ME 6101A: Engineering Design

Answer to the Question for the Semester

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I. INTRODUCTION

The course objectives in ME6101, Engineering Design, can be thought of as a house, similar to the one shown in Figure 1. Each new topic builds on previously presented themes. Learning takes place when students are able to “open the door” and understand how various course activities connect and add value to each other.

At the foundation of the house of learning in Figure 1 are the A0 Learning Goals, the Question for the Semester (Q4S), and Course Expectations. A0 Learning Goals were set by individual students at the beginning of the semester. These learning goals detail the personal goals that each student strives to achieve throughout the semester. The Q4S is the semester long question that students strive to answer. The Q4S sets the tone for learning throughout the semester by providing a set of learning topics that must be addressed in order to answer the Q4S. The course expectations were set by course orchestrators and describe what students should gain upon completing ME6101.

In the figure below, it is important to note the connection between material design, the requirements list, the augmented method, and the semester project. In our answer to the Q4S, we will show how each of these topics interact and add value to each other. Each topic that is discussed in the answer to the Q4S will be related back to A0 Learning Goals, the Q4S, and Course expectations.

![Figure 1. House of Learning in ME6101](imageURL)

II. CONTEXT

The appropriate background and context for the answer to the Question for the Semester is provided in the following section. The augmented and personalized Q4S is presented and discussed. In this section we also introduce the topic of material design. We show how material design is related to answering the Q4S, and is beneficial in achieving our semester learning goals. Background information and motivation of material design is also discussed in the following section.

I.1 Augmented and Personalized Q4S

Learning in ME6101 was based on the Question for the Semester (Q4S). One of the purposes of ME6101 was to equip students with the appropriate knowledge to provide a detailed answer to the Q4S.
By internalizing the Q4S at the beginning of the semester, students approached the class material and assignments with the correct mindset.

The original Q4S given by the course orchestrators is shown below:

Original Q4S:

We imagine a future in which geographically distributed engineers collaboratively develop, build and test solutions to design-manufacture problems encountered in the product realization process.

We recognize that solutions evolve over time. Accordingly, we expect you to build on what has been done before.

In this context, we want you to provide a method to support the realization of products for a global marketplace through distributed design and manufacture.

How should the Pahl and Beitz systematic design method be personalized and augmented to support the realization of products for a global marketplace in a distributed environment?

Our augmented and personalized Q4S within the context of material design is presented below. Additions to the original Q4S are underlined. We chose to incorporate material design topics in our augmented and personalized Q4S in order to meet our A0 Learning Goals and to match our graduate research topics. Several phrases were removed from the augmented and personalized Q4S so that we could more effectively achieve our semester learning goals.

Augmented and Personalized Q4S:

We imagine a future in which engineers design materials to meet increasingly complex requirements encountered in the product realization process.

We recognize that solutions evolve over time. Accordingly, we expect to build on what has been done before.

In this context, we want to provide a method to support the realization of products through integrated product, material, and process design.

How should the Pahl and Beitz systematic design method be personalized and augmented to support the realization of products through integrated product, material, and process design?

II.2 Justification of Changes in Augmented Q4S

The Q4S was augmented in order to better address the learning goals for our semester project.

Phrases removed from original Q4S

In our answer to the Q4S, we do not discuss issues such as “geographically distributed engineers”, “global marketplace”, and “distributed design and manufacture”. Since we are relatively new to the vast field of material design, we feel that we have achieved greater value in ME6101 by directing our attention exclusively towards material design. It would be a valuable exercise to analyze the role of materials design in the future, distributed and global world of 2020. However, we feel that in order to speculate about the role of material design in 2020 we should have a better understanding of the history, role, and
benefits of material design. By focusing on material design, we will also be able to move towards achieving our learning goals for the semester project.

**Phrases added to augmented and personalized Q4S**

Phrases such as “design materials”, “integrated product, materials, and process design”, and “Pahl and Beitz systematic design method” are included in the augmented Q4S. In the answer to the Q4S, we will augment the Pahl and Beitz systematic design method to include steps for the integrated design of products and materials. We will also use the answer to the Q4S to present an argument for the implementation of material design in the product design process.

The key drivers in the augmented and personalized Q4S are underlined in the following text box.

**Augmented and Personalized Q4S – Key Drivers:**

<table>
<thead>
<tr>
<th>We imagine a <strong>future</strong> in which engineers <strong>design materials</strong> to meet <strong>increasingly complex requirements</strong> encountered in the <strong>product realization process</strong>.</th>
</tr>
</thead>
<tbody>
<tr>
<td>We recognize that solutions evolve over time. Accordingly, we expect to <strong>build on what has been done before</strong>.</td>
</tr>
<tr>
<td>In this context, we want to <strong>provide a method</strong> to support the realization of products through <strong>integrated product, material, and process design</strong>.</td>
</tr>
<tr>
<td>How should the <strong>Pahl and Beitz systematic design method</strong> be personalized and augmented to support the realization of products through <strong>integrated product, material, and process design</strong>?</td>
</tr>
</tbody>
</table>

**Drivers in augmented and personalized Q4S**

- **Future** – The proposed material design method should be useful for concurrent product material design problems in the future. We assume that the future of engineering design will be characterized by globally distributed design, increased computational power, and complex multifunctional design requirements.
- **Design materials** – We believe that design materials will be an integral part of the product design process of the future where product requirements become multifunctional and complex, and computational power increases.
- **Increasingly complex requirements** – Product requirements of the future will be complex and multifunctional in nature. A change in product requirements will necessitate the design of materials to meet product requirements.
- **Product realization process** – The method that we are proposing incorporates aspects of material design in the product design process. Material design takes place along the same timeline as the associated product design.
- **Build on what has been done before** – We have built our integrated product/material/process design method on the work of others that are more experienced in the engineering design domain. Such individuals include: Pahl and Beitz, G. B. Olsen, M. F. Ashby, D. L. McDowell, and C. C. Seepersad.
• **Provide a method** – The outcome of our answer to the Q4S is a method that supports the concurrent design of products and materials. This design method is based on the Pahl and Beitz detail design method¹.

• **Integrated product, material, and process design** – We propose that the best way to design materials for product designs is to follow a concurrent product and material design process. By design new materials and products throughout the semester, we were able to design and refine a method for concurrent product and material design.

• **Pahl and Beitz systematic design method** – The integrated product and material design method presented in our answer to the Q4S was based on the Pahl and Beitz systematic product design method.

## II.4 Material Design Background

### II.4.1 Definition of Material Design

Material design is the process of tailoring material properties to meet the requirements of specific design problems². Materials can be tailored or adapted to produce new materials with specific properties and performance levels. Material requirements detail the minimum material performance level necessary for a successful product design.

Perhaps it is best to illustrate the meaning of material design with an example.

Consider that you are designing a sandwich. You are planning to pile a variety of items in your sandwich, so you decide that the bread you use should be particularly strong. You also wish to make a sandwich with health benefits, so you would like to choose bread that is made from whole grains. After visiting the bakery, you cannot find any bread that satisfactorily meets your bread requirements. Therefore, you decide to bake your own bread.

The product that you are designing is a sandwich. The material that you are designing is bread.

![Materials Design – Bread Baking Example](image)

In the bread baking example, material design begins with material requirements and ends at material realization. We will revisit this bread baking example later, but for now we turn our attention to the history of material design.

II.4.2 History of Designing New Materials

By understanding the history and progression of material design innovation we can more accurately develop a systematic method for designing materials and products simultaneously. Studying the history of material design also helps us in our research as graduate students.

Material Design THEN

Materials have been discovered for centuries. The impact of new materials on civilization is evident in the naming of historical periods such as the Stone Age, Bronze Age, Iron Age, and Silicon Age. Ancient civilizations combined mud and straw to create bricks. Blacksmiths created stronger metals by adding carbon and adjusting tempering processes. Even within modern history, materials such as plywood and Styrofoam have been created because of their desirable performance characteristics. Material design in the past consisted of a trial-and-error design method in which new materials were often discovered by chance.

Material Design NOW

In the fast-paced engineering design world of today, we do not have the time or resources to rely on trial-and-error design methods to discover new materials. Research is currently being conducted in order to define a systematic design method for integrated product and material design. Materials are currently designed using techniques such as rapid manufacturing, product topology design, and functionally graded materials. Several examples of current materials design research are found below in Figure 3.

Material Design in the FUTURE

In material design of the future, engineers will be able to tailor the microstructure of materials in order to achieve specific material performance requirements. Material design will no longer be based on trial-and-error processes. In future material design processes, engineers will have a greater understanding of how the various length scales of a material (nanostructure, microstructure, mesostructure, etc.) affect the overall material performance. Interactions between the various length scales will be fully modeled and

![Figure 3. Current Material Design Research](image-url)
understood. As material design processes and techniques move towards perfection, scientists and engineers will be able to design a material to meet almost any performance requirement.

II.4.3 Material Design

Designing new materials can be shown as a chain of related length scales as displayed in Figure 4 below. The processing link represents manufacturing processes used to create a material. A material’s processing path affects its nanostructure. Various process paths include melting temperature, quenching time, and chemical reactions. The structure link represents the microstructure of the material. The processing path directly affects a material’s microstructure. A material’s microstructure is identified by (for example) chemical elements, element size, element location, and dislocations. The property link in the chain below represents the physical properties of the material. The microstructure of a material directly impacts the properties of the material. Material properties describe the behavior of a material and can be found in many engineering material tables (for example, Young’s Modulus, density, thermal conductivity, etc.). The performance of a material describes how a part constructed from the given material behaves under certain loading conditions. Material properties are a clear indication of the performance of a material.

Current material design processes are deductive in nature (bottom-up). Changing the processing of a material adjusts its microstructure. Adjusting the microstructure of a material changes the properties and performance of the material. Material design of the future will consist of an inductive (top-down) approach. Designers will specify the material performance at the beginning of the design process. The property, microstructure, and processing will be determined based on the material performance requirements. In order to practice successful top-down material design, significant research must be conducted to characterize the inductive property – structure relationship and the inductive structure – processing relationship.

Figure 4. Material Design Processes

II.4 Why Material Design?

The purpose of this section is to address several questions fundamental to material design. For example, why should engineers consider designing new materials rather than using existing ones? What are the benefits of material design? When is it advantageous for engineers to design new materials? To answer these questions, we have discussed three methods of incorporating materials in the product design process. Conceptual examples are provided for each method. However, in the project report, we have provided a comprehensive example that employs the three methods of incorporating materials in the product design process. After discussing these three methods and providing conceptual examples, we will draw some useful conclusions regarding the role of materials in component design.

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II.4.1 Material-Driven Design

Material-driven design describes a paradigm of incorporating materials in product designs. Materials are chosen based on availability, familiarity, or previous success. Materials are not tailor-made to meet specific design requirements. Historically, material-driven design was a very popular method of incorporating materials in the product design process when materials and engineering expertise were limited.

A flowchart describing material-driven design is presented below in Figure 5.

![Figure 5. Material-Driven Design Model](image)

Under the material-driven design paradigm, product material and product requirements are known at the beginning of the design process. Based on the product material and product requirements, the layout and dimensions of the product are determined. By choosing the product material early in the design process, a significant portion of design freedom is lost at the beginning of product design.

Material-driven design can be illustrated by considering a blacksmith in the Middle Ages. Suppose a blacksmith is to design a sword for one of the local knights. At the beginning of the design process, the blacksmith knows the product requirements (overall geometry of sword, sword should not fail), and the blacksmith determines that the sword should be made from iron. Iron was chosen because it is readily available, and the blacksmith has the proper tools and training to work with this material. Based on the product requirements and material that was chosen at the beginning of the design process, the blacksmith is limited in the product layout and dimensions that can be chosen and still remain within the product requirements. By specifying that the sword should be made from iron at the beginning of the design process, the blacksmith loses valuable design freedom early in the design process.

II.4.2 Material Selection

Material selection is a method of using a material database to select the best material for product designs. By following materials selection techniques, the most appropriate material is selected from all known materials in order to satisfy product requirements and goals.

A flowchart describing material selection is presented below in Figure 6.

![Figure 6. Material Selection Model](image)

At the beginning of the product design process that implements material selection techniques, the product requirements are known. The designer also has access to a vast material database that describes
properties of materials under various conditions. Throughout the design process, the number of feasible materials is reduced based on product requirements, product loading, and design goals. At the end of the design process, the product material is selected and the product dimensions and layout are determined. Under material selection, the link between product material and product layout / dimensions is weaker than in material-driven design. As the coupling between product material and product geometry weakens, design freedom is preserved until later in the design process.

The material selection method that was researched in order to answer the Q4S is found in the textbook *Materials Selection in Mechanical Design* by Michael F. Ashby. The material selection process begins with a database containing all known materials. Screen and ranking techniques reduce the number of feasible material based on product geometry and loading conditions. The resulting subset of feasible materials is further reduced by conducting further research on these materials. At this stage in the material selection process, engineering expertise plays a role in eliminating materials that would be poor choices in the overall product design. After the prime candidates have been selected, local load conditions combined with design goals lead to the final material choice. This material selection process contains many subjective elements. Human expertise and error factor into the final material choice. A graphical representation of the material selection technique in this textbook is provided below in Figure 7.

![Figure 7. Material Selection Method by Ashby](image)

In order to distinguish material selection from material design, reconsider the bread baking example from Figure 2. In materials design, bread was tailor-made for the specific design problem. The resulting bread matched the material requirements exactly. In material selection, the design process started with a database of bread located at the bakery. A loaf of bread was chosen that best achieved the design requirements. The loaf of bread was not tailored for the specific design requirements.

A figure comparing material selection and material design in the context of the bread baking example is shown below in Figure 8.

Material design is discussed in more detail in the following section.

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II.4.3 Material Design

Material design is developing and constructing materials with specific qualities to meet design requirements. The number and variety of new materials that can be designed is only limited by available elements, physical laws, and chemical laws.

A flowchart describing material design is presented below in Figure 7.

At the beginning of the material design process, the product requirements (and material requirements) are known. Product layout and dimensions can also be specified at the beginning of the design process if it is advantageous for the designer to do so. At the end of the design process, the product material is specified. Determining the product layout and dimensions can be delayed until the end of the design process also. In the material design paradigm, there is a weak coupling between product material and product layout / dimensions. As the coupling between product material and layout / dimensions decreases to zero, the product can be designed separately from the material.

Specifying the layout / dimensions of a product at the beginning of the design process is useful in product designs that have very small dimensions or dimensions with tight tolerances. For example, in many MEMS applications, the dimensions of the individual parts are crucial to the success of the overall system. In this instance, it would be useful to specify the part dimensions at the beginning of the material design process, and then design a material that would perform favorably for the given dimensions. On the other hand, with many part designs, the dimensions / layout of the part do not have tight constraints. For such product designs, it would be advantageous to maintain the design freedom of the product layout / dimensions until later in the design process. By maintaining the design freedom of the product layout / dimension, you do not impose unnecessary limits on the material that is being designed.
II.4.4 Comparison of Methods

A comparison of the three methods of incorporating materials in the product design process is given below in Figure 10. When comparing the three methods, we paid particular attention to design freedom at various stages in the design process and the relationship between product material and product dimensions. In general, we observed that as you move from traditional methods to material design methods, product dimensions and product material becomes less dependent on one another. Also, moving from traditional methods to material design methods resulted in greater design freedom in later stages of the design process. It is also important to note that material design is the only method of incorporating materials in the product design process in which product layout / dimensions can be specified at the beginning or determined at the end of the design process. The concepts presented here are explored in more depth in the semester project report.

III. BASE METHOD

III.1 Original Pahl and Beitz Systematic Design Method

In our study of engineering design in ME6101, we investigated a well-known and successful systematic design method based on the work of Pahl and Beitz.5 The Pahl and Beitz (P&B) detail design method was first published in 1977, and is based on a series of engineering design best practices. This systematic design approach was the base method that the students in ME6101 used to develop their own updated and personalized systematic design methods. The complete and uninterrupted version of the P&B design method has been inserted in Appendix 1.

In order to develop a design method for the future world of engineering design, it was important to study the structure of a design method that has proven to be successful. The following section takes a closer look at the original, unaugmented P&B design method. The four sections in P&B are presented and

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analyzed. At the end of this section, we provide a critical evaluation of the P&B method. We also point out the information gaps where the original P&B method does not accommodate the design of materials. In the following sections, some information has been leveraged from Assignment 1 written by Chad Ryther in ME6101, fall 2004.6

III.1.1 Phase 1: Plan and Clarifying the Task

The first phase of the P&B method involves planning and clarifying the design task. The input information into Phase 1 consists of specific information, such as the design task and company goals, and more general information, such as an understanding of relevant markets and the economy. In Phase 1, product ideas are generated and a product proposal is formulated. The most important step in Phase 1 is to clarify the design task. Without a thorough understanding of the goals of the product, an accurate requirements list cannot be written.

The outcome of Phase 1 in the P&B design method is a requirements list. The requirements list is a collection of goals that the product should aim to achieve. The requirements list is made up of demands (non-negotiable limits) and wishes (negotiable targets). It records the exact desired performance of the product. Developing a detailed and accurate requirements list is crucial to the success of the product design. Each step in the following phases of P&B relates back to the requirements list. Developing a precise requirements list is analogous to setting definite goals at the beginning of a long journey.

In the planning and clarifying the task phase, the authors cover two main points. First, one must carefully plan the product to account for the market, corporate skills and economic reality. This results in a detailed product proposal. Second, by further clarifying the task, the designer gathers the information about the requirements and constraints on the product and records them on the requirements list. This “specification of information” is required to define the design problem for the designer.

A visual representation of Phase 1 is presented below in Figure 11.

![Figure 11. Original P&B - Phase 1](image)

III.1.2 Phase 2: Conceptual Design

The second phase in the P&B detail design method is Conceptual Design. The information that the designer inputs into this phase is the requirements list that was elaborated in Phase 1. The design

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6 Ryther, Chad, “Assignment 1: Getting to Know Your Book”, ME6101 Engineering Design, Fall 2004, Instructed by Dr. Farrokh Mistree, George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.
specifications drive the decisions that are made during the Conceptual Design phase. At the close of this phase, a concept is presented.

The first step in developing a concept is to abstract to identify the essentials of the problem. “This means ignoring what is particular or incidental and emphasizing what is general and essential. Such generalization leads straight to the crux of the task.” Next, function structures are established for the design problem. Creating function structures allows the overall product to be broken down into possible method of transferring energy, information, and / or matter. Function structures are combined to form working principles and working structures. These working principles and working structures are combined to form concept variants. Concept variants are analyzed further to determine the best concept. This selected concept, or principal solution, is the output information from the Conceptual Design phase. Information regarding the principal solution is sent to the next phase of P&B. It is important to note that at with each step in Conceptual Design, design decisions are compared to the requirements list.

The details of Conceptual Design are listed below in Figure 12.

III.1.3 Phase 3: Embodiment Design

During the Embodiment Design phase the preliminary and definitive layouts are produced. Embodiment Design is divided into two sections. The first part of Embodiment Design results in the preliminary layout. In order to develop the preliminary layout, the first part of Embodiment Design begins with the concept that was developed in Phase 2. The form of the design and material are first determined. Preliminary product layouts are developed and refined. After evaluate the preliminary layouts against technical and economic criteria and the requirements list, the preliminary layout is determined.

The second part of Embodiment Design begins with the input information associated with the preliminary product layout. Weaknesses in the preliminary layout are eliminated, and the overall layout design is refined. The layout is optimized according to goals stated at the beginning of the design process. A preliminary parts list and manufacturing documents are generated. The second part of Embodiment Design results in a definitive layout.

The steps in the Embodiment Design phase of P&B are displayed in Figure 13.

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III.1.4 Phase 4: Detail Design

The final stage of the P&B design process is Detail Design. In Detail Design a complete parts list is generated. In addition, documentation describing product manufacturing processes, assembly, transportation, and operation are developed. In the final stage of P&B designers take the definitive layout and produce sufficient documentation to support the realization, use, and disposal of the product. As with all other phases in P&B, the Detail Design phase must be in agreement with the requirements list that was generated at the beginning of the design process.

The steps of the Detail Design phase are shown below in Figure 14.
III.2 Requirements List

In ME6101, the emphasis was not placed on designing products (as in the textbook *Engineering Design*). Instead, students focused on designing design processes. Therefore, the requirements lists that were generated detailed the goals and restrictions of successful design processes.

The following requirements list (in Table 1) was identified for the P&B design method. After studying the P&B method, we ‘reverse engineered’ a requirements list based on the overall goals of P&B. The requirements list has been divided into general and specific requirements. General requirements relate to the overall goals and flavor of P&B. Specific requirements deal with the individual phases in the P&B design method. The requirements have been marked as either a ‘demand’ or ‘wish’. As stated previously, demands are non-negotiable, whereas wishes have some flexibility.

Table 1. Requirements List - Original P&B

<table>
<thead>
<tr>
<th>#</th>
<th>Demand/Wish</th>
<th>Requirements</th>
<th>Responsible</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>General Requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>D</td>
<td>Encourage problem directed approach</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>W</td>
<td>Be applicable to every type of design activity</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>D</td>
<td>Facilitate the application of known solutions</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>W</td>
<td>Be easily taught and learned</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>D</td>
<td>Should facilitate inventiveness and guide the abilities of the designers</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>D</td>
<td>Serve as a basis of communication (clearly understood products)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>D</td>
<td>Be compatible with concepts, methods, and findings of many disciplines</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>D</td>
<td>Be compatible with modern computing technology</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>D</td>
<td>Not rely on finding solutions by chance</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>D</td>
<td>Emphasize the need for objective evaluation of results</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>D</td>
<td>Should be open to adaptation, augmentation, and personalization</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>D</td>
<td>Should dispel prejudice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific Requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>D</td>
<td>Define Problem</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>W</td>
<td>Evaluate market and economic situation</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>D</td>
<td>Identify constraints and clarify boundary conditions</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>W</td>
<td>Search for product/concept ideas</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>W</td>
<td>Set clear attainable goals</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>D</td>
<td>Develop requirements list</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>D</td>
<td>Develop Concepts</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>D</td>
<td>Abstract problem into solution neutral statement</td>
<td></td>
</tr>
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<td></td>
</tr>
<tr>
<td>21</td>
<td>D</td>
<td>Create function structure</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>D</td>
<td>Search for variants</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>D</td>
<td>Search for solution principles for sub-functions</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>D</td>
<td>Combine solution principles into concepts</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>D</td>
<td>Evaluate</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>D</td>
<td>Principle solution variants</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>D</td>
<td>Preliminary concept layout</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>D</td>
<td>Cost</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>D</td>
<td>Safety</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>W</td>
<td>Quality</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>D</td>
<td>Make Decisions</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>D</td>
<td>Assist engineer in making design decisions</td>
<td></td>
</tr>
</tbody>
</table>

### III.3 Core Transformations

Core transformations are the way in which information changes as one moves through the design process. In order to determine the core transformation in P&B, we first looked at the information that is known at the beginning and end of each phase. After observing the nature at the beginning and end of each phase, we deduced the information transformations that were taking place. The core transformations associated with the original P&B method are given below in Table 2.

**Table 2. Core Transformations - Original P&B**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Info at START</th>
<th>Core Transformation</th>
<th>Info at END</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1: Plan and Clarify</td>
<td>• Project task&lt;br&gt;• Relevant markets&lt;br&gt;• Economy</td>
<td>• Project task used to create project proposal&lt;br&gt;• Project proposal used to generate a requirements list</td>
<td>• Document describing market and economy&lt;br&gt;• Requirements List&lt;br&gt;• Product goals and constraints</td>
</tr>
<tr>
<td>Phase 2: Conceptual Design</td>
<td>• Document describing market and economy&lt;br&gt;• Requirements List&lt;br&gt;• Product goals and constraints</td>
<td>• Requirements list used to specify function structures&lt;br&gt;• Function structures transformed into working principles&lt;br&gt;• Working principles used to choose principal solution</td>
<td>• Product divided into subsections of function structures&lt;br&gt;• Principal solution</td>
</tr>
<tr>
<td>Phase 3.1: Embodiment Design</td>
<td>• Product divided into subsections of function structures&lt;br&gt;• Principal solution</td>
<td>• A preliminary layout is assigned to the principal solution&lt;br&gt;• The design goes from an abstract concept to a product with form</td>
<td>• Preliminary layout</td>
</tr>
<tr>
<td>Phase 3.2: Embodiment Design</td>
<td>• Preliminary layout</td>
<td>• The preliminary layout is refined and weak spots are removed</td>
<td>• Definitive layout</td>
</tr>
<tr>
<td>Phase 4: Detail Design</td>
<td>• Definitive layout</td>
<td>• Definitive layout is given dimensions and a parts list is created&lt;br&gt;• Documentation on the lifecycle of the product is produced</td>
<td>• Detail part drawings&lt;br&gt;• Parts list&lt;br&gt;• Manufacturing, assembly, use, and disposal instructions</td>
</tr>
</tbody>
</table>
The following section relating to the underlying assumption and necessity of the core transformation was leveraged from Assignment 1 written by Chad Ryther in ME6101, fall 2004.8

Underlying Assumptions in Core Transformations

Planning and Clarifying the Task
In the P&B design method, it is assumed that someone in the company or a customer actually has a product idea. Second, product requirements and constraints are assumed to be accurate and properly categorized.

Conceptual Design
It is assumed that the designer can break down the requirements into a primary function with several sub functions. Also, we assume that scientific principles which fulfill those functions exist. However, we do not assume that those principles have previously been identified or discovered by humans.

Embodiment Design
The fundamental assumption of this phase is that a product can be built that makes use of the scientific principle identified in the previous phase. In this phase it is critical to assume that the designer will be able to objectively rate layouts and identify weak areas and incompatibilities.

Detail Design
First, the designer must assume that the definitive layout is designed in such a way that available materials and techniques may be used to create it and that the design is define enough that it may be further refined. We also assume that there are multiple methods of producing the same part and that some methods have advantages over others. Finally, the transformation of the production design into an actual product assumes the producer and user will have certain levels of education about the manufacture and use of the product and that any additional education may be provided by the designer as required.

Importance of Core Transformations

Planning and Clarifying the Task
These core transformations are required to provide the designer with a problem to solve. If you do not accomplish these transformations you might develop a product that you do not need.

Conceptual Design
The transformation of the product into function structures breaks down the design problem into pieces small enough for the designer to solve. Identifying the principle which will yield each of these functions in the best and easiest manner is the crux of design.

Embodiment Design
Both the preliminary and definitive layout demonstrates that the design can provide the functions required of the product proposal.

Detail Design
Refinement of the definitive layout is required to provide the fabrication team some specification to which to build the product. Without this transformation some design work would be accomplished by the fabricator ad hoc. Further improvement of the design for production methods is not absolutely required but for any economically viable product it must be accomplished. Finally, the knowledge transfer from designer to fabricator, user and maintainer must be accomplished effectively to create a useful product.

III.4 Critical Evaluation of Base Method and Gap Analysis

In the following section, we present a critical evaluation of the original P&B detail design method. This analysis will focus on information gaps that are present in each of the phases of P&B. Our state of mind
as we reviewed the original P&B came from the perspective of our research and desire to develop a systematic design method that supports the concurrent design of products and materials. With this in mind, many of the gaps identified in the original P&B relate to material design. A cursory investigation was conducted in order to point out the gaps in P&B for the future world of engineering design in 2020. Since developing a systematic approach to material design is such a new and vast research field, we felt that we would achieve more value from our answer to the Q4S by focusing on material design, rather than the world of 2020.

In the following section, we have pointed to several key points in which the original P&B design method is insufficient for supporting the integrated design of products and materials.

- **Global team development** – We speculate that the material design process will be most widely used in the future when design processes will take place all across the globe. We also assert that the successful design of materials will require a team of scientists and engineers from all different backgrounds (mechanical engineering, materials engineers, chemists, physicists, computer science specialists, etc.). Therefore, we feel that at the beginning of the design process, time and resources should be devoted to the development of an appropriate team of designers. The original P&B method does not address this need for bringing together people from different educational and cultural backgrounds in order to create a successful design.

- **Use of design tools in Conceptual Design** – In the original P&B method, the design information transforms from a requirements list to a principal solution during the Conceptual Design phase. This core transformation requires many design decisions to be made early in the design process. Implementing design tools, such as ideation techniques, management and planning tools, and the preliminary and selection DSP, would assist the designer in making informed decisions early in the design process.

- **Identify areas for designing new materials** – In the original P&B method, there is little guidance for how to incorporate materials into product designs. Since material design is a relatively new research field, the original P&B does not address the option of designing new materials. In our augmented method, we propose that design new materials compatible with the product design and requirements list should be considered in the product design process. Therefore, at the beginning of the design process, we propose that designers begin looking for areas that support the design of new materials.

- **Multiscale design** – All product design problems can be thought of as multiscale design. The various scales are divided along length scales or hierarchical levels of abstraction. In the product design process, designers should be aware of the various scales in the product design, as well as the higher order scales that the product will need to interface with (e.g., a product that is part of a larger system). The original P&B design method does not mention that the interaction and impact of the product design in a larger, multiscale design problem should be considered throughout the design process.

- **Select or design material** – As states previously, the original P&B design method promotes material selection in the product design process. However, if we consider the fact that products and their related materials can be designed concurrently, the choice of whether to select or design a material should be considered. Obviously, one would only design a material if it is economically advantageous, or if no other material could be satisfactorily incorporated in the product design.

- **Computational Tools** – Computation power has increased significantly since the original P&B was drafted. Therefore, the role of computers in the product design process is noticeably missing in the original P&B method. Computers could be used at all stages in the design process – communication among team members, exploring the feasible design space, creating and selecting a principal solution, determining the preliminary and definitive layouts, and generating appropriate product documentation.
Use of the WWW – Since the original P&B design method was written before the age of computers, the use of the internet as a source of information and communication is not included. The internet is a valuable design tool because of its ability to gather, retrieve, and sort large amounts of information. The internet also provides a medium in which distributed engineers can all work on the same design project. In the complex, distributed environment of the future, the internet is an essential design tool that facilitates the flow of communication and information.

IV. AUGMENTED METHOD

IV.1 Augmented Pahl and Beitz Systematic Design Method

In the following section, we present our method augmented P&B method, which includes the incorporation of material design in the product realization process. The augmented method contains both personalizations and augmentations. Personalizations directly relate to incorporating material design in the product realization process. Augmentations do not deal specifically with material design; these changes to the base method provide an overall infrastructure that can support the material design process. Key aspects of the method will be discussed in detail. Changes to the original P&B detail design method are shown in blue in the figures below.

IV.1.1 Phase 0: Global Team Development

The Phase 0: Global Team Development section was added to the original P&B method to support the need for globally distributed and multi-disciplinary design teams. We observe that designing materials must be a multi-disciplinary project. Experts are needed from engineering design, materials science, mechanical engineering, chemistry, physics, and computer science. We also speculate that collaboration from such a diverse set of experts will most likely take place in the virtual world of distributed design. Therefore, we found it necessary to begin the product design process by gathering a team, establishing a team structure, setting standard ways of communicating information, and creating a PEI diagram.

The fourth step in Phase 0 includes the creation of a data organization structure. This file sharing database is used throughout the design process to record and share information. The format of information that is posted to the file sharing database is standardized to accommodate for the distributed design team with experts from different fields. At the end of each phase in the following augmented method, we recommend that all new information be posted to the file sharing database. This augmentation is important because it reminds the design team the important locations in the design process to record information.

At this stage of the design process, the requirement list has not yet been established. However, the decisions made during Phase 0 should be in agreement with the requirements list. Therefore, we recommend that after the requirements list is created, the design team go back to the decisions that were made during Phase 0 and adjust any disagreeable decisions to be in accordance with the requirements list.

The steps in the global team development phase are shown below in Figure 15. Each step in Phase 0 was written in blue text to show that this phase does not exist in the original P&B design method.
IV.1.2 Phase 1: Planning and Clarifying the Task

Phase 1 in the augmented P&B method involves planning and clarifying the design task. The input information into this phase is the PEI diagram that was generated in Phase 0. At the end of this phase, a product requirements list is specified. More information about the purpose of Phase 1 can be found in the discussion of Phase 1 for the original P&B design method (Section III.1.1).

Several changes were made to the original steps in Phase 1. First, the use of ideation techniques was incorporated to aid in the selection of product ideas. This augmentation was added to give the designers more direction of how they should go about selecting product ideas. Next, the design team is instructed to identify portions of the product design that are compatible with available material design principles and techniques. This augmentation was added in order to encourage the consideration of material design in the early stages of the product design process. If a portion of the product design is identified as a likely candidate for material design, the designers can make future design decisions in agreement with this goal. Finally, the last step of this phase is to publish all new information on the file sharing database. As mentioned before, this is to ensure that designers make a conscious effort to pause from the creative act of design and post all new information to where others can access it.

A complete list of the steps in Phase 1 of the augmented P&B method is displayed below in Figure 16.
Plan and clarify the task:
Analyze the global market and the company situation
Find and select product ideas using ideation techniques
Formulate a product proposal
Clarify the task
Identify areas for materials design
Elaborate a requirements list
Publish requirements list on the file sharing system/database

Figure 16. Augmented P&B - Phase 1

IV.1.3 Phase 2: Conceptual Design

In comparison to the original P&B design method, Phase 2: Conceptual Design in the augmented method has been broken up into several stages. The augmented method was divided into sections in order to provide more guidance to the designer at this critical part early in the design process. Also, in completing the semester project, our team spent a large amount of time in conceptual design. Therefore, we have more experiential knowledge to contribute to this phase than to other phases in the design process.

The input information for Conceptual Design is the part requirements list. During the first part of conceptual design, the goal is to determine a group of the most likely to succeed concepts. These concepts can relate to the overall part, or to part material. We have introduced the use of attention directing tools and the preliminary selection DSP to assist the designers in making informed decisions. We also discuss the use of material function structures, which are analogues to part function structures, in conceptual design.

Material function structures can be thought of as the part function structures discussed in P&B; however, material function structures exist at smaller length scales. For example, consider a product design in which one needs a material with the following characteristics: high strength, low density, water-resistant, non-corrosive in saltwater, and magnetic. These characteristics are analogues to the functions of a part. The next step is for the designer to list many ways to achieve the previous material characteristics. In order to create working structures, feasible paths along the function structures are identified. Combining part function structures (discussed in the original P&B) and material function structures will result in concepts at multiple length scales. Adding material function structures in conceptual design is our way of incorporating aspects of material design early in the design process. By considering the design of materials in conceptual design, we are encouraging a more concurrent multiscale design solution. However, we do not expect the material to be designed at the same pace as the product. Developing some feasible ideas of how material design can be incorporated in product design will be of use in the main material design section located in Phase 3: Embodiment Design. All new information that is generated during this part of Phase 2 is posted to the file sharing database.

During the second part of Conceptual Design, the goal is to determine the design alternatives for the part. The input information to this part of Conceptual Design is a collection of most likely to succeed part concepts. Design alternatives are combined (if possible) and refined. High level economic and technical criteria for the most likely to succeed concepts are determined. Once this additional information is added to the most likely to succeed concepts, they become the design alternatives. All new information is posted to the file sharing database at the end of this section.
The final portion of Conceptual Design begins with the input information of the design alternatives. The selection DSP is employed in order to determine the one or two best design alternatives. The final alternatives are evaluated against economic and technical criteria. Based on this new information, the best alternative, or principal solution is determined. At the end of this phase, all new information is posted to the file sharing database.

A comprehensive view of the augmented Phase 2: Conceptual Design is shown below in Figure 17. All augmentations from the original P&B are written in blue.

![Figure 17. Augmented P&B - Phase 2](image)

**IV.1.4 Phase 3: Embodiment Design**

The goal of the Embodiment Design phase in the augmented P&B method is to determine the definitive layout and material for the product design. The basic structure of Embodiment Design from the original P&B method was not changed. However, the method for incorporating materials in the product design was expanded to include material design.
Embodiment Design is divided into two parts. The input information in the first part of Embodiment Design is the principal solution found in Phase 2. Materials are incorporated in this principal solution via material selection or material design techniques. A more thorough explanation of this is given in the following sections. The cDSP was added to the original P&B to assist the designer in determining material and product layouts. The output information for this part of Embodiment Design is the preliminary product (and material) layout. As usual, at the end of this part of Phase 3, all new information (including all material information) is posted to the file sharing database.

The second part of Embodiment Design begins with the preliminary product (and material) layout. The original P&B method was left unaltered, except for a few additions. The use of computer tools to check for errors, disturbing influences and minimum costs was added to the original P&B method. As with previous phases, all information is published on the file sharing database at the end of this phase.

A step-by-step representation of the augmented Phase 3: Embodiment Design is presented in the figure below.

IV.1.5 Phase 3: Embodiment Design – Materials in Product Design

In the following three sections, we discuss the incorporation of materials in the product design process through material selection and material design. Each of the three phases discussed below belong in Phase 3: Embodiment Design (see Figure 18 above for exact location). The information collected during the material sub-process is fed back into the product design process in Phase 3: Embodiment Design.

IV.1.5a Phase 3a: Planning and Clarifying the Task

The goal of Phase 3a (Figure 19) is to plan and clarify the task of incorporating a material in the product design process. The input information for this phase is the product information determined in Phase 0 – Phase 2. At the end of Phase 3a, a material requirements list is generated. The material requirements
The steps in Phase 3a also deal with the multiscale aspect of materials incorporated in product designs. Therefore, the first three steps guide the designer to research, understand, and model the role and interactions of materials at various length scales. Completing these steps requires input from various specialists, and the use of computational tools. Since multiscale design is currently the subject of much research and is currently not fully understood, significant approximations may need to be established in order to complete the first three steps in Phase 3a.

The role of the material to satisfy the part requirement list is analyzed. Next, a material requirements list is generated. For most product designs, the part requirements list is superior if there is a conflict between the part and material requirements lists. Finally, all new information is published on the file sharing database system.

**IV.1.5b Phase 3b: Material Selection**

In Phase 3b the designer proceeds through the steps of material selection in order to incorporate materials in the product design. Phase 3b is based on the work by Michael F. Ashby and is detailed in his textbook, *Materials Selection in Mechanical Design*. At the beginning of this phase, the material requirements are known. A thorough explanation of the material selection process can be found in Section II.4.2. The output information from phase 3b is the selected material. The selected material must be within the requirements lists from the part and the material. If a material that meets the part and material requirements can be selected from previously existing materials, the designers do not need to proceed to the materials design portion of this phase (phase 3c). However, if a suitable material cannot be found, the designers must proceed to phase 3c in order to design a material that meet part and materials requirements.

The material selection portion of the augmented product design process can be found below in Figure 20.

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**IV.1.5c Phase 3c: Material Design**

Phase 3c details an inductive (or top-down) process for designing materials for the product realization process. The input information to this phase is the material requirements list developed during Phase 3a: Planning and Clarifying the Task. The steps in the material design process were determined (reverse engineered) after completing an example involving material design. A detailed explanation of each step in this phase has been provided below.

The material design process is shown in Figure 21. The dotted line connecting the material selection and material design phases indicates that the material design phase will not be implemented in all product design processes. Designers should proceed to Phase 3c: Material Design only if a suitable material cannot be determined during Phase 3b: Material Selection.
Description of steps in material design method:

1. *Research available techniques for material design* –
2. *Choose best technique for given design problem* –
   The first two steps in the material design process involve the research, analysis and selection of techniques available to design new materials. Current material design techniques include (but are not limited to) alloying, topology design, functionally graded materials, surface treatments, and composites. The best material design technique for a given product design problem is a function of the part requirements list, geometry, and loading conditions. In many ways, this step requires the designer to make a ‘blind’ decision because he or she cannot predict the actual best material design technique for the design problem. However, using design tools such as the preliminary selection and selection DSP can aid in the decision making process. Material design specialists should be consulted at this stage in the material design process in order to choose the best material design technique for the design problem.

3. *Develop material models* – Once the material design technique has been chosen, it is time to develop material models that capture the requirements, geometry, loading, and design technique of the part and material. With current material knowledge and computing power, this step may involve several iterations. The goal in completing this step is to develop computer programs in which the user can observe the effects changing material performance requirements on the design of the material.

4. *Model the processing-structure-property-performance (p-s-p-p) interactions of the material* –
5. *Develop simulations that capture the p-s-p-p interaction* –

Figure 21. Augmented P&B - Phase 3c
The fourth and fifth steps in the material design process require the designer to model and develop simulations for the processing-structure-property-performance (p-s-p-p) interactions in the material. These steps illustrate the multiscale nature of designing materials. Since our aim is to provide an inductive approach to designing materials, it is important that designers are able to travel along the p-s-p-p path from performance to processing. Modeling and developing simulations that capture the p-s-p-p chain of a material involve high-power computer tools, large amounts of material information, and experts from many fields. Once the p-s-p-p chain has been modeled, the material can be designed from part performance to material manufacturing processing path.

6. **Design material using simulation models** – After the necessary models have been developed, the material is designed in accordance with part and material requirements lists. Before the material solution is found, the various material models must be joined. If the material p-s-p-p chain has been modeled thoroughly and accurately, this step in the material design process should be relatively simple to complete.

7. **Analyze the effect of material on various length scales of product design** – Once the material has been designed, it is important to analyze the effect of the material on the part design at larger length scales. For example, the part design may be incorporated in a larger system design. The material should not violate and system requirements set at larger length scales in the multiscale design problem. Designers should also consider how the material design of a single part can help meet overall system requirements and goals.

8. **Publish material design information to file sharing database** – As with each phase in the augmented method, new information regarding the material design should be recorded and posted to the file sharing database. This step is important for communicating information throughout the design team as well as increasing knowledge in the material design community.

**IV.1.6 Phase 4: Detail Design**

The last phase in the augmented method is Detail Design. The input information in the detail design phase is the definitive product layout and material. The purpose in completing this phase is to document the decisions made during the product design process. For a more thorough explanation of the role of Detail Design in the product design process, see Section III.1.4.

This phase was not significantly augmented from the original P&B method. The phrase “and material models” was added to the first step indicating that information in the material models should be documented as part of the product description. As usual, all information generated during this phase of the augmented method should be recorded and posted to the file sharing database.
IV.2 Requirements List

The following section contains two requirements lists that were used in developing the augmented method. The first requirements list (in Table 3) details the general and specific requirements that were used to update the original P&B method. Items in plain text indicate requirements that were reverse engineered from the original P&B method. Items underlined and italicizes are requirements developed to update the original P&B to support the incorporation of material design in the product design process.

The requirements list in Table 4 lists requirements that were developed specifically to incorporate material design in the augmented P&B method. The material design requirements list was written based on our experience in completing a material design example of a cantilever beam. This material design example problem is discussed in more detail in the validation section and in the project report. In the material design requirements list, O stand for requirements for the Original P&B design, P stands for Personalizations, and A stand for Augmentations in our material design method.

Table 3. Requirements List - Updated P&B

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<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Problem Statement:</strong></td>
<td>Identify the requirements list for the augmented and personalized Pahl and Beitz systematic design method useful in the global, collaborative, and distributed engineering design world of 2020.</td>
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<tr>
<td><strong>#</strong></td>
<td><strong>Demand/Wish</strong></td>
<td><strong>Requirements</strong></td>
<td><strong>Responsible</strong></td>
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<tr>
<td><strong>General Requirements</strong></td>
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<tr>
<td>1</td>
<td>D</td>
<td>Encourage problem directed approach</td>
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<tr>
<td>2</td>
<td>W</td>
<td>Be applicable to every type of design activity</td>
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<tr>
<td>3</td>
<td>D</td>
<td>Facilitate the application of known solutions</td>
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<td>4</td>
<td>W</td>
<td>Be easily taught and learned</td>
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<td>D</td>
<td>Should facilitate inventiveness and guide the abilities of the designers</td>
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<tr>
<td>D</td>
<td>Serve as a basis of communication (clearly understood products)</td>
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<tr>
<td>D</td>
<td>Be compatible with concepts, methods, and findings of many disciplines</td>
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<tr>
<td>D</td>
<td>Be compatible with modern computing technology</td>
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<td>D</td>
<td>Not rely on finding solutions by chance</td>
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<tr>
<td>D</td>
<td>Emphasize the need for objective evaluation of results</td>
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<td>D</td>
<td>Should be open to adaptation, augmentation, and personalization</td>
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<td>D</td>
<td>Should Dispel Prejudice</td>
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<td>D</td>
<td>Facilitate collaborative design</td>
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<tr>
<td>D</td>
<td>Facilitate design by engineers that are globally distributed</td>
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<tr>
<td>D</td>
<td>Enhance communication of ideas among team members</td>
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<tr>
<td>D</td>
<td>Be compatible with all languages</td>
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<td></td>
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<tr>
<td>D</td>
<td>Consider ideas from all regions of the world</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Support working amongst members across different time zones</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Use computers to aid in design and communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Store and transmit documents electronically</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Search for ideas and solutions via the world wide web</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>Design using computer tools such as simulations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Design for open engineering systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Maintain design freedom in the early stages of the design process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>Design for mass customization through open engineering systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Design for mutability, modularity, and robustness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Design for distributed design-manufacture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>Integrated design of product and process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Design for manufacture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Design for assembly</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Specific Requirements**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Establish Team</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Identify global designers and suppliers</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Select team members and leaders</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Develop data organization structure</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Create project goals and timeline</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Establish a team contract</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Define Problem</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>Evaluate market and economic situation</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Identify constraints and clarify boundary conditions</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>Search for product/concept ideas</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>Set clear attainable goals</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Develop requirements list</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Develop Concepts</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Abstract problem into solution neutral statement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Use computational tools tool to explore design space</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Create function structure</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Search for variants</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Search for solution principles for sub-functions</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4. Requirements List – Material Design in P&B

| --- | --- | --- | --- |

**Problem Statement:**
Identify the requirements list for the augmented and personalized Pahl and Beitz systematic design method that will satisfy the needs of integrated design of products, materials, and processes.

<table>
<thead>
<tr>
<th>#</th>
<th>Demand/Wish</th>
<th>Requirements</th>
<th>OPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>D</td>
<td>Encourage problem directed approach</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
<td>Facilitate the application of known solutions</td>
<td>O</td>
</tr>
<tr>
<td>3</td>
<td>W</td>
<td>Be easily taught and learned</td>
<td>O</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>Should facilitate inventiveness and guide the abilities of the designers</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>D</td>
<td>Serve as a basis of communication (clearly understood products)</td>
<td>A</td>
</tr>
<tr>
<td>6</td>
<td>D</td>
<td>Be compatible with concepts, methods, and findings of many disciplines</td>
<td>O</td>
</tr>
<tr>
<td>7</td>
<td>D</td>
<td>Be compatible with modern computing technology</td>
<td>A</td>
</tr>
<tr>
<td>8</td>
<td>D</td>
<td>Not rely on finding solutions by chance</td>
<td>O</td>
</tr>
<tr>
<td>9</td>
<td>D</td>
<td>Emphasize the need for objective evaluation of results</td>
<td>O</td>
</tr>
<tr>
<td>10</td>
<td>D</td>
<td>Should be open to adaptation, augmentation, and personalization</td>
<td>A</td>
</tr>
<tr>
<td>11</td>
<td>D</td>
<td>Should dispel prejudice</td>
<td>O</td>
</tr>
<tr>
<td>12</td>
<td>D</td>
<td>Facilitate collaborative design</td>
<td>A</td>
</tr>
<tr>
<td>13</td>
<td>D</td>
<td>Use computers to aid in design and communication</td>
<td>A</td>
</tr>
<tr>
<td>14</td>
<td>D</td>
<td>Store and transmit documents electronically</td>
<td>A</td>
</tr>
<tr>
<td>15</td>
<td>D</td>
<td>Search for ideas and solutions via the world wide web</td>
<td>A</td>
</tr>
</tbody>
</table>
### IV.3 Core Transformations

Core transformations are the way in which information changes as one moves through the design process. In order to determine the core transformation in the augmented P&B method, we first looked that the information that is known at the beginning and end of each phase. After observing the nature at the beginning and end of each phase, we deduced the information transformations that were taking place. The core transformations for the augmented P&B method are displayed below in Table 5.
In the following two sections, we discuss the underlying assumptions and importance of the core transformations associated with the incorporation of material in the product design process. Refer to Section III.3 for an explanation of the underlying assumptions and importance of the core transformations that take place in the remainder of the product design process.

Table 5. Core Transformations - Augmented P&B

<table>
<thead>
<tr>
<th>Phase</th>
<th>Info at START</th>
<th>Core Transformation</th>
<th>Info at END</th>
</tr>
</thead>
</table>
| Phase 0: Global Team Development | • Project task  
• Relevant markets  
• Economy  
• Company goals | • The design team is chosen based on the project tasks and goals  
• The project tasks are mapped into a P&E diagram | • PEI diagram  
• Relevant design team  
• Team contract  
• File sharing database |
| Phase 1: Plan and Clarify | • PEI diagram | • Project task used to create project proposal  
• Project proposal used to generate a requirements list | • Document describing market and economy  
• Requirements list for part  
• Product goals and constraints |
| Phase 2.1: Conceptual Design | • Part requirements list | • Requirements list used to specify function structures  
• Function structures transformed into working principles  
• Working principles used to choose likely concepts | • Most likely to succeed concepts |
| Phase 2.2: Conceptual Design | • Most likely to succeed concepts | • Concepts are combined and evaluated against economic and technical criteria | • Design alternatives |
| Phase 2.3: Conceptual Design | • Design alternatives | • Alternative is chosen by implementing the selection DSP  
• Evaluate against economic and technical criteria | • Alternative (principal solution) |
| Phase 3.1: Embodiment Design | • Alternative (principal solution) | • A preliminary layout is assigned to the principal solution  
• The design goes from an abstract concept to a product with form | • Preliminary layout |
| Phase 3.1a: Embodiment Design | • Part information from Phase 0 – Phase 3.1  
• Part requirements list | • Material task is planned and clarified  
• Multiscale nature of material design problem is considered | • Material requirements list |
| Phase 3.1b: Embodiment Design | • Material requirements list  
• Database of available materials | • Material selection process | • Selected material |
| Phase 3.1c: Embodiment Design | • Material requirements list | • Determine material design technique  
• Develop material models  
• P-S-P-P chain of material relationships is modeled | • Designed material |
| Phase 3.2: Embodiment Design | • Preliminary layout | • The preliminary layout is refined and weak spots are removed  
• Product and material are analyzed using computational tools | • Definitive layout and product material |
| Phase 4: Detail Design | • Definitive layout and product material | • Definitive layout is given dimensions  
• and a parts list is created  
• Documentation on the lifecycle of the product is produced | • Detail part drawings  
• Parts list  
• Material specifications  
• Manufacturing, assembly, use, and disposal instructions |
Underlying Assumptions in Core Transformations

Phase 3.1a – Planning and Clarifying the Task
In this phase, it is assumed that the goal of the design process is to create a product (not a process or service) and materials will be incorporated in the product design. It is also assumed that the product is a part of a larger, system design problem. Finally, we assume that the designers have access to materials experts, material information, and computational tools.

Phase 3.1b – Material Selection
In this phase of the design process, we assume that the designer is familiar with the material selection process detailed by Michael F. Ashby. It is also assumed that the design team has access to a vast amount of material information and the computer software to sort and display this information. Finally, we assume that the designer has the knowledge and computational power to determine whether or not a material exists that meets the product and material requirements lists.

Phase 3.1c – Material Design
There are many assumptions associated with the material design phase. First, we assume that there exists a material design technique that is suitable for the given material design problem. We also assume that the design team is able to create material models and model the material interaction along the p-s-p-p chain. This assumption may be invalid considering the current understanding of the property-structure and structure-processing relationships in materials. However, we believe that these relationships will be more accurately and thoroughly understood in the future. Next, we assume that a material can be designed that meets the product and material requirements and obey chemical and physical laws. Finally, we assume that the effect on larger length scales in the multiscale design problem can be modeled and predicted.

Importance of Core Transformations

Phase 3.1a – Planning and Clarifying the Task
In this phase, the material task is defined and a material requirements list is generated. The goals for the material are also established. This core transformation is also important because it requires that the material requirements list be in agreement with the product requirements list. In order to choose or design the best material for the product, it is important that the design team complete each step in this phase thoroughly.

Phase 3.1b – Material Selection
During the material selection phase, the material requirements list is used as a guide to select the best material for the product design. In most product design processes, implementing material selection techniques will be sufficient to incorporate materials in the product design process.

Phase 3.1c – Material Design
In Phase 3.1c, a material is designed based on the product and material requirements lists. In this core transformation, the designers do not simply choose the best material for the job. Instead, a material is tailor-made to meet the exact design requirements. This core transformation is important to the product design process; in addition, this core transformation represents a paradigm shift in the way that materials are incorporated in the product design process. Materials are no longer static entities. Designers now have the capability to alter materials for specific design purposes.

IV.4 Critical Evaluation of Augmented Method and Gap Analysis

In the following section, we present a critical evaluation of our augmented method. First, we compare the augmented method to the gaps that were identified in the original P&B method. Next, we address how the augmented method addresses the incorporation of material design in the product design process. Finally, we identify any gaps in the augmented method, and future work that will help fill those gaps.
IV.4.1 Augmented Method Compared to P&B Base Method

The gaps that were identified in the original P&B method have been listed below. We have identified how the augmented method attempts to resolve each gap. Gaps in the original method that were fully addressed in the augmented method are marked with a check mark.

- **Global team development** – Phase 0: Global Team Development was added to the augmented method. This phase facilitates the organization of a team of experts from around the world. Several key points in this phase are the establishment of a design team and team structure, a file sharing database with standard conventions of communicating information, and the completion of a PEI diagram. This phase is particularly important in the field of material design where collaboration from experts from a variety of fields is necessary for successful material designs.

- **Use of design tools in Conceptual Design** – The use of design tools, such as attention directing tools, the preliminary selection DSP, and the selection DSP, have been added to the Conceptual Design phase. The purpose of these tools is to assist the designer in making decisions. As design problems become increasingly complex, it is important to use design tools to point out the best solutions when they are non-obvious.

- **Identify areas for designing new materials** – In Phase 1: Plan and Clarify the Task, designers are encouraged to look for areas to incorporate material design in the product design process. This augmentation was added to show that once the task has been defined, it is not too early to think about material design.

- **Multiscale design** – Multiscale design aspects were addressed in the augmented method in Phase 2: Conceptual Design and Phase 3c: Material Design. In Phase 2 the idea of function structures and working principles was addressed in relationship to material functions structures. Also, in the material design phase of the augmented method, the impact of material on the other scales of the multiscale design problem was considered.

- **Select or design material** – In the augmented method, the designer is given the option to select a material or design a material to be incorporated in the product design. Designers are encouraged to design a new material on if there does not exist a material that meets the product and material requirements lists.

- **Computational Tools** – Computational tools are used throughout the augmented method. In Phase 0: Global Team Development, computers are used as a way of organization and communication among team members. Also, computers and the internet are used to store and share information in a distributed design environment. In the material selection phase, computers are used to sort and display information of existing materials. In the material design phase, designers use computers to create material models, model the p-s-p-p chain of materials, and design the desired material.

- **Use of the WWW** – The WWW is used as a means of communication and data storage in each phase of the augmented method. The internet is also used as an extensive database of material information that is useful in the material selection process.

IV.4.2 Augmented Method and Material Design

Our main goal in augmenting the base P&B method was to create a product design method that could support the design of materials. In our critical evaluation of the augmented method, it is important to investigate whether this goal has been achieved.

**Creating an Environment for Material Design**

The first step in incorporating the design of materials in the product design process was to create an environment and scaffolding to support material design. Setting the stage for material design begins in
Phase 0: Global Team Development. During this phase relevant experts are gathered to create the appropriate design team. A file sharing database is established to accommodate for distributed design. At various points throughout the design process, designers are reminded to post new information to the file sharing database. This reminder ensures that information will be available to other designers when needed. Posting information regularly is also a good way to keep track of the progression of information and decisions in the design process.

The use of computational tools is necessary for the design of materials. Computer tools have been added to the base method in each phase. The use of computer tools is particularly important when the design begins to select or design a material for the product. Computer tools also allow for the modeling and analysis of the multiscale nature of the material design problem.

Incorporating the material selection technique is also crucial in the material design process. Before designers can proceed to the material design process, they must be sure that there is not material in existence that can meet the given product and material requirements. Being aware of materials that narrowly fail to meet the material requirements also gives designers a basis for beginning the material design process.

Material Design Method
The material design method in the augmented P&B method is detailed in Phase 3c of the first part of Embodiment Design. The material design method starts with the material requirements lists. Through a series of modeling and simulation steps, the material is designed to meet the given requirements. In providing a detailed method for the design of materials, we have achieved our original goal of developing a product design method that supports material design.

IV.4.3 Augmented Method – Gaps and Future Work
In the following section, we have listed several knowledge gaps in our augmented method. These gaps map into future work that can be addressed in additional courses, papers, and /or research.

- **Material design in a distributive environment** – The infrastructure for distributive material design was introduced in the augmented method; however, we feel that this topic will require more research and examples before an effective framework from distributive material design is established. In material design examples that are related to our research (such as the MURI project) we have observed the inefficiencies of material design in a distributive environment. Simply reminding teams to post relevant information to a file sharing database is not enough to ensure the efficient flow of information. How can files created in different software packages communicate? How can we standardize language and work standards for designers located around the globe? What is the most efficient way to split up the design task? These questions should be addressed in future work associated with our material design method.

- **Modeling the P-S-P-P material chain** – In the material design phase of the augmented method, designers are instructed to develop simulations that capture the p-s-p-p interaction chain of materials. The development of such a simulation program is currently the topic of much material design research. In materials research today, there is little known about the inductive property-structure and structure-processing relationships in materials. To expect a material design team in the near future to develop conclusive p-s-p-p relationships imposes unrealistic expectations. Perhaps a more realistic goal for current material design problems is to explore the deductive known relationships in existing materials in order to aid in the material design process. For future work, we should investigate the inductive property-structure and structure-processing relationships in materials.

- **Deductive models in a inductive process** – In the material design phase of our augmented method, we presented an inductive process. However, in designing materials, we make use of deductive modeling programs. In the future, it would be interesting to investigate the effect of
deductive modeling tools on an inductive process. More work should also be invested in infusing inductive characteristics in our current material modeling techniques.

- **Multiscale design** – The idea of multiscale design was mentioned in our augmented method. One of the later steps in the material design phase recommends that the designers predict how the designed material affects the product design at larger length scales. This cursory look at multiscale design in the material design process is insufficient. In our future work on multiscale design, we should consider the following questions: How should the various scales be modeled? How can we model the interactions among scales? Is it acceptable to take a deductive approach to multiscale design? By incorporating answers to the preceding questions in our augmented method, we will have significantly improved our contribution to the field of material design.

V. VERIFICATION OF AUGMENTED METHOD

V.1 Validation Square

In terms of making progress towards validating our augmented method, we consider the Validation Square construct. The Validation Square is a tool that can be used to ease the leap of faith required to move from theory to practice in engineering design methodology. The progression of building confidence in the usefulness of the method is broken into four stages:

1. **Theoretical Structural Validity** – Is the method internally consistent and logical?
2. **Empirical Structural Validity** – Is the selected example appropriate to test the method?
3. **Empirical Performance Validity** – Did the use of the method in that example result in a successful outcome?
4. **Theoretical Performance Validity** – Can we assume that the method can be successfully applied to other example problems?

If we have answered ‘yes’ to all four of the previous questions, then we have significant confidence in proposing that the method is truly valid. The Validation Square is presented below in Figure 23.

![Figure 23. Validation Square](image-url)
Now, we consider the application of the Validation Square to our augmented method and example problem. In the following paragraphs, we discuss how our augmented method and example problems relate to each quadrant of the Validation Square.

1. **Theoretical Structural Validity** –
   - The material design portion of the augmented method was reverse engineered after completing several example problems involving material design. Since this portion of the augmented method was modeled after a successful material design process, we claim that the augmented method is internally consistent.
   - The material selection portion of the augmented method was taken from Asbhy’s textbook *Materials Selection in Mechanical Design*. This method is a commonly accepted method used in many product design applications. Therefore, we believe that the material selection portion of the augmented method is internally consistent.
   - The remainder of the augmented was based on the P&B design method. The P&B design method is based on engineering design best practices. This method is also widely accepted as a valuable and consistent design method. Although we augmented the P&B method, our augmentations did not change the overall flow and flavor of the P&B method. Since the remainder of our augmented method was based on the P&B method, we assert that the augmented method is internally consistent.

2. **Empirical Structural Validity** – A cantilever beam and its material were designed as an example problem to support our augmented method for the design of materials. The example problem included each of the aspects addressed in our augmented method. However, we feel that perhaps the beam example was oversimplified. It would be valuable to complete a more complex multiscale design example (such as the design of the fan / shaft subassembly and assembly) before we claim, with confidence, the empirical structural validity of our method.

3. **Empirical Performance Validity** – The results obtained from completing the design of a cantilever beam and its material were interesting, predicted, and useful. By obtaining useful results when the augmented material design method was applied to the cantilever example problem, we begin to feel confident that our augmented method contains empirical performance validity. However, as mentioned in the previous paragraph, the cantilever example problem may be too simple to test the intricacies of our augmented method. Before we can fully claim the empirical performance validity of our augmented method, we must observe the results that are obtained after completing a more complex, multiscale example (such as the design of the fan / shaft subassembly and assembly).

4. **Theoretical Performance Validity** – At this point in our research, we cannot claim with confidence that our augmented method will produce useful results when applied to additional product / material design problems. One way to build our confidence in this area is to complete a variety of examples in which the product and material are designed as part of a multiscale design problem.

The updated and personalized Validation Square is displayed below in Figure 24. The bold, solid line around the first quadrant indicates that we are confident of the theoretical structural validity of our augmented method. The wide dashed line surrounding the second quadrant shows that there are currently several holes in our argument before we can claim with confidence that our augmented method is empirically structurally valid. The small dashed line around the third quadrant shows that we observe quite a few areas for improvement in our method and example problems before we can claim the empirical performance validity of our augmented method. Finally, there is no border surrounding the fourth quadrant of the Validation Square. This indicates that we currently have no basis to claim the theoretical performance validity of our augmented method.
Material design method was reverse engineered from material design example (design of cantilever beam).

Beam example involved the design of new materials. However, the example may have been too simple.

V.2 Project Description

The Semester Project consisted of three main deliverables. The first deliverable was for the project team to illustrate the integrated design of product and material by designing a loaded cantilever beam and its associated material. The next deliverable included a more comprehensive, multiscale material design example. In the comprehensive example, the concurrent product and material design of a fan shaft subassembly was investigated. The final semester project deliverable was for Stephanie and Hannah to present two lectures on material design to the ME6101 class. Thorough descriptions of the project tasks are given below.

Material Design – Simple Example:
The simple example is intended to show the benefits of material design over material driven-design and material selection. Therefore, we developed an example involving the design of a square-cross-section cantilever beam for minimum mass and specified deflection. To compare the three methods, the design of the beam was carried out using each of the three methods. The full example problem is included in the Project Report, Appendix 2. Both Hannah and Stephanie worked to develop the simple example with significant assistance from Greg Mocko on the material design portion.

Material-Driven Design
In the material-driven design portion of the simple example, the material for the beam is chosen by the designer based on her experience with the material. The equation for the deflection of the beam is then solved to find the width of the beam. There is a direct connection between the material choice and the product dimensions.

Material Selection
In the material selection portion of the example, the designer goes through a systematic process to determine the material based on the constraints and objectives of the problem. Once the material has been chosen, the beam deflection equation is solved to find the width of the beam. In this case, the material choice does determine the size of the beam directly, as in material-driven design; however, the actual material choice is determined from the product requirements systematically, and is less subject to designer bias for or against certain materials.
Material Design
In the material design portion of the simple example, the material is designed concurrently with the beam width. In order to design the beam, a model for the beam material is created and is integrated into a part model for the beam. The part model incorporates the external forces applied to the beam as well as internal effects due to the beam material, such as the force due to the weight of the beam itself. This part model is then used to explore the design space and select the best combination of design parameters.

Material Design – Comprehensive Example:
The comprehensive example is intended to demonstrate material design within a multi-scale design problem that is solved by a team of distributed, collaborative engineers. The design problem chosen for this demonstration is the design of a system of ventilation fan assemblies. The multi-scale nature of this problem is shown in Figure 25.

![Figure 25. Multi-Scale Nature of Ventilation System](image)

To meet the collaboration criterion, the design of the fan blade was assigned to Emad Samandiani, a fellow ME6101 and SRL student, while the design of the shaft was assigned to Hannah and Stephanie. Ideally, our material design method will be used to design this multi-scale system; however, the method for material design was not reverse-engineered until late in the semester. Nevertheless, Emad has created the part model for the fan blade, and once the material model has been developed, it will be linked to the fan blade model. Part and material models will also be developed for the shaft. Both the fan blade and shaft models will then be incorporated into an assembly model. Models may also be developed for the motor and duct.

When developed, the assembly model will incorporate a number of multi-scale interactions. Besides the direct interactions between the materials and their associated parts, there are also interactions between parts in the assemblies. For example, the weight of the fan blade will apply a load to the shaft. Also, the duct, motor, and shaft shapes and sizes will have aerodynamic effects on the performance of the fan blades. All of these interactions will be captured in the assembly model. In future work, the assembly model and associated part models will be completed, and the design parameters will be selected with a cDSP.

Lecture Material:
In addition to the development of the examples, we also put together two lectures on material design for our fellow students in ME6101. The first lecture, developed and given by Hannah, covered the background and motivation for material design. The majority of the information for this lecture came from our literature review and is covered in detail in the answer to the Q4S. The second lecture, developed and given by Stephanie, covered the applications of material design. Specifically, the simple and comprehensive examples were explained in detail. The majority of the information for the second lecture
V.3 Project Motivation

We have four goals for undertaking the semester project. We want to develop and validate our material design method, meet our A0 goals for ME 6101, provide lecture materials for ME 6101 and ME 3180, and add value to our personal research goals.

Why do we need to validate method? Explain aspect to be verified.
Our first goal for the semester project is to use the project to help us develop and validate our augmented method. We want to use the project to help us develop the method because there is no systematic method for the design of materials, so there is no existing method that we can augment. We hope that we will be able to reverse engineer our material design method once we have tried to achieve material design by conducting an example. Once we have our augmented method, we will also use the project to validate an aspect of the method. Using the Validation Square construct, we hope to use the project to assess the empirical structural validity and empirical performance validity of our material design method.

What are our goals, how will the project help us to meet them?
Our A0 goals are shown below along with the anticipated value and reasoning. This table was leveraged from our project proposal.

<table>
<thead>
<tr>
<th>A0 Goal for PRJ</th>
<th>Anticipated Value</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Learn how to frame questions for future research and determine the scope of</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Master’s Theses</td>
<td>Value &gt; 1</td>
<td>The semester project on materials design will allow us to learn about materials design and determine the scope of our Master’s Theses.</td>
</tr>
<tr>
<td>2. Learn about current materials design processes in order to build on them</td>
<td>Value &gt; 1</td>
<td>In completing the semester project, we will be investigating the history, benefits, current uses, and future uses of materials design. Part of</td>
</tr>
<tr>
<td>for future materials design research</td>
<td></td>
<td>the project will require that we become familiar with current materials design processes.</td>
</tr>
<tr>
<td>3. Learn to apply materials design concepts to engineering problems, and vice</td>
<td>Value &gt; 1</td>
<td>The example problems in the semester project will require that we apply our materials design theory to specific design problems.</td>
</tr>
<tr>
<td>versa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Learn to communicate research findings in the academic community via</td>
<td>Value = 1</td>
<td>The semester project will be the ‘laboratory’ in which we perform tests and collect data that we will use in writing conference papers. The</td>
</tr>
<tr>
<td>conference and journal papers</td>
<td></td>
<td>practice of writing the end of semester report will also be a valuable exercise.</td>
</tr>
<tr>
<td>5. Learn to “work smart” in a group setting</td>
<td>Value &gt; 1</td>
<td>By dividing up this large project and performing distributed design, we are learning how to work smart in a group setting.</td>
</tr>
</tbody>
</table>

What are our research goals, how will the project help us to meet them?
Our research goal for this semester is to determine research questions to address in our Master’s theses. This project will help us to meet this goal by identifying gaps in the literature that we would like to pursue in further research. By completing the project, we will gain a deeper understanding of the challenges in systematic material design, and we will be able to focus our future efforts on addressing those challenges.

Why are lecture materials needed for ME3180 and ME6101? What do we hope to achieve with lectures?
Our final goal for the project is to develop lecture materials for ME6101 and ME3180, Machine Design. We want to develop lecture materials on material design for ME6101 because the theme of this semester is the integrated design of products, processes and materials. The information we gather for our project will be presented to our classmates in ME6101 to introduce them to the topic so that they can include augmentations for material and multi-scale design into their answers to the Q4S.
We also want to develop ways of integrating material design topics in the Machine Design curriculum for the Woodruff School in Savannah. Jitesh Panchal will be teaching Machine Design in Savannah and wants to introduce the students to topics in material design early in their engineering education. The course will be designed to build on topics from ME1170 (Engineering Graphics), ME2016 (Computing Techniques), ME2110 (Creative Decisions & Design), CoE2001 (Statics), CoE3001 (Deformable Bodies), and ME3201 (Mechanics of Materials), some of which will be restructured to include more use of computational methods and information technology. Our goal in developing lecture materials for ME3180 is to put together at least one simple design example that includes material design and could be incorporated into the curriculum of Machine Design.

**V.4 Project to Verify Augmented Method**

This project is useful for assessing the validity of our augmented method. Specifically, the semester project is useful for assessing empirical structure validity and empirical performance validity of our proposed method. Empirical structural validity and empirical performance validity are the second and third steps, respectively, to building confidence in the theoretical performance validity of our method. Empirical structural validity refers to the appropriateness of the chosen example to the proposed method. In our case, the aspect of our method that we are trying to verify is the material design process in the augmented method. Since our cantilever beam example does involve the design of the material, it is an appropriate example for this method; however, the requirements for the cantilever beam are not complex. As such, the cantilever beam example may be too simplified to adequately assess the validity of the method.

Empirical performance validity refers to the ability to produce useful results for the chosen example problem. Indeed, the results of our simple example are predicted, interesting, and useful. The results are predicted because the stronger material is concentrated more heavily at the base of the cantilever, where the largest bending moment is applied, while the lighter, weaker material is used throughout the remainder of the beam. Although the simple example results are useful, the oversimplification of the problem requirements, and the multitude of simplifying assumptions that were applied to solve the problem combine to reduce the confidence in the empirical performance validity of the method.

The confidence in both the empirical structural validity and the empirical performance validity of the proposed method will be increased upon completion of the comprehensive example.

**V.5 Project Results**

The results for the design of a loaded cantilever beam are discussed below. As a result of the tasks undertaken in this project, we have shown that systematic material design has promise for achieving better product performance than material selection. This conclusion is demonstrated by the results of the three simple cantilever beam designs, summarized in Table 7.

<table>
<thead>
<tr>
<th>Material-driven Design</th>
<th>Material Selection</th>
<th>Material Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material(s)</td>
<td>Iron</td>
<td>Steel, Aluminum</td>
</tr>
<tr>
<td>width (a), m</td>
<td>0.033</td>
<td>0.036</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>16.92</td>
<td>6.93</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>1.58</td>
<td>9.14</td>
</tr>
</tbody>
</table>

As shown in the table, material selection did improve the product performance by reducing the mass of the beam and achieving a higher safety factor; however, the material design beam was able to achieve an even lower mass and higher safety factor. It is counter-intuitive that adding steel to an aluminum beam would result in an overall less massive beam, but by only adding steel in the areas that experience
the largest bending moment, the material design beam capitalizes on the strength of steel and the low density of the aluminum simultaneously. Although the simple example has many limiting assumptions, we assert that these results are still valuable as motivation for future material design research.

The results of the comprehensive ventilation system design are still to be determined. Once the modeling and simulation of the part and assembly interactions is complete, design parameters can be determined using a compromise Decision Support Problem. Completion of this more complex example will add value to our argument for the validity of our augmented method.

VI. UTILITY

In the following section, we discuss how the augmented method provides a complete and satisfactory answer to the Q4S.

VI.1 Augmented Method as Answer to Q4S

The augmented and personalized Q4S is given below.

We imagine a future in which engineers design materials to meet increasingly complex requirements encountered in the product realization process.

We recognize that solutions evolve over time. Accordingly, we expect to build on what has been done before.

In this context, we want to provide a method to support the realization of products through integrated product, material, and process design.

How should the Pahl and Beitz systematic design method be personalized and augmented to support the realization of products through integrated product, material, and process design?

In order to successfully answer the Q4S, we must provide a method (based on the P&B method) that supports the realization of products through integrated product, material, and process design. Our augmented method should also be applicable in the future, when we assume that materials will be designed in order to meet increasingly complex product requirements. Several key phrases in the augmented Q4S are listed below and discussed.

“Provide a method…” – The augmented method contains the steps needed to carry out the product design process. The augmented method is complete and internally consistent.

“Build on what has been done before” – The augmented method was based on the P&B design method. The overall layout and scaffolding of the original P&B method were maintained in the augmented method. The material selection of the augmented method was based on Ashby’s textbook *Materials Selection in Mechanical Design*.

“…Integrated product, material, and process design” – The augmented method supports the design of materials in the product design process. The material design portion is imbedded in the augmented method and takes place at various points during the product design process. The augmented method also supports the research and development of various methods for designing materials.

VI.2 Augmented Method and Requirements List

In order for a complete assessment of the utility of our augmented method, we also investigated how well our augmented method addressed several key requirements from our requirements lists. In the following
table, we presented several key requirements and the steps or phases in the augmented method that address the requirements.

Table 8. Key Requirements Reflected in Augmented Method

<table>
<thead>
<tr>
<th>Key Requirement</th>
<th>Step / Phase in Augmented Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establish Team</td>
<td>Phase 0: Global Team Development</td>
</tr>
<tr>
<td>Identify relevant experts needed for material design</td>
<td></td>
</tr>
<tr>
<td>Select team members and leaders</td>
<td></td>
</tr>
<tr>
<td>Develop data organization structure</td>
<td></td>
</tr>
<tr>
<td>Create project goals and timeline</td>
<td></td>
</tr>
<tr>
<td>Establish a team contract</td>
<td></td>
</tr>
<tr>
<td>Serve as a basis of communication (clearly understood products)</td>
<td>Publish information on database</td>
</tr>
<tr>
<td>Facilitate collaborative design</td>
<td>Plan and clarify task using the 7 management and planning tools</td>
</tr>
<tr>
<td>Facilitate the application of known solutions</td>
<td></td>
</tr>
<tr>
<td>Should facilitate inventiveness and guide the abilities of the designers</td>
<td>Decision-making based on attention directing tools and preliminary selection and selection DSP</td>
</tr>
<tr>
<td>Not rely on finding solutions by chance</td>
<td></td>
</tr>
<tr>
<td>Make Decisions</td>
<td>Method for designing new materials</td>
</tr>
<tr>
<td>Assist engineer in making design decisions</td>
<td></td>
</tr>
<tr>
<td>Design for distributed design-manufacture</td>
<td>Use computational tools in design process</td>
</tr>
<tr>
<td>Allow for design of product, material, and design process</td>
<td></td>
</tr>
<tr>
<td>Facilitate inductive materials design methods</td>
<td></td>
</tr>
<tr>
<td>Must allow for equal consideration of the selection and design of materials</td>
<td>Galdzer information from product design when planning material design task</td>
</tr>
<tr>
<td>Identify function structure equivalent</td>
<td></td>
</tr>
<tr>
<td>Search for variants</td>
<td></td>
</tr>
<tr>
<td>Search for solution principles for sub-functions</td>
<td></td>
</tr>
<tr>
<td>Combine solution principles into concepts</td>
<td></td>
</tr>
<tr>
<td>Be compatible with modern computing technology</td>
<td></td>
</tr>
<tr>
<td>Use computers to aid in design and communication</td>
<td></td>
</tr>
<tr>
<td>Store and transmit documents electronically</td>
<td></td>
</tr>
<tr>
<td>Search for ideas and solutions via the world wide web</td>
<td></td>
</tr>
<tr>
<td>Design using computer tools such as simulations</td>
<td></td>
</tr>
<tr>
<td>Validate model using computational tools</td>
<td></td>
</tr>
<tr>
<td>Be compatible with concepts, methods, and findings of many disciplines</td>
<td></td>
</tr>
<tr>
<td>Allow for design of product, material, and design process</td>
<td></td>
</tr>
<tr>
<td>Define Problem</td>
<td></td>
</tr>
<tr>
<td>Identify constraints and clarify boundary conditions</td>
<td>Develop material requirements list</td>
</tr>
<tr>
<td>Search for product/concept ideas</td>
<td></td>
</tr>
<tr>
<td>Set clear attainable goals</td>
<td></td>
</tr>
<tr>
<td>Develop requirements list</td>
<td></td>
</tr>
<tr>
<td>Should dispel prejudice</td>
<td></td>
</tr>
<tr>
<td>Allow for design of product, material, and design process</td>
<td>Design of material</td>
</tr>
<tr>
<td>Facilitate inductive materials design methods</td>
<td></td>
</tr>
<tr>
<td>Must allow for equal consideration of the selection and design of materials</td>
<td></td>
</tr>
</tbody>
</table>

VII. LEARNING

At the beginning of the semester, we determined 5 goals that we strived to achieve upon completion of ME6101. Each task that was undertaken as part of ME6101 was related, in some way, to our semester learning goals. Now that we have reached the end of the course, we look back on our semester learning and have assessed how our participation in ME6101 helped us to achieve our semester learning goals. Our semester learning goals as well as a brief explanation of the meaning of value (in the context of ME6101) are presented below.
Semester learning goals:
1. Learn how to frame questions for future research and determine the scope of our Master’s Theses
2. Learn about current materials design processes in order to build on them for future materials design research
3. Learn to apply materials design concepts to engineering problems, and vice versa
4. Learn to communicate research findings in the academic community via conference and journal papers
5. Learn to “work smart” in a group setting

Value:

\[ \text{Value} = \frac{\text{Benefit}}{\text{Time Invested}} \]

- \( \text{Value} > 1 \): You have moved closer to completing your goals in a time-efficient manner. You were able to get out more than what you invested. Value > 1 represents a positive return on investment.
- \( \text{Value} = 1 \): You have moved closer to completing your goals in a less time-efficient manner. You were able to get out the same amount that you invested. Value = 1 represents a net gain of zero.
- \( \text{Value} < 1 \): You have moved closer to completing your goals. However, you got out less than what you invested. Value < 1 represents a negative return on investment.
- \( \text{Value} = 0 \): You did not move any closer to completing your goals. You received no benefit in participating in the given activity, regardless of the time that was invested.
- \( \text{Value} < 0 \): You have moved farther away from achieving your goals. You are in a worse position now than before you participated in the given activity.

VII.1 Group Learning

1. Learn how to frame questions for future research and determine the scope of our Master’s Theses
   \( \text{Value} > 1 \)
   In answering the Q4S, we have explored the history, benefits, and applications of material design. We also developed a method for incorporating the design of materials in the product realization process. Investigating these topics has helped us to determine the gaps in current material design technology, and the scope of our Master’s Theses. Completing the semester project involving material design allowed us to learn about various material design techniques. We have begun an example problem that can be used in our Master’s Theses.

2. Learn about current materials design processes in order to build on them for future materials design research
   \( \text{Value} > 1 \)
   In the background / motivation section of our answer to the Q4S, we discussed current material design techniques and how they can be applied to engineering problems. We also explored material selection and its link to material design. The augmented method that was developed for the answer to the Q4S provides us with a framework for completing material design problems in the future. In completing the semester project, we investigated the history, benefits, current uses, and future uses of material design. As part of research for completing the project we become familiar with current materials design processes and will be able to build on this knowledge to complete material design problems in the future.
3. Learn to apply materials design concepts to engineering problems, and vice versa

   \( \text{Value > 1} \)

   In the answer to the Q4S we included several conceptual material design examples; we also discussed the role of material design in an engineering design process. By completing the example problems for the semester project we were required to apply our theoretical material design knowledge to a physical design problem.

4. Learn to communicate research findings in the academic community via conference and journal papers

   \( \text{Value = 1} \)

   The information that we obtained while preparing our answer to the Q4S will allow us to write a conference paper on history, benefits, and examples of material design. The examples completed as part of the semester project will provide us with supporting evidence in to be included in one or two conference papers in material design during the spring semester. The practice of writing the end of semester reports was also a valuable exercise in communicating our ideas in the academic community. Once we complete a conference paper on material design, the value assigned to this semester learning goal will be greater than one.

5. Learn to “work smart” in a group setting

   \( \text{Value > 1} \)

   At this stage in our graduate studies and for completing our Master’s degree, we are conducting materials design research as a team. Answering the Q4S as a team has allowed us to adapt to working with each other in an academic group setting. By dividing up the tasks in the project and answer to the Q4S, we are learning how to work smart in a group setting.

In the following sections, we discuss individual learning that took place as we completed the steps in order to provide an answer to the Q4S.

VII.2 Individual Learning – Hannah Muchnick

The personal A0 learning goals for Hannah are listed below. She discusses how completing the answer to the Q4S has helped her to achieve her learning goals.

1. Improve critical thinking skills

   \( \text{VALUE > 1} \)

   Answering the Q4S provided me with many opportunities to develop my critical thinking skills. To start with, I performed a critical evaluation of the history, current uses, and goals of the design of materials. I needed to understand the scope of material design before I could develop a material design method in the product design process. Also, analyzing the base method from a material design perspective and developing the augmented method to support material design required much critical thinking. Completing the semester project as a way of validating the material design method required me to determine an internally consistent and efficient method for incorporating material design in the product design process.

2. Learn how to frame questions for future research and determine the scope of Master’s thesis

   \( \text{VALUE > 1} \)

   By augmented my Q4S to include the systematic design of materials, I have made significant progress towards framing a question for my Master’s thesis. I have researched valuable information regarding the background and motivation of material design, which will be very useful for my Master’s thesis. In completing the answer to the Q4S and material design example problem, I have observed several gaps in current approaches to material design. Identifying gaps in current knowledge will allow me to frame an interesting and valuable graduate research topic.

3. Learn about current material design processes in order to build on them for future material design research
In studying the background and motivation for designing materials, I learned about many current material design techniques and how to apply them to material design problems. I also have observed how current material design techniques can be altered to produce more flexible and desirable material design results. This knowledge will be very useful as I continue with a material / topology design problem for my Master’s thesis.

4. Learn to communicate research findings in the academic community by writing conference and journal papers

Completing the answer to the Q4S, project report, semester learning essay, and ME6101 lectures has allowed me to develop my communication skills in the academic community. With the material design knowledge and examples that were obtained in ME6101, I plan to write a conference paper to be submitted in the spring semester. The writing and oral communication skills that I developed in ME6101 will allow me to complete a conference paper that clearly lays out the material design examples and conclusions that I wish to convey.

5. Learn to “work smart” individually and in a group setting

The majority of the tasks in ME6101 were completed in a group setting. My Master’s research will be closely coordinated with other students in the SRL. Therefore, it is important that I learn to work efficiently with other students. By completing many joint assignments in ME6101, I feel that I have a greater understanding for how to accomplish large tasks with the help of others. I have developed my planning, time management, and communication skills. Working in a group for ME6101 prepared me for collaborative projects and papers in my future graduate research.

VII.3 Individual Learning – Stephanie Thompson

The personal A0 learning goals for Stephanie are listed below. She discusses how completing the answer to the Q4S has helped her to achieve her learning goals.

1. Learn how to frame questions for future research and determine the scope of our Master’s Theses

By designing and completing the semester project, I have learned how to frame a question for research. Also, by answering the Q4S and completing the project, I have learned a lot more about material design and the challenges that exist in creating a systematic method for material design. I have also learned how material design and multi-scale design are related.

2. Learn about current materials design processes in order to build on them for future materials design research

By conducting the literature review for the project, I discovered many methods for changing the material properties of a product locally to meet performance goals. Through developing the simple example for our project, I also learned the similarities and differences between material-driven design, material selection, and material design. Learning about these other methods has prepared me to build on them in the future.

3. Learn to apply materials design concepts to engineering problems, and vice versa

Designing and completing the semester project has directly addressed this learning goal. In designing the project, I learned how to adapt example problems for material design applications. By completing the project, I learned how to apply material design methods to example problems.

4. Learn to communicate research findings in the academic community via conference and journal papers
Value = 1
Although I have not yet written a conference paper, the method and examples developed in ME 6101 will be leveraged for a conference paper in the spring. I have also learned a lot about communicating new concepts by giving a lecture on material design applications to my fellow students in ME 6101. By giving the midterm presentation, lecture, and end of semester presentation, I learned that presenting new concepts can be very challenging, and that the arguments must be very clear. This will help me as I write conference papers, because I will remember that the reader may not have as deep of an understanding of the subject material as I do. The value is only 1 for this goal because a paper has not actually been written yet.

5. Learn to “work smart” in a group setting
Value > 1
Working with Hannah, Emad, Greg, Jitesh and Farrokh has definitely been a group setting! Hannah and I meticulously organized the project so that we would maximize our individual value. We also configured Emad’s portion of the project to benefit all team members. By splitting up the work as we have done, I believe we have indeed learned how to “work smart”.
Appendix 1 – Original P&B

Phase 1: Planning and clarifying

Task
Market, company, economy

Plan and clarify the task:
Analyze the market and the company situation
Find and select product ideas
Formulate a product proposal
Clarify the task
Elaborate a requirements list

Requirements list
(Design specification)

Develop the principle solution:
Identify essential problems
Establish function structures
Search for working principles and working structures
Combine and firm up into concept variants
Evaluate against technical and economic criteria

Concept
(Principal Solution)

Develop the construction structure:
Preliminary form design, material selection and calculation
Select best preliminary layouts
Refine and improve layouts
Evaluate against technical and economic criteria

Preliminary layout

Define the construction structure:
Eliminate weak spots
Check for errors, disturbing influences and minimum costs
Prepare the preliminary parts list and production and assembly documents

Definitive layout

Prepare production and operating documents:
Elaborate detail drawings and parts lists
Complete production, assembly, transport, and operating instructions
Check all documents

Product Documentation

Solution

Phase 2: Conceptual design

Phase 3: Embodiment design

Phase 4: Detail design
Appendix 2 – Augmented P&B

Phase 0: Global team development
- Identify global team members and determine responsibilities
- Develop team structure and establish communication flow
- Select leaders for each distributed team and global project leader
- Establish communication methods, file naming conventions, and data organization structure
- Create and publish a PEI diagram outlining goals, milestones, and responsibilities

Requirements list
- Develop the principle solution:
  - Identify essential problems
  - Establish solution neutral function structures at various length scales
  - Search for working principles and working material structures at various length scales
  - Use attention directing tools
  - Perform preliminary selection DSP
  - Publish findings on the file sharing system/database

Alternative (Principal Solution)
- Develop the construction structure:
  - Preliminary form design, material selection and calculation
  - Material selection or material design
  - Determine best preliminary material and product layouts using cDSP
  - Evaluate against technical and economic criteria
  - Publish findings on the file sharing system/database

Information: Adapt the requirements list
- Develop design alternatives:
  - Combine and firm up design alternatives
  - Determine economic and technical criteria for alternative
  - Publish findings on the file sharing system/database

Most likely to succeed concepts
- Choose alternative for principal solution:
  - Perform selection DSP
  - Evaluate against economic and technical criteria
  - Publish findings on the file sharing system/database

Phase 1: Planning and clarifying task
- Analyze the global market and the company situation
- Find and select product ideas using ideation techniques
- Formulate a product proposal
- Clarify the task
- Identify areas for materials design
- Establish a requirements list
- Publish requirements list on the file sharing system/database

Phase 2: Conceptual design
- Develop the principle solution:
  - Identify essential problems
  - Establish solution neutral function structures at various length scales
  - Search for working principles and working material structures at various length scales
  - Use attention directing tools
  - Perform preliminary selection DSP
  - Publish findings on the file sharing system/database

Phase 3: Embodiment design
- Develop design alternatives:
  - Combine and firm up design alternatives
  - Determine economic and technical criteria for alternative
  - Publish findings on the file sharing system/database

Phase 4: Detail design
- Incorporate material in product design
- Prepare production and operating documents:
  - Elaborate detail drawings, parts lists, and material models
  - Complete production, assembly, transport, and operating instructions
  - Check all documents
  - Publish documents

Solution
- Plan and clarify the task:
  - Analyze the global market and the company situation
  - Formulate a product proposal
  - Clarify the task
  - Identify areas for materials design
  - Establish a requirements list
  - Publish requirements list on the file sharing system/database

Definitive layout and material
- Prepare production and operating documents:
  - Elaborate detail drawings, parts lists, and material models
  - Complete production, assembly, transport, and operating instructions
  - Check all documents
  - Publish documents

Task
- Market, company, economy

PEI Diagram
- Develop the principle solution:
  - Identify essential problems
  - Establish solution neutral function structures at various length scales
  - Search for working principles and working material structures at various length scales
  - Use attention directing tools
  - Perform preliminary selection DSP
  - Publish findings on the file sharing system/database

Design Alternatives
- Choose alternative for principal solution:
  - Perform selection DSP
  - Evaluate against economic and technical criteria
  - Publish findings on the file sharing system/database

Most likely to succeed concepts
- Select leaders for each distributed team and global project leader
- Establish communication methods, file naming conventions, and data organization structure
- Create and publish a PEI diagram outlining goals, milestones, and responsibilities

Incorporate material in product design
Plan and clarify the role of materials:
- Analyze the multiscale aspect of the product design
- Model the interactions of various length scales
- Determine the affect of material at various length scales
- Analyze the role of materials to satisfy product requirements
- Elaborate a material requirements list
- Publish requirements list on the file sharing system/database

Material Requirements

Material selection:
- Obtain material database for all known materials
- Screen and rank available materials based on product requirements, geometry, and loading
- Reduce subset of available materials using additional sources (specialized software, WWW, handbooks, engineering expertise)
- Select best material based on local conditions
- Analyze the affect of material choice on various length scales of product design
- Analyze material choice based on product requirements
- If selected material does not meet product requirements, proceed to material design Phase 3c
- Publish possible material choice on the file sharing system/database

Selected Material

Material design:
- Research available techniques for materials design
- Choose best technique for given design problem
- Develop material models
- Model the processing-structure-property-performance of material
- Develop simulations that capture p-s-p-p interaction
- Design material using simulation models
- Analyze the effect of material on various length scales of product design
- Publish information regarding designed material on the file sharing system/database

Designed Material

Material information to product design process