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 Deliver 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.
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.

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.

![DIPM - Lockheed Martin Satellite Bracket Design Capstone Project](image-url)
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.
虽然有过去几个学期，我们的团队，由四个子团队组成，成功地为洛克希德马丁公司生产了两个不同的GPS卫星托架设计。我们的最终产品包括数字托架设计和对创建它们所使用的软件包的详细评估、每个设计的物理模型以及用于有效设计增材制造的资源、充分测试了所使用的材料的性质，并提供了设计创新在增材制造过程中的应用的工具和学习模块。

与CU丹佛大学的合作为我们的学生团队提供了一个独特的机会，让他们在真实世界中应用他们在学术生涯中获得的技能。我们能够与专业工程师互动，并更好地理解他们的方法和实践。在整个项目的持续过程中，我们从我们的用户那里直接接收反馈，这在帮助我们迭代和改进我们的工作，以创建两个成功的托架系统方面是非常有帮助的。

我们非常感谢洛克希德马丁公司赞助我们的项目并提供资源，尤其是布莱恩·卡普林、鲍勃·劳舍和乔·布洛克，他们在我们整个项目的过程中不断地提供反馈和建议。我们非常感谢CU丹佛大学机械工程系，特别是马丁·邓恩和克里斯·伍德的努力，他们为了我们有机会参与这样一个独特的项目而促成与洛克希德马丁公司的合作伙伴关系。我们也要向我们的学术导师和顾问，特别是克里斯·亚卡基和丹·詹森，表示感谢，他们对我们的成功至关重要，因为他们提供了必要的指导和帮助。此外，监督机械工程中心和增材制造实验室的校园工作人员，包括杰克·科雷斯、汤姆·图伊和尼克·戴蒙德，非常乐意地教导我们如何使用必要的工具，并帮助我们完成工作。
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

Design Innovation Title

Design for Additive Manufacturing

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 (AlSi10Mg). 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 which has been dubbed the 4D’s. Within the DI framework, each of the 4D’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 give engineers an overall process to follow. Design Innovation for Additive Manufacturing (DIAAM) 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. 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-release/double-diamond-university-accents-impact-design-
2) https://www.designcouncil.org.uk/news-release/double-diamond-1-7-years
Design Innovation Process

Design for Additive Manufacturing

Discover

Define

The design innovation framework is based on Design Council's Double Diamond and its subsequent 4 steps approach to design. The adaptable model offers design teams a strategic progression through the entire evolution of product development. With a focus on ideation, this model has made great strides since its inception in 2004.

The four key phases, known as the 4D, is a series of focused exploration in particular aspects of the design process. Each phase uses divergent or convergent 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.

Develop

Deliver

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 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 Bubble

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 factors in 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 insights and ideas 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 view of thought, designers should strive to open minds 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 trivial 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 minds. 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 needs to flow more freely where people are in a secure setting and not considered 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.

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

Know the Need
Learning Module (Is AM the Right Tool)

Is AM the Right Tool?

Why? Quality AM machines are sophisticated and expensive. They are designed to create parts that are near-net shape, meaning the part can be produced close to its final shape. This would be impossible, or extremely expensive, when made by conventional means. Making simple parts, other than the testing parts, is not utilizing the machine to its full potential and wastes valuable printing time.

What? Avoid using AM simply because they can be made by AM machines. AM is a great option for prototyping parts. However, it is not always the appropriate method to use. AM machines are expensive and not flexible enough for mass production. Therefore, any part made by AM should utilize the full capability of the machine. Parts that can be manufactured quickly and most effectively by traditional methods should not be utilized, making AM.

Procedure: Describe the reasons for using AM (see Tech Brief below).

Best Practice: Avoid using AM just because it can be made.

Examples of Items that are well suited for AM:

- **Performance Enhancement**
  - Figure 1: Rapid tooling
  - Figure 2: Simple high-impact parts

- **Ease of Design**
  - Figure 3: Thin sections
  - Figure 4: Oblique sections

- **Customization**
  - Figure 5: Individualized parts

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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 to the heart of the project by getting to know the needs, desires, and wants of the stakeholders. At times, the stakeholders will believe they have the best way to proceed with a project, and everything relies on a single direction to proceed and not ensure the true need or desired result they sought. It is not only possible that specific information is immediately needed, but we see what the engineers see problems, which leads to some types of innovation. Engineers need their own teacher to ask questions and thoroughly investigate the project before proceeding with creating their end solution.

It is worthwhile to study the end users with the stakeholders behind the project. As mentioned, engineers need to be out there, so they can help them gain insight into the project requirements. With a hard-line, interrogative style, it would be necessary. The questioning does need to be specifically targeted to model the behavior of significant users. Understanding the mindset and feeling of the stakeholders involved will go a long way to produce a product/service well-received. The engineers themselves should take an empathic approach when speaking with the stakeholders. Engineers also need to be objective in order to understand and implement the entire design process. All of these interactions will help to produce a product that satisfies the needs of the stakeholders. Collecting fundamental information at the onset of the project will help reduce the number of iterations needed to reach a quality product and stream 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 survey approaches, use, user or customer the PSS. The result of several customer interviews lends to the list of customer needs.

Interview Questions

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

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 3D (or 3D) 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 percent 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 feel is best suited for prototype development? FFF or FDM. fused deposition 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 we are producing a large number of parts, are there any problems with AM or a disadvantage? Do you think AM is best suited for low production high quality parts & applications?
14. Where do you see AM going in the future?
Open Communication

Creating pathways for open communication, and continuing the sharing, 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 project. Shifting a part of the 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 ran a survey 15 years after the Robe Diamond design campaign where the 4D’s were first used, to see how people have used, adapted, and evolved the process to address design challenges throughout the world. This was helping Design Council to further refine the 4D’s and keep up with change 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 to change 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

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 yield the most beneficial information. Search for the problems that are truly interesting to individual stakeholder. People tend to open up more when talking about things that are bothering or creating a sense of great concern.

Elements that are in the title of a stakeholder may come out during straightforward questions about the project but may need to be asked indirectly. Simply asking, “What is the most interesting 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 iteration.

Website links:

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

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

Define Bubble

Incorporating 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 discovery focus to get at the heart of what is needed in the project opportunity and why.

The designers should be conscientious and careful in fairly assess the information before them in a diligent and jujurous manner. Their efforts are directed toward obtaining our users’ precise fundamental definitions of what is needed to solve the opportunity in the most plausible fashion.

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

This is a good area to exploit individual innovations 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 CE Design Design Method Cards. The website for Design Council is [https://www.designcouncil.org.uk/xerox/opinion/design.methods.step.2.define](https://www.designcouncil.org.uk/xerox/opinion/design.methods.step.2.define)

References:
[https://www.standarddesign.org/gallery/occupant.htm](https://www.standarddesign.org/gallery/occupant.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 endorsed design knowledge, or design principles. Creating the tool, we must make choices regarding the means of communication. Technically, the tool needs to be able to be used by any student, teacher, or professional, as well as how the representation and tool will be used.

Figure: Diagram AM Design Principle Card

AM Design Principle Cards

- Pressure-Sensitive Features
  - Pressure-Sensitive Features by printing from an orientation which requires no supports or post-processing.
  - Press the surface of the object directly into the printed material, creating a feature that can be used by the user to interact with the object.
  - Pressing the surface of the object directly into the printed material, creating a feature that can be used by the user to interact with the object.
  - Pressing the surface of the object directly into the printed material, creating a feature that can be used by the user to interact with the object.

- Stabilizer Design
  - Stabilizer Design by printing functional parts that are made of a material and connected to the object to provide stability.
  - Stabilizer Design by printing functional parts that are made of a material and connected to the object to provide stability.
  - Stabilizer Design by printing functional parts that are made of a material and connected to the object to provide stability.

- Tooling Design
  - Tooling Design by printing functional parts that are made of a material and connected to the object to provide stability.
  - Tooling Design by printing functional parts that are made of a material and connected to the object to provide stability.
  - Tooling Design by printing functional parts that are made of a material and connected to the object to provide stability.

- Customization
  - Customization by printing functional parts that are made of a material and connected to the object to provide stability.
  - Customization by printing functional parts that are made of a material and connected to the object to provide stability.
  - Customization by printing functional parts that are made of a material and connected to the object to provide stability.

- Functional Design
  - Functional Design by printing functional parts that are made of a material and connected to the object to provide stability.
  - Functional Design by printing functional parts that are made of a material and connected to the object to provide stability.
  - Functional Design by printing functional parts that are made of a material and connected to the object to provide stability.

- Assembly
  - Assembly by printing functional parts that are made of a material and connected to the object to provide stability.
  - Assembly by printing functional parts that are made of a material and connected to the object to provide stability.
  - Assembly by printing functional parts that are made of a material and connected to the object to provide stability.

- Environment
  - Environment by printing functional parts that are made of a material and connected to the object to provide stability.
  - Environment by printing functional parts that are made of a material and connected to the object to provide stability.
  - Environment by printing functional parts that are made of a material and connected to the object to provide stability.

- Printing
  - Printing by printing functional parts that are made of a material and connected to the object to provide stability.
  - Printing by printing functional parts that are made of a material and connected to the object to provide stability.
  - Printing by printing functional parts that are made of a material and connected to the object to provide stability.
House of Quality

House of Quality is a part of a larger process called QFD, which stands for Quality Function Deployment. It represents a diagram that shows the relationship between customer needs and product attributes. The House of Quality helps improve the product development process by breaking down customers' needs into specific product attributes.

Website links:
- System need and functions: https://www.dimodules.com/systemfunctions
- Hierarchy of purpose: https://www.dimodules.com/hierarchyofpurpose
Develop

Develop Bubble.docx

Design Innovation Methods

Design Innovation Methods.pdf

Accelerated Life Testing

Accelerated Life Testing.docx

Develop

Developers need to explore all possible solutions with an open mind (divergent thinking). Concepts discussed need to be considered along with the most logical ones. All ideas are acceptable and each idea generated should be evaluated and subsequently accepted or rejected, or the best of several narrowed.

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

Audlt/ded thinking is required to finally evaluate all of the ideas before deciding on which one to pursue. The design must be positive and looking for providing a quality solution and not become creatively limited in any specific area.

This is where prototypes are developed for testing. Rapid prototyping using 3D printers is a great way to get quick feedback by using a physical representation of a part, even if it is scaled down.

References:
https://www.formnext.com/3dprinting/design-thinkers-the-double-diamond-model-43847303799

Design Innovation Methods

Accelerated Life Testing

Accelerated Life Testing.docx

Accelerated Life Testing

Figure: Example of accelerated aging

Accelerated life tests are component tests performed for short period of time at worst conditions that may cause failures, which represent the normal lifetime of the component under normal condition. The factors which are likely to cause failures include:

- Stress
- Humidity
- Vibration
- Pressure
- Temperature
- Humidity
- Temperature

Accelerated testing are performed usually for following purpose:

- To study and assess how fast failures occur with different factors.
- To allow enough failure data at extreme condition to accurately project (extrapolate) what the distribution of a factor will be in use that can cause failures.

<table>
<thead>
<tr>
<th>Failure Causes</th>
<th>Design Limits</th>
<th>Environmental Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>figure 7: Types of testing units.</td>
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</tbody>
</table>

The figure below shows an example of accelerated life testing, where a Lockheed Martin (LM) 3D-printed bracket is being analyzed by Finite element analysis (FEA) model to test the bracket against extreme load testing load.

Figure: FEA model of LM 3D-printed bracket testing. Load for extreme load testing.

Types of standard Accelerated Testing:

1. Qualitative accelerated test:
   - These tests use small sample size for extreme conditions (very high level of failure conditions) 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 Bubble

Deliver

The last step in the design process is 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 cost of producing each prototype for evaluation and testing. This is important in creating prototypes quickly which allows for more iterations to be done before a final product is realized. 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 and our strategies are conceptual 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 these groups went about implementing the design process and the outcome of the products. They can be used to obtain other perspectives and ideas about testing the design in motion. The case studies can be found at https://www.designcouncil.org.uk/resources/index
Learning Module (Software Selection)

Software Rating Tool

<table>
<thead>
<tr>
<th>Features</th>
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<th>nTopology</th>
<th>Simulink</th>
<th>Winner</th>
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<td>4</td>
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<tr>
<td>Workflow</td>
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<tr>
<td>Topology Optimization</td>
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<td>4</td>
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<tr>
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<td>nTopology</td>
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<td><strong>Average</strong></td>
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<td>3.30</td>
<td>2.4</td>
<td>Ansys</td>
</tr>
</tbody>
</table>
Design for Manufacturing

Design for Manufacturing (DFM) is a methodology 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 meets the requirements for quality, cost, and flexibility. This allows the design process to be more efficient and effective, leading to lower costs and increased profitability.

FMEA

Failure Mode Effect Analysis (FMEA) is a structured approach for identifying all possible failures in a design, assessing their consequences, and establishing controls to prevent or detect failures.

1. Define the system and its components.
2. Identify all possible failure modes and effects.
3. Assess the risk associated with each failure mode.
4. Implement controls to mitigate the risk.

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.
2. Define the system, process, or service to be analyzed.
3. Define the failure modes.
4. Identify the causes of each failure mode.
5. Assess the risk associated with each failure mode.

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DIPM Spreadsheet

DI Process Mapping (DIPM)
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=RDKnqFAHwYETg&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/]


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]


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/iaa-turns-to-metal-additive-manufacturing-for-engine-test-parts/]

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:

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=&cvuid8469A0F8688B4F84B3CD8CA4276F0722

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

Support Material Learning Module

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

Renishaw pictures
Video for Support Material


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
REFERENCES


