find is best suited for prototype development? FFF or FDM. Fused filament fabrication
9. What type of problems do you typically run into with the AM process?
10. What are the advantages to using AM for prototypes?
11. Is using additive manufacturing your method of choice when manufacturing the final product?
12. Is this the first-time using AM for part manufacturing?
    Do you consider traditional manufacturing processes or are you set on using AM for the final product from the beginning?
13. What are the challenges in AM when making a final product?
    If you are producing a large number of items (mass production) is AM at a disadvantage? Do you think AM is best suited for low production high specialty parts & applications?
14. Where do you see AM going in the future?

Open Communication

Open Communication.docx


Open Communication / Co-Creation

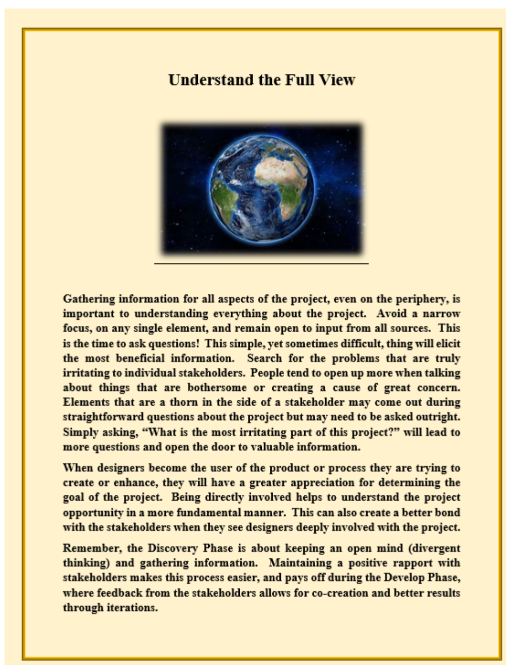
Creating pathways for open communication, and continuing the dialog, is essential for obtaining information throughout the project. As a project continues, it is necessary to include the stakeholders with progress and obtain feedback, which, in turn, will help refine the part. Refining a part with feedback from the stakeholder is referred to as co-creation, and is completely dependent upon open and honest communication between the parties involved.

Interestingly enough, Design Council sent out surveys 15 years after the Double Diamond design strategy (the 4D's) was finalized, to see how people have used, adapted, and evolved the process to address design challenges throughout the world. This is helping Design Council to further refine the 4D's and keep up with changes people are experiencing and how they have reacted.

This is a very good example of obtaining feedback after a solution to design challenges has been developed, to further refine the design and make it better as changes take place over time. Open communication between designers and stakeholders must stay intact, not just for the initial design, but for the lifetime of the design.

Understand the Full View

Understand the Full View.docx


Understand the Full View

Gathering information for all aspects of the project, even on the periphery, is important to understanding everything about the project. Avoid a narrow focus, on any single element, and remain open to input from all sources. This is the time to ask questions! This simple, yet sometimes difficult, thing will elicit the most beneficial information. Search for the problems that are truly irritating to individual stakeholders. People tend to open up more when talking about things that are bothersome or creating a cause of great concern. Elements that are a thorn in the side of a stakeholder may come out during straightforward questions about the project but may need to be asked outright. Simply asking, "What is the most irritating part of this project?" will lead to more questions and open the door to valuable information.

When designers become the user of the product or process they are trying to create or enhance, they will have a greater appreciation for determining the goal of the project. Being directly involved helps to understand the project opportunity in a more fundamental manner. This can also create a better bond with the stakeholders when they see designers deeply involved with the project.

Remember, the Discovery Phase is about keeping an open mind (divergent thinking) and gathering information. Maintaining a positive rapport with stakeholders makes this process easier, and pays off during the Develop Phase, where feedback from the stakeholders allows for co-creation and better results through iterations.

Website links:

Create Scenarios: https://www.dimodules.com/scenarios

Journey map: https://www.dimodules.com/scenarioshttps://www.dimodules.com/userjourneymap

Define

Define Bubble

Define Bubble.docx

Define

Interpreting the information gathered in discovery, allows designers to view the opportunity in a new and creative way. Discovery information will lead the design team into a narrowing focus to get at the heart of what is needed in the project opportunity and why.

The designers should be conscientious and careful to fairly assess the information before them in a diligent and prudent manner. Their efforts are directed toward obtaining one or more precise fundamental definitions of what is needed to solve the opportunity in the best possible fashion.

Designers should try to be insightful by looking into the motivations, needs, desires, irritations, etc. of the stakeholders. Often times, good insight will come about through the frustrations or complaints by a stakeholder about something specific. Inferring problems can be useful, but should be corroborated with the stakeholder rather than just assuming a specific problem is detected.

This is a good area to exploit individual intuitiveness and then discuss what comes to mind with the design group. There are a number of different methods for evaluating information from Design Council and CU Denver Design Method Cards. The website for Design Council is

https://www.designcouncil.org.uk/news-opinion/design-methods-step-2-define

References:

https://naturalarches.org/gallery-spaceart.htm

AM Design Principle

AM Design Principle.docx

AM Design Principle

Opportunity

The opportunity here is to create an educational and professional representation and design tool that helps designers learn and understand the principles of design with additive manufacturing. The tool is meant to disseminate codified design knowledge, or design principles. In creating the tool, we must make choices regarding the medium of communication (i.e. textual/visual), the organization and structure (layout and categorization), as well as how the representation and tool will be used.

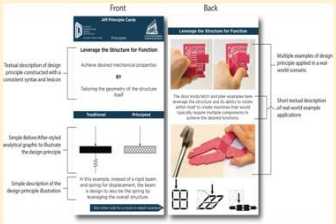


Figure: Example AM Design Principle Card

1

Table: Extracted AM design principles

1	Preserve small features by printing them in an orientation which requires no support material
2	Preserve surface finish by printing artefacts in an orientation which requires no support material
3	Prevent part warping by minimizing cross sectional area and residual stresses
4	Improve print success by orienting a part with the lowest vertical aspect ratio
5	Reduce weight, material cost, and preserve stability by replacing solid volumes with cellular structures
6	Eliminate assembly steps and time by printing functional joints and interfaces directly
7	Integrate additional functionality by incorporating components or features in unused internal volumes
8	Enable custom processes (i.e. low-medium volume production) by identifying features that are complex or require high levels of user-based customization
9	Achieve desired mechanical properties by tailoring the geometry of the mesostructure
10	Reduce print time by orienting the shortest dimension parallel to the slowest fabrication direction
11	Ensure printability by scaling artefacts and removing non-critical volumes
12	Improve accuracy of critical curves and profiles by orienting critical curves and profiles in the plane of highest resolution
13	Satisfy alternative functional requirements by scaling the artefact
14	Satisfy different parametric requirements by scaling the artefact
15	Minimize design time and effort by reusing already-designed component geometry
16	Leverage the capabilities of the selected AM technology by using comparably high resolution .STL files
17	Accommodate different AM technologies' capabilities by using high-resolution .STL files
18	Improve printability by designing with the resolution limitations of the selected AM process in mind
19	Add function(s) to artefacts by incorporating functional features into non-functional aesthetic models
20	Minimize assembly time and number of components by incorporating snaps fits when possible
21	Reduce production time by standardizing the assembly process
22	Incorporate existing low-cost components by integrating the necessary standard interfaces
23	Improve manufacturability by dividing the artefact into smaller components

2

Categories of AM Principle Types

In extracting the AM principles, it was observed that some principles related to the design of parts themselves, whereas some principles provided for a shift in the printing, design, and business processes. In order to help designers to distinguish these principle types, the Principle Card deck is color coded. Blue, red, orange, and green relate to product, process, design-process, and printing principles respectively as shown in the figure below. The categories are specified as follows:

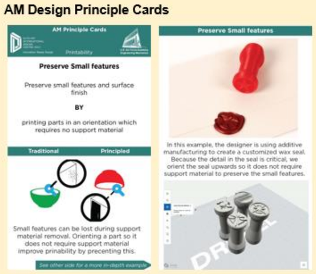
- *Product* – These principles provide for innovative avenues in the physical design of parts and products with additive manufacturing.
- *Process* – These principles provide for innovative avenues to change the larger business process around a product, such as manufacturing at the point of consumption or on demand inventories for replacement parts.
- *Design Process* – These principles provide innovative avenues for leveraging AM to enhance a product design process although not necessarily as a final means of manufacturing a product.
- *Printing* – These principles provide innovative avenues for improving and insuring printability of components specifically when considering design for manufacturing with AM.

(a) (b) (c) (d)

Figure: Cards from Different Design Principle Categories. (a) Product, (b) Business Process, (c) Design Process, & (d) Printability Principles of Designing with AM.

3

AM Design Principle Cards



4

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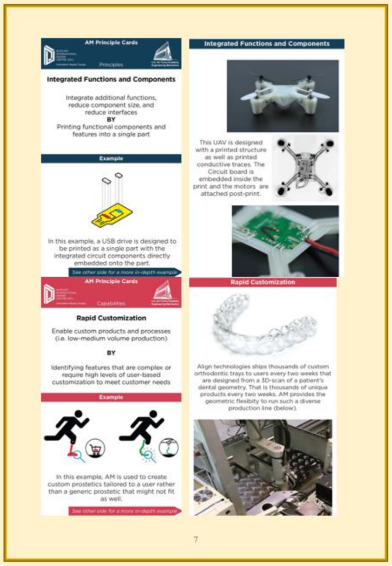

AM Principle Cards
Principles

Integrated Functions and Components

Integrate additional functions, reduce component size, and reduce interfaces
BY
Printing functional components and features into a single part

Example

In this example, a USB drive is designed to be printed as a single part with the integrated circuit components directly embedded onto the part.

See other side for a more in-depth example

Integrated Functions and Components

This UAV is designed with a printed structure as well as printed conductive traces. The Circuit board is embedded inside the print and the motors are attached post-print.

AM Principle Cards
Capabilities

Rapid Customization

Enable custom products and processes (i.e. low-medium volume production)

BY

Identifying features that are complex or require high levels of user-based customization to meet customer needs

Example

In this example, AM is used to create custom prostetics tailored to a user rather than a generic prostetic that might not fit as well.

See other side for a more in-depth example

Rapid Customization

Align technologies ships thousands of custom orthodontic trays to users every two weeks that are designed from a 3D-scan of a patient's dental geometry. That is thousands of unique products every two weeks. AM provides the geometric flexibity to run such a diverse production line (below).

7


AM Principle Cards
Principles

Leverage the Structure for Function

Achieve desired mechanical properties

BY

Tailoring the geometry of the structure itself

Traditional	Principled

In this example, instead of a rigid beam and spring for displacement, the beam is design to also be the spring by leveraging the overall structure.

See other side for a more in-depth example

Leverage the Structure for Function

The door knob/latch and plier examples here leverage the structure and its ability to rotate within itself to create machines that would typically require multiple components to acheive the desired functions.

AM Principle Cards
Printability

Reduce Print Time

Reduce print time

BY

Orienting the shortest dimension parallel to the slowest fabrication direction

Traditional	Principled

Many AM technologies like FDM are much slower in the vertical direction so reorienting the part to be horizontal makes the print faster and more stable

See other side for a more in-depth example

Reduce Print Time

Printing this airfoil could take days if it were oriented vertically, but few printers are large enough to print it on it's side. The time savings of printing such object on their side is so intriguing that Autodesk created a printer specifically to be able to do that!

8


AM Principle Cards
Principles

Scale for Requirement

Satisfy different parametric requirements

BY

Scaling the design

Traditional	Principled

For example, one could take the design for an ordinary spoon, scale it to be larger and create a spoon for serving. This would save the time of creating a new design

See other side for a more in-depth example

Scale for Requirement

In this example, a parametric customization tool is used to change the dimensions of this mobile phone wall holder/mount. The parametric design tool allows the user to adjust or scale the dimensions of the original part to accomodate their own phone as there are many different makes and models.

AM Principle Cards
Principles

Reuse Digital Geometries

Minimize design time and effort

BY

Reusing already-designed component geometry where CAD data is already available

Traditional	Principled

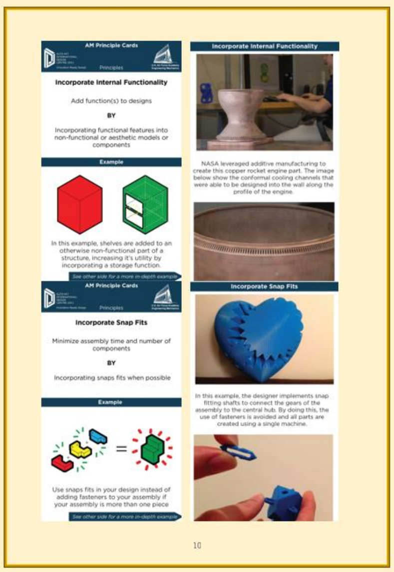
When designing a new component, time and effort may be saved if certain geometries can be reused from previous designs and existing CAD data.

See other side for a more in-depth example

Reuse Digital Geometries

In this example, a user wanted to create a different accessory for a dremel tool. Rather than measuring and sizing the attachment thread on a dremel, the User leveraged an existing thread design to create their accessory.

9


AM Principle Cards
Principles

Incorporate Internal Functionality

Add function(s) to designs

BY

Incorporating functional features into non-functional or aesthetic models or components

Example

In this example, shelves are added to an otherwise non-functional part of a structure, increasing it's utility by incorporating a storage function.

See other side for a more in-depth example

Incorporate Internal Functionality

NASA leveraged additive manufacturing to create this copper rocket engine part. The image below show the conformal cooling channels that were able to be designed into the wall along the profile of the engine.

AM Principle Cards
Principles

Incorporate Snap Fits

Minimize assembly time and number of components

BY

Incorporating snaps fits when possible

Example

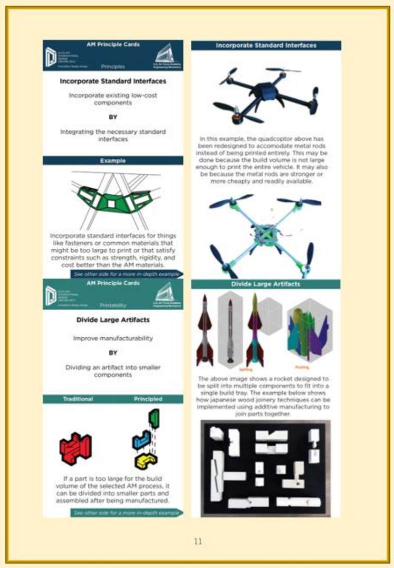
Use snaps fits in your design instead of adding fasteners to your assembly if your assembly is more than one piece

See other side for a more in-depth example

Incorporate Snap Fits

In this example, the designer implements snap fitting shafts to connect the gears of the assembly to the central hub. By doing this, the use of fasteners is avoided and all parts are created using a single machine.

10


AM Principle Cards
Principles

Incorporate Standard Interfaces

Incorporate existing low-cost components

BY

Integrating the necessary standard interfaces

Example

Incorporate standard interfaces for things like fasteners or common materials that might be too large to print or that satisfy constraints such as strength, rigidity, and cost better than the AM materials.

See other side for a more in-depth example

Incorporate Standard Interfaces

In this example, the quadcopter above has been redesigned to accomodate metal rods instead of being printed entirely. This may be done because the build volume is not large enough to print the entire vehicle. It may also be because the metal rods are stronger or more cheaply and readily available.

AM Principle Cards
Printability

Divide Large Artifacts

Improve manufacturability

BY

Dividing an artifact into smaller components

Traditional	Principled

If a part is too large for the build volume of the selected AM process, it can be divided into smaller parts and assembled after being manufactured.

See other side for a more in-depth example

Divide Large Artifacts

The above image shows a rocket designed to be split into multiple components to fit into a single build tray. The example below shows how japanese wood joinery techniques can be implemented using additive manufacturing to join parts together.

11


AM Principle Cards
Design

Printed Perturbation Study

Improve learning in prototypes

BY

Printing several variations of a design and comparing them

Example

Leverage AM to print variations of the same concept all at once to quickly compare many different options.

See other side for a more in-depth example

Printed Perturbation Study

In this example, researchers developed a new concept for a spoon specifically for feeding babies. As the tip's design was critical to the product's effectiveness, the team leveraged AM to design, manufacture, and test many different variations of the spoon's geometry.

AM Principle Cards
Design

Enhance Concept Generation

Improve the concept generation process and outcomes

BY

Printing simple prototypes of a design or its subsystems

Example

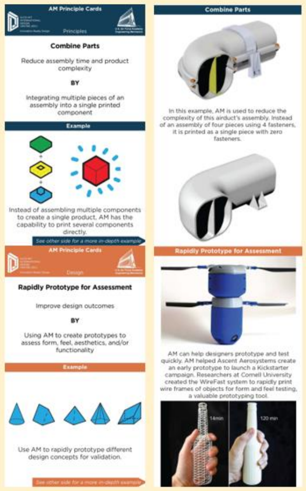
Use AM to rapidly produce ideas during concept generation to help communicate ideas

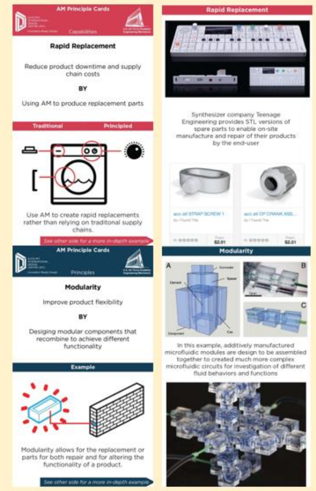
See other side for a more in-depth example

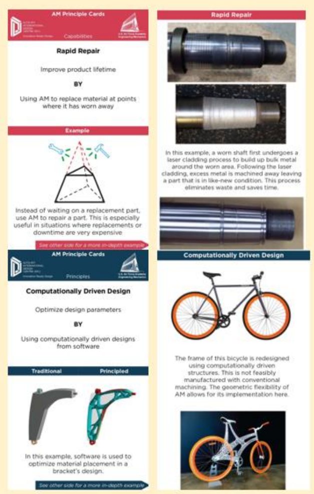
Enhance Concept Generation

Design requires iteration. AM allows for the rapid development of prototypes from as early as ideation. Use AM to validate ideas early on and refine them as your team progresses. These examples show the sheer number of iterations undertaken to develop a final product. All are enabled by AM.

12







References

Perez, K. B., Anderson, D. S., & Wood, K. L. (2015). Crowdsourced design principles for leveraging the capabilities of additive manufacturing. *In The Proceedings of the 20th International Conference on Engineering Design (ICED15)*, Milan.

Perez, B., Hilburn, S., Jensen, D., & Wood, K. L. (2018). Design principle-based stimuli for improving creativity during ideation. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 0954406218809117.

Perez, K.B. (2019). "Design Innovation with Additive Manufacturing (AM): An AM-centric Design Innovation Process," *PhD Dissertation*, Singapore University of Technology and Design (SUTD).

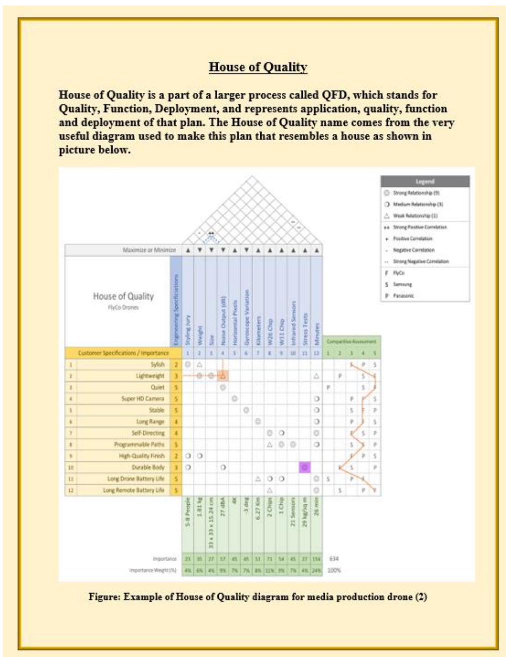
18

Learning Module (Support Material)

Learning Module (Support Material).pp

House of Quality

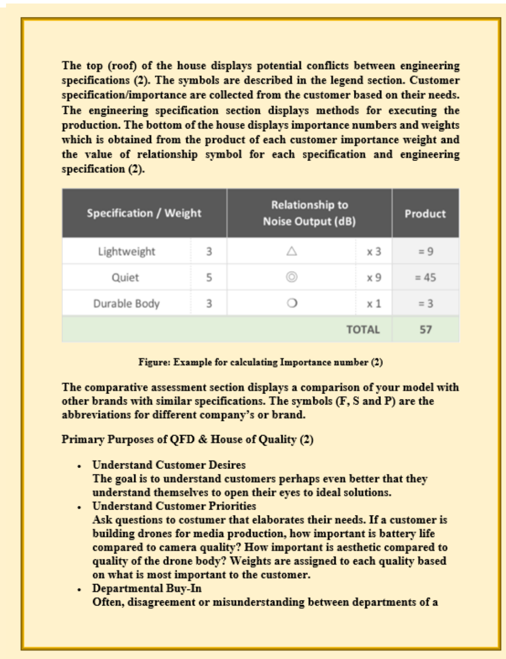
House of Quality.docx



House of Quality

House of Quality is a part of a larger process called QFD, which stands for Quality, Function, Deployment, and represents application, quality, function and deployment of that plan. The House of Quality name comes from the very useful diagram used to make this plan that resembles a house as shown in picture below.

Figure: Example of House of Quality diagram for media production drone (2)



The top (roof) of the house displays potential conflicts between engineering specifications (2). The symbols are described in the legend section. Customer specification/importance are collected from the customer based on their needs. The engineering specification section displays methods for executing the production. The bottom of the house displays importance numbers and weights which is obtained from the product of each customer importance weight and the value of relationship symbol for each specification and engineering specification (2).

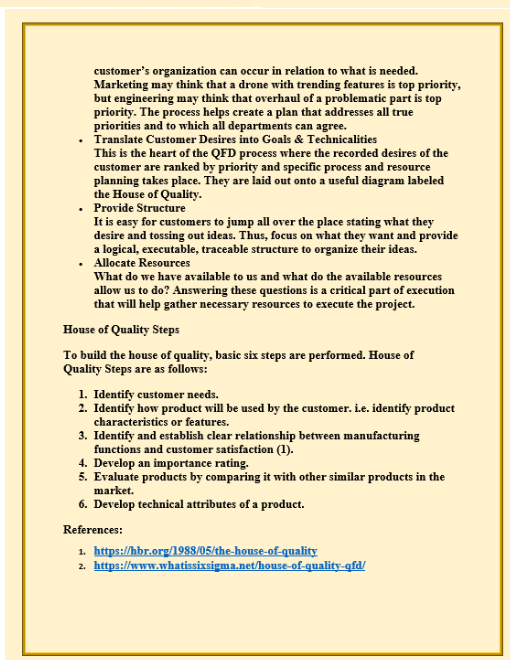
Specification / Weight		Relationship to Noise Output (dB)		Product
Lightweight	3	△	x 3	= 9
Quiet	5	◎	x 9	= 45
Durable Body	3	❍	x 1	= 3
			TOTAL	57

Figure: Example for calculating Importance number (2)

The comparative assessment section displays a comparison of your model with other brands with similar specifications. The symbols (F, S and P) are the abbreviations for different company's or brand.

Primary Purposes of QFD & House of Quality (2)

- Understand Customer Desires
  The goal is to understand customers perhaps even better that they understand themselves to open their eyes to ideal solutions.
- Understand Customer Priorities
  Ask questions to costumer that elaborates their needs. If a customer is building drones for media production, how important is battery life compared to camera quality? How important is aesthetic compared to quality of the drone body? Weights are assigned to each quality based on what is most important to the customer.
- Departmental Buy-In
  Often, disagreement or misunderstanding between departments of a



customer's organization can occur in relation to what is needed. Marketing may think that a drone with trending features is top priority, but engineering may think that overhaul of a problematic part is top priority. The process helps create a plan that addresses all true priorities and to which all departments can agree.

- Translate Customer Desires into Goals & Technicalities
  This is the heart of the QFD process where the recorded desires of the customer are ranked by priority and specific process and resource planning takes place. They are laid out onto a useful diagram labeled the House of Quality.
- Provide Structure
  It is easy for customers to jump all over the place stating what they desire and tossing out ideas. Thus, focus on what they want and provide a logical, executable, traceable structure to organize their ideas.
- Allocate Resources
  What do we have available to us and what do the available resources allow us to do? Answering these questions is a critical part of execution that will help gather necessary resources to execute the project.

House of Quality Steps

To build the house of quality, basic six steps are performed. House of Quality Steps are as follows:

1. Identify customer needs.
2. Identify how product will be used by the customer. i.e. identify product characteristics or features.
3. Identify and establish clear relationship between manufacturing functions and customer satisfaction (1).
4. Develop an importance rating.
5. Evaluate products by comparing it with other similar products in the market.
6. Develop technical attributes of a product.

References:

1. https://hbr.org/1988/05/the-house-of-quality
2. https://www.whatissixsigma.net/house-of-quality-qfd/

Website links:

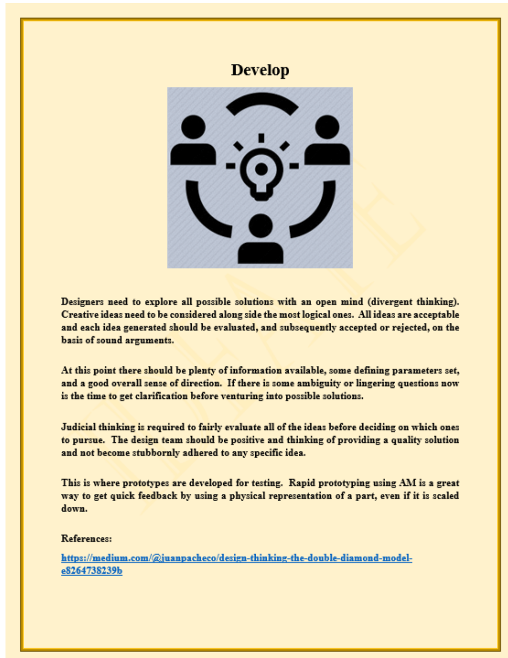
System need and functions: https://www.dimodules.com/systemfunctions

Hierarchy of purpose: https://www.dimodules.com/hierarchyofpurpose

Develop

Develop Bubble

Develop Bubble.docx



Develop

Designers need to explore all possible solutions with an open mind (divergent thinking). Creative ideas need to be considered along side the most logical ones. All ideas are acceptable and each idea generated should be evaluated, and subsequently accepted or rejected, on the basis of sound arguments.

At this point there should be plenty of information available, some defining parameters set, and a good overall sense of direction. If there is some ambiguity or lingering questions now is the time to get clarification before venturing into possible solutions.

Judicial thinking is required to fairly evaluate all of the ideas before deciding on which ones to pursue. The design team should be positive and thinking of providing a quality solution and not become stubbornly adhered to any specific idea.

This is where prototypes are developed for testing. Rapid prototyping using AM is a great way to get quick feedback by using a physical representation of a part, even if it is scaled down.

References:

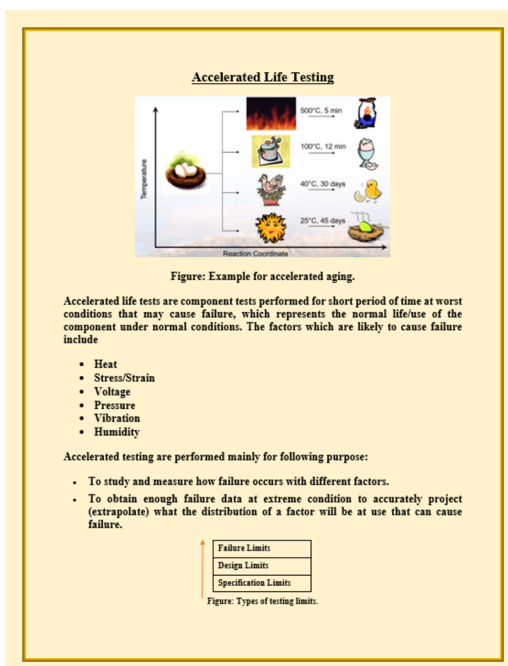
https://medium.com/@juanpacheco/design-thinking-the-double-diamond-model-e8264738239b

Design Innovation Methods

Design Innovation Methods.pdf

Accelerated Life Testing

Accelerated Life Testing.docx



Accelerated Life Testing

Figure: Example for accelerated aging.

Accelerated life tests are component tests performed for short period of time at worst conditions that may cause failure, which represents the normal life/use of the component under normal conditions. The factors which are likely to cause failure include

- Heat
- Stress/Strain
- Voltage
- Pressure
- Vibration
- Humidity

Accelerated testing are performed mainly for following purpose:

- To study and measure how failure occurs with different factors.
- To obtain enough failure data at extreme condition to accurately project (extrapolate) what the distribution of a factor will be at use that can cause failure.

Failure Limits
Design Limits
Specification Limits

Figure: Types of testing limits.

The figure below shows an example of accelerated life testing, where a Lockheed Martin (LM) satellite bracket is being analyzed by finite element analysis (FEA) model to test the bracket against extreme load during launch.

Figure: FEA model of LM Satellite Bracket testing protocol for extreme launch load

Types of standard Accelerated Testing:

1. Qualitative accelerated test:
   - These tests use small sample size with extreme conditions (very high level of failure condition) and are often used for product improvement to increase reliability of the product.
2. Quantitative accelerated test:
   - These tests are used to develop a time-to-failure information of a product. Since expected life of most products are often years, and are not used continuously, accelerated test is performed continuously until failure is observed.

References:

Sandia National Laboratories: https://energy.sandia.gov

Deliver

Deliver Bubble

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Deliver

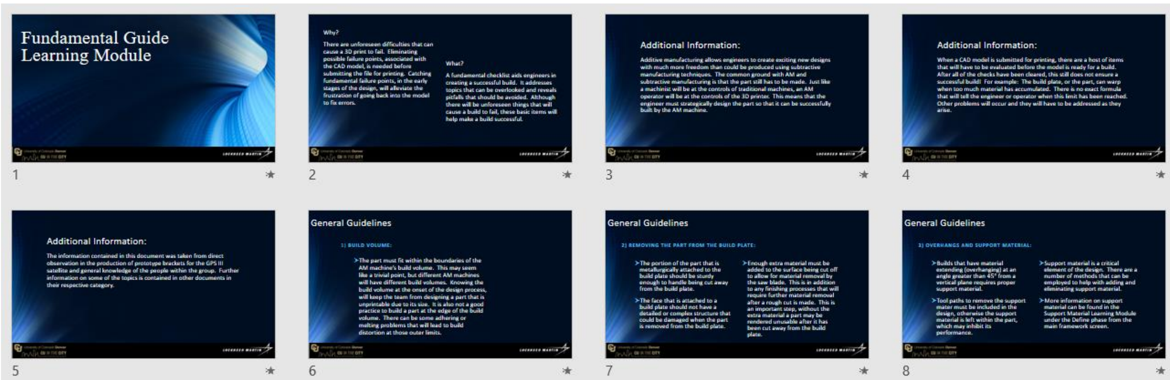
The first 3D's contain the bulk of the design process. Now it is time to produce prototypes and evaluate them based on the project goals. Using feedback from stakeholders and users of the product, further prototypes are developed. This is often the point in a design process where time and monetary expenditures become large. This is often due to the effort of producing each prototype for evaluation and testing. AM is superb at creating prototypes quickly which allows for more iterations to be done before a final product is reached. When the final product has been created, end user testing and evaluation is performed to ensure that the product is going to function as intended.

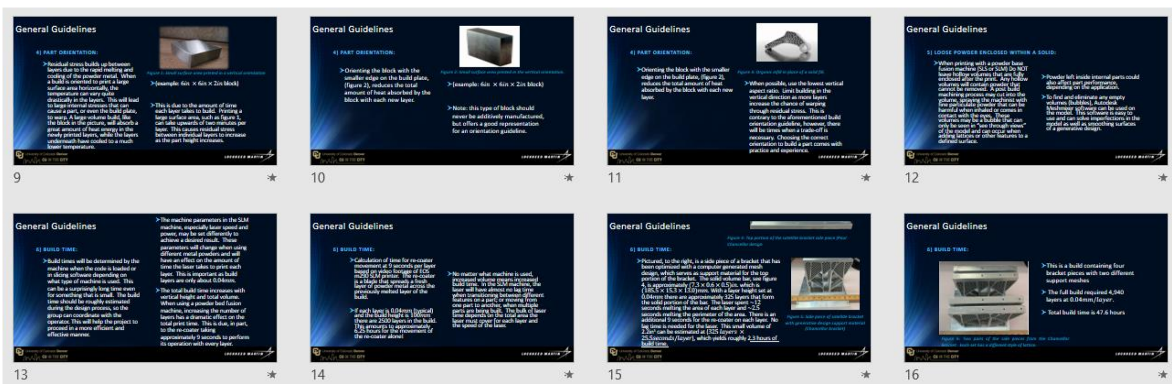
From a general product design perspective, this is where product roll out strategies are conceived and full-scale production goes into effect. When the product is a specialty part, used in small numbers, or highly customized, the primary focus should be on testing and meeting the required design parameters.

Design Council has case studies with information on how each of those groups went about implementing the design process and the outcome of the products. They can be used to obtain other perspectives and ideas about setting the design in motion. The case studies can be found at https://www.designcouncil.org.uk/resources/search

Learning Module (Fundamental Guide)

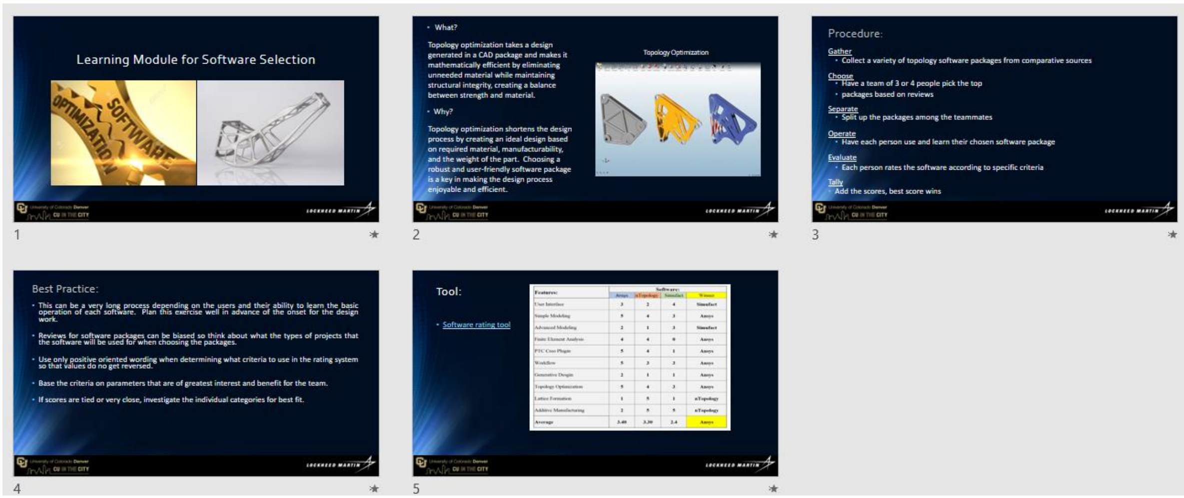
Learning Module
(Fundamental Guide).





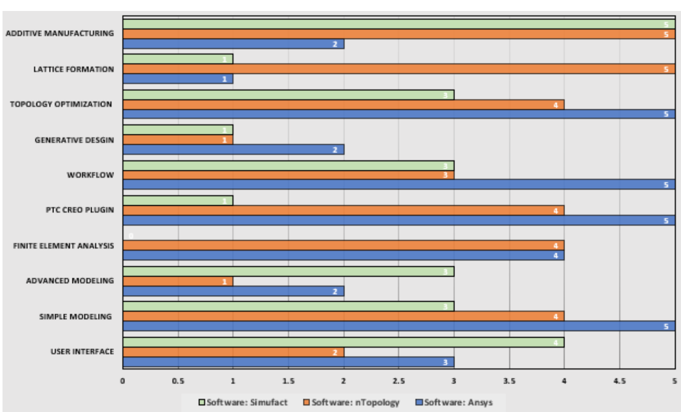
Learning Module (Software Selection)

Learning Module (Software Selection).p



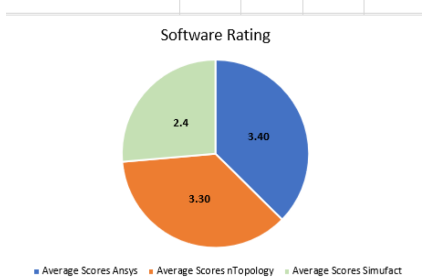
Software Rating Tool

Software rating tool.xlsx



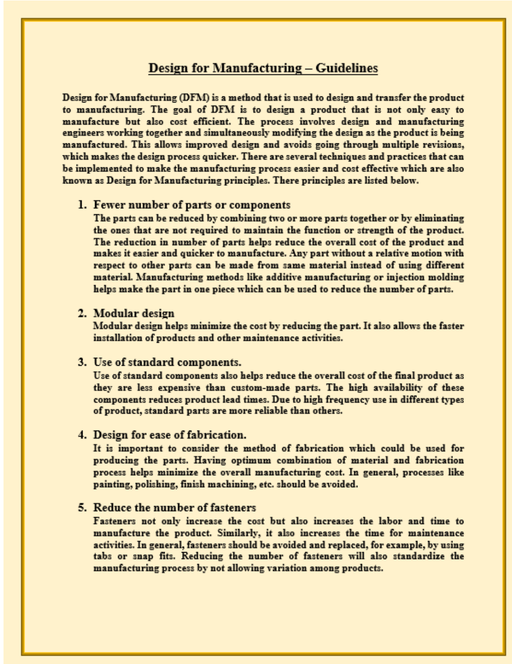
Features:	Software:			
	Ansys	nTopolog	Simufact	Winner
User Interface	3	2	4	**Simufact**
Simple Modeling	5	4	3	**Ansys**
Advanced Modeling	2	1	3	**Simufact**
Finite Element Analysis	4	4	0	**Ansys**
PTC Creo Plugin	5	4	1	**Ansys**
Workflow	5	3	3	**Ansys**
Generative Desgin	2	1	1	**Ansys**
Topology Optimization	5	4	3	**Ansys**
Lattice Formation	1	5	1	**nTopology**
Additive Manufacturing	2	5	5	**nTopology**
Average	3.40	3.30	2.4	**Ansys**

Average Scores		
Ansys	nTopology	Simufact
3.40	3.30	2.4



Design for Manufacturing

Design for Manufacturing.docx



Design for Manufacturing – Guidelines

Design for Manufacturing (DFM) is a method that is used to design and transfer the product to manufacturing. The goal of DFM is to design a product that is not only easy to manufacture but also cost efficient. The process involves design and manufacturing engineers working together and simultaneously modifying the design as the product is being manufactured. This allows improved design and avoids going through multiple revisions, which makes the design process quicker. There are several techniques and practices that can be implemented to make the manufacturing process easier and cost effective which are also known as Design for Manufacturing principles. There principles are listed below.

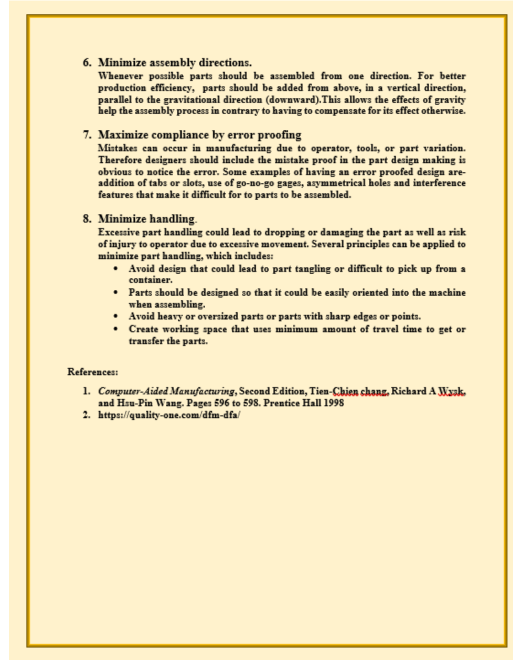
1. Fewer number of parts or components
   The parts can be reduced by combining two or more parts together or by eliminating the ones that are not required to maintain the function or strength of the product. The reduction in number of parts helps reduce the overall cost of the product and makes it easier and quicker to manufacture. Any part without a relative motion with respect to other parts can be made from same material instead of using different material. Manufacturing methods like additive manufacturing or injection molding helps make the part in one piece which can be used to reduce the number of parts.

2. Modular design
   Modular design helps minimize the cost by reducing the part. It also allows the faster installation of products and other maintenance activities.

3. Use of standard components.
   Use of standard components also helps reduce the overall cost of the final product as they are less expensive than custom-made parts. The high availability of these components reduces product lead times. Due to high frequency use in different types of product, standard parts are more reliable than others.

4. Design for ease of fabrication.
   It is important to consider the method of fabrication which could be used for producing the parts. Having optimum combination of material and fabrication process helps minimize the overall manufacturing cost. In general, processes like painting, polishing, finish machining, etc. should be avoided.

5. Reduce the number of fasteners
   Fasteners not only increase the cost but also increases the labor and time to manufacture the product. Similarly, it also increases the time for maintenance activities. In general, fasteners should be avoided and replaced, for example, by using tabs or snap fits. Reducing the number of fasteners will also standardize the manufacturing process by not allowing variation among products.



6. Minimize assembly directions.
   Whenever possible parts should be assembled from one direction. For better production efficiency, parts should be added from above, in a vertical direction, parallel to the gravitational direction (downward).This allows the effects of gravity help the assembly process in contrary to having to compensate for its effect otherwise.

7. Maximize compliance by error proofing
   Mistakes can occur in manufacturing due to operator, tools, or part variation. Therefore designers should include the mistake proof in the part design making is obvious to notice the error. Some examples of having an error proofed design are- addition of tabs or slots, use of go-no-go gages, asymmetrical holes and interference features that make it difficult for to parts to be assembled.

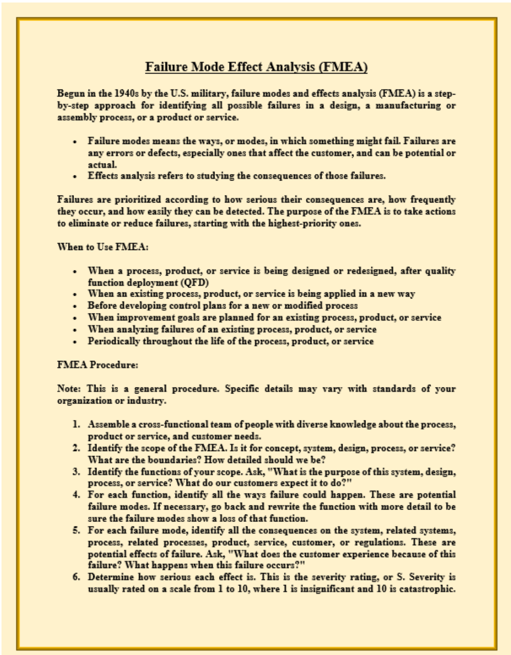
8. Minimize handling.
   Excessive part handling could lead to dropping or damaging the part as well as risk of injury to operator due to excessive movement. Several principles can be applied to minimize part handling, which includes:
   - Avoid design that could lead to part tangling or difficult to pick up from a container.
   - Parts should be designed so that it could be easily oriented into the machine when assembling.
   - Avoid heavy or oversized parts or parts with sharp edges or points.
   - Create working space that uses minimum amount of travel time to get or transfer the parts.

References:

1. *Computer-Aided Manufacturing*, Second Edition, Tien-Chien chang, Richard A Wysk, and Hsu-Pin Wang. Pages 596 to 598. Prentice Hall 1998
2. https://quality-one.com/dfm-dfa/

FMEA

FMEA.docx



Failure Mode Effect Analysis (FMEA)

Begun in the 1940s by the U.S. military, failure modes and effects analysis (FMEA) is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service.

- Failure modes means the ways, or modes, in which something might fail. Failures are any errors or defects, especially ones that affect the customer, and can be potential or actual.
- Effects analysis refers to studying the consequences of those failures.

Failures are prioritized according to how serious their consequences are, how frequently they occur, and how easily they can be detected. The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones.

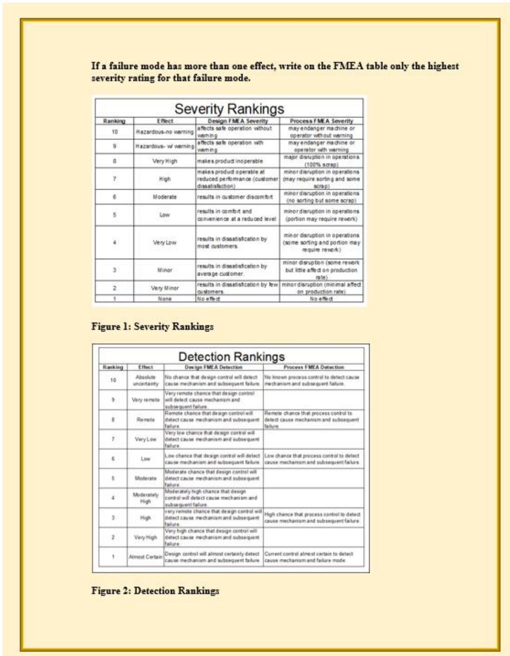
When to Use FMEA:

- When a process, product, or service is being designed or redesigned, after quality function deployment (QFD)
- When an existing process, product, or service is being applied in a new way
- Before developing control plans for a new or modified process
- When improvement goals are planned for an existing process, product, or service
- When analyzing failures of an existing process, product, or service
- Periodically throughout the life of the process, product, or service

FMEA Procedure:

Note: This is a general procedure. Specific details may vary with standards of your organization or industry.

1. Assemble a cross-functional team of people with diverse knowledge about the process, product or service, and customer needs.
2. Identify the scope of the FMEA. Is it for concept, system, design, process, or service? What are the boundaries? How detailed should we be?
3. Identify the functions of your scope. Ask, "What is the purpose of this system, design, process, or service? What do our customers expect it to do?"
4. For each function, identify all the ways failure could happen. These are potential failure modes. If necessary, go back and rewrite the function with more detail to be sure the failure modes show a loss of that function.
5. For each failure mode, identify all the consequences on the system, related systems, process, related processes, product, service, customer, or regulations. These are potential effects of failure. Ask, "What does the customer experience because of this failure? What happens when this failure occurs?"
6. Determine how serious each effect is. This is the severity rating, or S. Severity is usually rated on a scale from 1 to 10, where 1 is insignificant and 10 is catastrophic.



If a failure mode has more than one effect, write on the FMEA table only the highest severity rating for that failure mode.

Severity Rankings

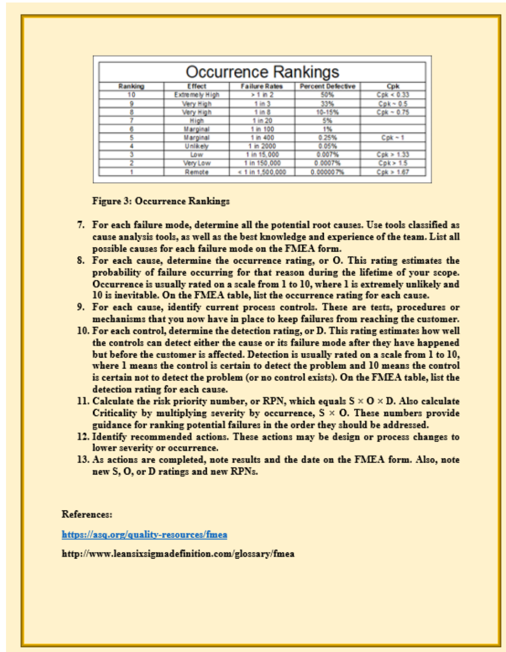
Ranking	Effect	Design FMEA Severity	Process FMEA Severity
10	Hazardous-no warning	affects safe operation without warning	may endanger machine or operator without warning
9	Hazardous- w/ warning	affects safe operation with warning	may endanger machine or operator with warning
8	Very High	makes product inoperable	major disruption in operations (100% scrap)
7	High	makes product operable at reduced performance (customer dissatisfaction)	minor disruption in operations (may require sorting and some scrap)
6	Moderate	results in customer discomfort	minor disruption in operations (no sorting but some scrap)
5	Low	results in comfort and convenience at a reduced level	minor disruption in operations (portion may require rework)
4	Very Low	results in dissatisfication by most customers.	minor disruption in operations (some sorting and portion may require rework)
3	Minor	results in dissatisfication by average customer.	minor disruption (some rework but little affect on production rate)
2	Very Minor	results in dissatisfication by few customers.	minor disruption (minimal affect on production rate)
1	None	No effect	No effect

Figure 1: Severity Rankings

Detection Rankings

Ranking	Effect	Design FMEA Detection	Process FMEA Detection
10	Absolute uncertainty	No chance that design control will detect cause mechanism and subsequent failure.	No known process control to detect cause mechanism and subsequent failure.
9	Very remote	Very remote chance that design control will detect cause mechanism and subsequent failure.	
8	Remote	Remote chance that design control will detect cause mechanism and subsequent failure.	Remote chance that process control to detect cause mechanism and subsequent failure.
7	Very Low	Very low chance that design control will detect cause mechanism and subsequent failure.	
6	Low	Low chance that design control will detect cause mechanism and subsequent failure.	Low chance that process control to detect cause mechanism and subsequent failure.
5	Moderate	Moderate chance that design control will detect cause mechanism and subsequent failure.	
4	Moderately High	Moderately high chance that design control will detect cause mechanism and subsequent failure.	
3	High	very remote chance that design control will detect cause mechanism and subsequent failure.	High chance that process control to detect cause mechanism and subsequent failure.
2	Very High	Very high chance that design control will detect cause mechanism and subsequent failure.	
1	Almost Certain	Design control will almost certainly detect cause mechanism and subsequent failure.	Current control almost certain to detect cause mechanism and failure mode.

Figure 2: Detection Rankings



Occurrence Rankings

Ranking	Effect	Failure Rates	Percent Defective	Cpk
10	Extremely High	> 1 in 2	50%	Cpk < 0.33
9	Very High	1 in 3	33%	Cpk ~ 0.5
8	Very High	1 in 8	10-15%	Cpk ~ 0.75
7	High	1 in 20	5%	
6	Marginal	1 in 100	1%	
5	Marginal	1 in 400	0.25%	Cpk ~ 1
4	Unlikely	1 in 2000	0.05%	
3	Low	1 in 15,000	0.007%	Cpk > 1.33
2	Very Low	1 in 150,000	0.0007%	Cpk > 1.5
1	Remote	< 1 in 1,500,000	0.000007%	Cpk > 1.67

Figure 3: Occurrence Rankings

7. For each failure mode, determine all the potential root causes. Use tools classified as cause analysis tools, as well as the best knowledge and experience of the team. List all possible causes for each failure mode on the FMEA form.
8. For each cause, determine the occurrence rating, or O. This rating estimates the probability of failure occurring for that reason during the lifetime of your scope. Occurrence is usually rated on a scale from 1 to 10, where 1 is extremely unlikely and 10 is inevitable. On the FMEA table, list the occurrence rating for each cause.
9. For each cause, identify current process controls. These are tests, procedures or mechanisms that you now have in place to keep failures from reaching the customer.
10. For each control, determine the detection rating, or D. This rating estimates how well the controls can detect either the cause or its failure mode after they have happened but before the customer is affected. Detection is usually rated on a scale from 1 to 10, where 1 means the control is certain to detect the problem and 10 means the control is certain not to detect the problem (or no control exists). On the FMEA table, list the detection rating for each cause.
11. Calculate the risk priority number, or RPN, which equals $S \times O \times D$. Also calculate Criticality by multiplying severity by occurrence, $S \times O$. These numbers provide guidance for ranking potential failures in the order they should be addressed.
12. Identify recommended actions. These actions may be design or process changes to lower severity or occurrence.
13. As actions are completed, note results and the date on the FMEA form. Also, note new S, O, or D ratings and new RPNs.

References:

https://asq.org/quality-resources/fmea

http://www.leansixsigmadefinition.com/glossary/fmea

DIPM Spreadsheet

DI Process Mapping (DIPM)

DI Process Mapping (DIPM).xlsx

Design Innovation Appendix B

Additional references for the framework not included in the documents

Introduction / instruction video

Audacity software is used for music editing.

Soundtrack for introduction/instruction video: https://www.youtube.com/watch?v=a9j-v9EbBBM&list=RDKOqFAHwYETg&index=24 Dream Theater, Lines in the Sand (intro)

Pictures used in the introduction / instruction video

Seat belt comparison: https://www.wizcrafter.co.in/about-generative-design-the-benefits-of-the-technology/

Seat belt bracket (rapid prototyping): https://digitalengineering247.com/article/intrinsim-unveils-inaugural-generative-design-workflow-assessment-for-autodesk-fusion-360/

Valve part consolidation: https://additivemanufacturing.com/2018/06/12/wohlers-associates-to-host-design-for-additive-manufacturing-course-in-the-mountains-of-colorado/

Light weighting: https://www.metal-am.com/am-steel/

Audi coolant pipe: https://manufactur3dmag.com/volkswagen-envisions-demand-metal-potential-automotive-applications/

Arm cast: http://blog.naver.com/PostView.nhn?blogId=ahdoc&logNo=220482790714

Star Man: https://www.wattpad.com/story/211545464-their-creator-various-yandere-overwatch-x-creator

Faucet: https://www.additivemanufacturing.media/blog/post/3d-printed-faucets-illustrate-design-potential

Micro gears on keyboard: https://www.leolane.com/blog/tessas-weekly-picks-3d-printed-metal-details/?utm_content=buffer7915e&utm_medium=social&utm_source=pinterest.com&utm_campaign=buffer

4th industrial revolution: https://phys.org/news/2016-01-industry-additive.html

Pictures for Documents

Design Innovation Phase Bubble

GPS III: https://spacenews.com/lockheed-martin-confident-about-winning-gps-3-competition/

https://www.designcouncil.org.uk/news-opinion/what-framework-innovation-design-councils-evolved-double-diamond

Discover

https://www.designcouncil.org.uk/news-opinion/design-methods-step-1-discover

Know the Need

Diesel piston trad mfg. vs AM piston: https://www.motordetal.ru/en/technology/pistons/

https://www.metal-am.com/iav-turns-to-metal-additive-manufacturing-for-engine-test-parts/

1940’s piston: https://maritime.org/doc/fleetsub/diesel/chap3.htm

Is AM the Right Tool?

https://www.designlaunchers.com/what-is-3d-cad-modeling/

Customization: http://www.calglover.com/portfolio/additive-manufacturing-project/

Highly specialized: https://www.pinterest.com/pin/238690848974312358/

Spiral staircase long lead time: https://www.bing.com/images/search?view=detailV2&id=0F43DF69DDFD7C33D04E172B66B60E49F75BD2B3&thid=OIP.SwTKLksmNnpG5W1KnsMvsAHaEO&mediaurl=http%3A%2F%2Feverythreeweekly.com%2Fwp-content%2Fuploads%2F2017%2F03%2Fb2ff2ca7f96fd48bfa05b346ecebfa34-938x535.jpg&exph=535&expw=938&q=Long+Lead+Time+downward+spiral&selectedindex=19&ajaxhist=0&vt=0&eim=0

Easily machined parts: https://www.pinterest.co.uk/pin/288160076129381104/

Parts can be made quickly at low cost: https://www.indiamart.com/harsh-steel-ahmedabad/

Mass produced parts https://z2precision.com/mass-production/

Solid volume: https://kermatdi.com/i-120-g60-vr6-228mm-steel-single-mass-flywheel-22lbs.html

Larger than build volume: https://www.unicomechanical.com/large-milling-and-turning.html

Precision parts: http://aedm.co/Metal_Precision_Parts.html

What? At top of page: https://www.bing.com/shop?q=cnc+milling+machines+pics&qs=n&form=SHOPSB&sp=-1&pq=cnc+milling+machines+pics&sc=0-25&sk=&cvid=8469A0F8688B4F84B3CD8CA4276F0722

Know the Stakeholders

http://aot-eg.com/

Open Communication

https://redshoemovement.com/communication-quotes-famous-funny/

https://www.designcouncil.org.uk/news-opinion/double-diamond-15-years

Understand the Full View

https://www.thedouglasreview.com/nasa-releases-breathtaking-space-views-of-africa/

Support Material Learning Module

Different types of support material design: file:///C:/Users/17202/AppData/Local/Packages/Microsoft.MicrosoftEdge_8wekyb3d8bbwe/TempState/Downloads/Feature_article_-_Design_for_metal_AM_-_a_beginners_guide%20(1).pdf

Hexagon shape: https://www.pinterest.com/pin/711920653571461877/

file:///C:/Users/17202/AppData/Local/Packages/Microsoft.MicrosoftEdge_8wekyb3d8bbwe/TempState/Downloads/Feature_article_-_Design_for_metal_AM_-_a_beginners_guide%20(1).pdf

Renishaw pictures

https://www.materialise.com/en/resources/software/webinar-recording/how-to-use-simulation-and-reduce-costs-metal-am?utm_source=EventList&utm_campaign=7d1bd56e22-SOFT-AUTO-MetalPaperRecoaterDatapreptrack-EN-G&utm_medium=email&utm_term=0_d755a55d41-7d1bd56e22-68026331&ct=t()&goal=0_d755a55d41-7d1bd56e22-68026331

https://www.youtube.com/watch?v=bq_6DYyZPBQ - Texas A&M video supports and warping

Video for Support Material

Picture #1 https://www.materialise.com/en/resources/software/webinar-recording/how-to-use-simulation-and-reduce-costs-metal-am?utm_source=EventList&utm_campaign=7d1bd56e22-SOFT-AUTO-MetalPaperRecoaterDatapreptrack-EN-G&utm_medium=email&utm_term=0_d755a55d41-7d1bd56e22-68026331&ct=t()&goal=0_d755a55d41-7d1bd56e22-68026331 - Renishaw's support diagram

Picture #2 http://additivemanufacturing.com/2013/04/13/eos-dmls-economic-precise-and-digital-additive-manufacturing-am-of-removable-partial-dentures-rpd/

Pictures #3 https://additivemanufacturing.com/2015/07/02/concept-laser-in-situ-quality-assurance-with-qmmeltpool-3d-coaxial-inspection-with-qmmeltpool-3d/

Picture #4 https://www.materialise.com/en/cases/volum-e-Reduces-Metal-Support-Removal-e-Stage

Develop Bubble

https://www.iconfinder.com/icons/2309354/brainstorm_collaboration_discussion_generation_group_idea_icon

https://www.designcouncil.org.uk/news-opinion/design-methods-step-3-develop

Deliver

Picture at top of document: https://www.ifm.eng.cam.ac.uk/insights/design-for-transformation/using-additive-manufacturing-beyond-prototypes/

Fundamental Guide Learning Module

file:///C:/Users/17202/AppData/Local/Packages/Microsoft.MicrosoftEdge_8wekyb3d8bbwe/TempState/Downloads/KBlakePerezThesisSubmissionFINAL%20(1).pdf

https://www.youtube.com/watch?v=DgFQgTPENSM&t=134s

REFERNECES

[1] “Design Council.” *Design Council*, www.designcouncil.org.uk/.

[2] Perez, K. B., Lauff, C., Camburn, B, Wood, K. L. (2019). Design Innovation with Additive Manufacturing (AM): An AM-centric Design Innovation Process – K Blake Perez Thesis Submission FINAL.

[3] “What Is the Framework for Innovation? Design Council's Evolved Double Diamond.” *Design Council*, 10 Sept. 2019, www.designcouncil.org.uk/news-opinion/what-framework-innovation-design-councils-evolved-double-diamond.

[4] “Design Methods Step 1: Discover.” *Design Council*, 6 Apr. 2018, www.designcouncil.org.uk/news-opinion/design-methods-step-1-discover.

[5] Camburn, B. A., Auernhamer, J. M., Sng, K. H., Mingone, P. J., Arlitt, R. M., Perez, K. B., … Wood, K. L. (2017). Design Innovation: A Study of Integrated Practice. In *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Cleveland, Ohio.

[6] Seow, O., Tiong, E., Teo, K., Silva, A., Wood, K. L., Jensen, D. D, Yang, M. (2018). Design Signatures: Mapping Design Innovation Processes. In *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Quebec City, Canada.

[7] “Design Innovation Learning Modules - Modules.” *Dimodules*, www.dimodules.com/dilearningmodules.