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Introduction
The course material 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.

The Semester Project supports the roof of the house of learning, which in turn is composed of the Augmented Method and Verification and Validation. Accordingly, the semester project must support the augmented method and the verification of the method.

Material Design is the context for our project, and makes up the floor of the house of learning. The systematic design of materials is an emerging discipline in engineering design. Until recently, new materials were created through processes dominated by trial and error. A method for the design of materials has been proposed in our Answer to the Question for the Semester. In this project we seek to apply our proposed material design method to engineering problems in the format of example problems.

1. Context

The following section provides the context for the semester project as a summary of the answer to the question for the semester. The augmented and personalized Q4S, the field of Material Design, and the augmented method for material design are summarized below.

2.1 Summary of Q4S

The Q4S provides the mindset for ME 6101, and all assignments are geared toward preparing students to answer the Q4S. Our Q4S has been augmented and personalized to align more closely with our research interests and semester goals.

1.1.1. Augmented and personalized Q4S

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 is shown below. The underlined phrases have been added to direct our focus towards material design.

**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?

1.1.2. Justification and explanation of augmentations

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:**

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?

**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 method\(^1\).

- **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.

1.2. Summary of Materials Design

1.2.1. Definition

Material design is the process of tailoring material properties to meet the requirements of specific design problems. 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.

1.2.2. History

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.

*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 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.

1.2.3. Material Design

Designing new materials can be shown as a chain of related length scales as displayed in Figure 2 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.

![Image of material design processes]

**Figure 2: Material Design Processes**

### 1.2.4. Why Material Design?

There are three methods for incorporating materials into a product: material-driven design, material selection and material design. Material-driven design is the traditional method where the material is chosen first, often out of habit, and the product dimensions are dictated by the chosen material. Material selection is a systematic method for selecting the material in order to dispel designer bias. Material design seeks to determine the material and product layout simultaneously. 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 dependant 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.

---

### 1.3. Summary of Requirements List for Materials Design

A requirements list for our material design method was created. It includes both general and specific requirements. General requirements relate to the overall method while specific requirements relate to specific tasks and outcomes. The requirements list for our augmented method is shown in Table 1. Our augmented method for material design must meet these requirements.

**Table 1: Requirements List – Material Design in P&B**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem Statement:</td>
<td>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.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#</td>
<td>Demand/Wish</td>
<td>Requirements</td>
<td>OPA</td>
</tr>
<tr>
<td><strong>General Requirements</strong></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></td>
<td></td>
<td>Should dispel prejudice</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>------------------------</td>
<td>---</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>
<tr>
<td>16</td>
<td>W</td>
<td>Design using computer tools such as simulations</td>
<td>A</td>
</tr>
<tr>
<td>17</td>
<td>D</td>
<td>Design for distributed design-manufacture</td>
<td>A</td>
</tr>
<tr>
<td>18</td>
<td>D</td>
<td>Allow for design of product, material, and design process</td>
<td>P</td>
</tr>
<tr>
<td>19</td>
<td>D</td>
<td>Facilitate inductive materials design methods</td>
<td>P</td>
</tr>
<tr>
<td>20</td>
<td>D</td>
<td>Must allow for equal consideration of the selection and design of materials</td>
<td>P</td>
</tr>
</tbody>
</table>

**Specific Requirements**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Establish Team</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>D</td>
<td>Identify relevant experts needed for materials design</td>
<td>P</td>
</tr>
<tr>
<td>22</td>
<td>D</td>
<td>Select team members and leaders</td>
<td>A</td>
</tr>
<tr>
<td>23</td>
<td>D</td>
<td>Develop data organization structure</td>
<td>A</td>
</tr>
<tr>
<td>24</td>
<td>D</td>
<td>Create project goals and timeline</td>
<td>A</td>
</tr>
<tr>
<td>25</td>
<td>D</td>
<td>Establish a team contract</td>
<td>A</td>
</tr>
<tr>
<td>26</td>
<td>D</td>
<td>Define Problem</td>
<td>O</td>
</tr>
<tr>
<td>27</td>
<td>D</td>
<td>Identify constraints and clarify boundary conditions</td>
<td>O</td>
</tr>
<tr>
<td>28</td>
<td>W</td>
<td>Search for product/concept ideas</td>
<td>O</td>
</tr>
<tr>
<td>29</td>
<td>W</td>
<td>Set clear attainable goals</td>
<td>O</td>
</tr>
<tr>
<td>30</td>
<td>D</td>
<td>Develop requirements list</td>
<td>O</td>
</tr>
<tr>
<td>31</td>
<td>D</td>
<td>Develop Concepts</td>
<td>O</td>
</tr>
<tr>
<td>32</td>
<td>D</td>
<td>Abstract problem into solution neutral statement</td>
<td>O</td>
</tr>
<tr>
<td>33</td>
<td>D</td>
<td>Use computational tools tool to explore design space</td>
<td>A</td>
</tr>
<tr>
<td>34</td>
<td>D</td>
<td>Identify function structure equivalent</td>
<td>O,P</td>
</tr>
<tr>
<td>35</td>
<td>D</td>
<td>Search for variants</td>
<td>O</td>
</tr>
<tr>
<td>36</td>
<td>D</td>
<td>Search for solution principles for sub-functions</td>
<td>O</td>
</tr>
<tr>
<td>37</td>
<td>D</td>
<td>Combine solution principles into concepts</td>
<td>O</td>
</tr>
<tr>
<td>38</td>
<td>D</td>
<td>Evaluate</td>
<td>O</td>
</tr>
<tr>
<td>39</td>
<td>D</td>
<td>Principle solution variants</td>
<td>O</td>
</tr>
<tr>
<td>40</td>
<td>D</td>
<td>Preliminary concept layout</td>
<td>O</td>
</tr>
<tr>
<td>41</td>
<td>D</td>
<td>Cost</td>
<td>O</td>
</tr>
<tr>
<td>42</td>
<td>D</td>
<td>Safety</td>
<td>O</td>
</tr>
<tr>
<td>43</td>
<td>D</td>
<td>Quality</td>
<td>O</td>
</tr>
<tr>
<td>44</td>
<td>W</td>
<td>Ease of manufacture</td>
<td>A</td>
</tr>
<tr>
<td>45</td>
<td>D</td>
<td>Validate model using computational tools</td>
<td>P</td>
</tr>
<tr>
<td>46</td>
<td>D</td>
<td>Make Decisions</td>
<td>O</td>
</tr>
<tr>
<td>47</td>
<td>D</td>
<td>Assist engineer in making design decisions</td>
<td>O</td>
</tr>
<tr>
<td>48</td>
<td>D</td>
<td></td>
<td>O</td>
</tr>
</tbody>
</table>

### 1.4. Summary of Augmented Method

Our augmented method consists of five phases from zero to four. Phase 0: Global Team Development was added to the Pahl and Beitz base method to facilitate the organization of the design team before the design freedom is limited. This phase is particularly important because the design of materials will require collaboration of experts on various materials and length scales. The information input to phase 0 is the task, market, company and economy. The information output of phase zero is the PEI diagram.
Phase 1: *Planning and clarifying the task* was original to Pahl and Beitz. Our augmentations include the use of ideation techniques to find and select product ideas, the identification of areas for material design, and publishing the requirements list on the file sharing database. The information input to phase 1 is the PEI diagram, and the output is the requirements lists.

Phase 2: *Conceptual design* was also original to Pahl and Beitz. We have augmented this phase by dividing the phase into three steps: identifying most likely to succeed concepts, developing design alternatives, and choosing the principal solution. These steps are accomplished by developing function structures and working principles, generating concepts using ideation techniques, and paring down the concepts using the preliminary selection and selection DSPs. The output of phase 2 is the principal solution.

Phase 3: *Embodiment design* is the phase that incorporates material design. This phase is also divided into three steps: 3a. Plan and clarify, 3b. Material selection, and 3c. Material design. In the first step, a material requirements list is generated to augment the product requirements list. In the second step, the material is selected according to the material selection process. The selected material is then compared to the material and product requirements lists to evaluate its feasibility. If the selected material does not meet the requirements, then the designer(s) proceeds to the third step, where the material is designed. The material design step involves developing several models and running simulations to explore the design space. The designed or selected material is the output of phase 3, and the input to phase 4.

Phase 4: *Detail design* is the final phase of the design method. In this phase the final checks are made and all the supporting documentation is developed. The augmentation in this phase is to publish all documents on the file sharing database.

A diagram of the augmented method for material design is included in Appendix 1.

**2. Goals for Undertaking the Semester Project**

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.

**2.1. Develop and validate the augmented method**

*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. In our case, the aspect to be verified is the material design portion of our augmented method, consisting of phases 3b and 3c in Figure 5. 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.

**2.2. Meet course A0 goals**

*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 3. A0 Goals for Project Related to the Semester Project |
2.3. Add value to research goals

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.

2.4. Provide lecture materials for ME6101, ME3180

Why are lecture materials needed for these classes. What do we hope to achieve with lectures?

Our final goal for the project is to develop lecture materials for ME 6101 and ME 3180, Machine Design. We want to develop lecture materials on material design for ME 6101 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 ME 6101 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 ME 1170 (Engineering Graphics), ME 2016 (Computing Techniques), ME 2110 (Creative Decisions & Design), CoE 2001 (Statics), CoE 3001 (Deformable Bodies), and ME 3201 (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 ME 3180 is to put together at least one simple design example that includes material design and could be incorporated into the curriculum of Machine Design.

2.5. Requirements List for the project to meet these goals

What requirements are there for our choice of project in order to meet our goals?

The address our goals for the semester project, we have created a requirements list for our project. The requirements in this list refer to the choice of the project itself, and not requirements on the specific deliverables of the project. The project requirements list is shown in Table 2.

Table 2: Requirements for Semester Project

<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 our 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 for future materials design research</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 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 versa</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>4. Learn to communicate research findings in the academic community via conference and journal papers</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 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>
Problem Statement:

Identify the requirements list for the semester project for ME 6101.

<table>
<thead>
<tr>
<th>#</th>
<th>Demand/Wish</th>
<th>Requirements</th>
<th>Responsible</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D</td>
<td>Goal 1: Verify/Validate an aspect of augmented method</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>W</td>
<td>Goal 2: Provide opportunities for learning to meet A0 goals</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>D</td>
<td>A0.1: Learn to frame questions for future research</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>A0.2: Learn about current materials design research</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>W</td>
<td>A0.3: Learn to apply materials design concepts to engineering problems</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>D</td>
<td>A0.4: Learn to communicate in the academic community via conference papers</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>D</td>
<td>A0.5: Learn to &quot;work smart&quot; in a group setting</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>D</td>
<td>Goal 3: Provide Lecture materials for ME 3180 and ME 6101</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>D</td>
<td>ME 3180</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>D</td>
<td>Includes collaboration between multiple designers: Hannah, Stephanie and Emad</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>D</td>
<td>Goal 4: Add value to personal research</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>W</td>
<td>ME 6101</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>D</td>
<td>Identifies gaps in materials design research</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>W</td>
<td>Introduces H&amp;S to possible research questions for MS Thesis</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>W</td>
<td>Identifies drivers of materials design</td>
<td></td>
</tr>
</tbody>
</table>

3. Project Description

In the following section we discuss our semester project: how it was defined, what we hope to accomplish, and how it addresses the requirements that we have set for it.

3.1. Project overview

Once we determined the requirements list for our semester project, we developed a solution-neutral problem statement. The statement had to be abstract enough to address all the goals identified in Table 2. Our solution-neutral problem statement is:

Provide scaffolding for learning to integrate the design of product, material and process.

The key phrase in this statement is scaffolding for learning. Scaffolding provides support for accomplishing a monumental task, such as building a skyscraper. In ME 6101, scaffolding is provided to help us complete the end of semester submissions in the form of lectures, class assignments, learning essays, and feedback. Participating in lectures, completing assignments and learning essays, and receiving feedback all help to support the ME 6101 student as she works towards completing the final submissions. Likewise, we want to provide scaffolding for learning to integrate the design of the material with the design of the product and the design of the design process. To learn to integrate the design of
products, materials and processes, the students will need motivation, background information, examples to follow, and places to look for more information. We can provide this scaffolding by creating the example problems. As we investigate material design, we will develop the motivation, background information and references. So, in the process of creating the example problems, we will be providing scaffolding for learning about material design.

To satisfy our solution-neutral problem statement, our project deliverables will be two example problems. One simple example will be prepared for use with ME 3180. The simple example will show all steps and results in order to demonstrate the method. To demonstrate the motivation for material design, the simple example will include the design of a machine element by three methods: material-driven design, material selection, and material design. We will also use the development of this simple example as a testing ground for reverse engineering our method for material design.

The second example problem will be more comprehensive in nature and will demonstrate the design of a multi-scale assembly. This example will be used to show how the method applies to a more complex problem, and how material design contributes to multi-scale design. For this course, only the setup of this problem will be shown, but the example will be completed for future use in a conference paper and to more rigorously validate our material design method.

Developing these two examples for our semester project will address the requirements listed in Table 2. The simple example will help us to meet requirements 3, 7, 8 and 10. Specifically, developing the simple example will necessitate a literature review of past material design research, and that information will be compiled to address the motivation for material design (Reqs 3 & 8). Also, the simple example will be developed for an audience with an undergraduate-level understanding of mechanical engineering suitable for ME 3180, and it will be developed with help from Jitesh so that it will be useful for him in the future when he teaches ME 3180 (Reqs 7 & 8).

The comprehensive example will address requirements 5, 6, 9 and 11. The comprehensive example will be designed to be of suitable complexity for use in a conference paper in the future, and it will incorporate collaboration among several designers (Reqs 5 & 6). Also, the comprehensive example will be intended for graduate-level students and center on a multi-scale design problem (Reqs 9 & 11).

The remaining requirements (1, 2, 4, 12, 13, 14) will be met by developing both example problems. Both problems will follow an aspect of our proposed method for validation, and both examples will help us to identify gaps in the research (reqs 1 & 2). Obviously, both examples will be demonstrations of material design to engineering problems (req 3). Both of these examples will also add value to our future research by identifying gaps, helping us to identify possible research questions, and helping us to identify the drivers of material design (reqs 12-14). All of our project requirements will be addressed by the development of these example problems.

3.2. Requirements list for project

Once the deliverables of the project were identified, we created a requirements list for the example problems. The requirements list for the project deliverables are shown in Table 3. General requirements apply to both example problems, while the specific requirements are different for each example.

Table 3: Requirements List for Project Deliverables
4. Project Tasks

With the requirements list for project deliverables in hand, we next turned to the project schedule. The tasks necessary for completion of the project were organized in a PEI diagram.

4.1. PEI diagram

The PEI diagram is a method for organizing the tasks of a project according to the phase of the project, the events that occur, and the information generated. We began creation of our PEI diagram by listing the information that would be created. Next, we determined what events would produce that information. Finally, we organized the events and information into phases to complete the diagram. Our PEI diagram is illustrated in Table 4. Our project is composed of three phases: Clarification of Task, Example Development, and Data Analysis and Publishing. In the first phase, we organized the requirements of our project, conducted a literature review and identified the example problems that we would pursue. The result of the Clarification of Task phase was our project proposal. In the second phase, Example Development, we used the background information gathered in phase one to prepare the material-driven and material selection portions of our simple example. We also planned out how to prepare the material design portion of the simple example. The result of phase two was our midterm presentation and report. The final phase, Data Analysis & Publishing, concluded the project in the context of ME 6101, although some tasks are still to be completed to achieve our research goals. In the final phase we finalized the material design portion of the simple example, reverse engineered our method for material design, planned the comprehensive example, and collected the information in two lectures on material design for ME 6101 as well as the End of Semester Submissions (PRJ, Q4S). The tasks that we plan to complete in the future are the comprehensive example and preparation of a conference paper based on the results of this project and the comprehensive example.

<table>
<thead>
<tr>
<th>#</th>
<th>Demand/Wish</th>
<th>Requirements</th>
<th>Resp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D</td>
<td>Suitable for use with the validation square</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>D</td>
<td>Easily taught and learned</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: PEI Diagram for Semester Project
4.2. Description of tasks

In this section we describe the tasks that were undertaken to complete the semester project. The responsibilities of each of the group members for each task is also detailed below.

4.2.1. Background Research

Before we could begin to design a new material, we conducted a literature review of research in material design. Hannah reviewed Material Selection in Mechanical Design by Michael Ashby to learn about the process of material selection. Stephanie read a paper on the design of functionally graded materials4. Material selection is a systematic method for selecting the best material for a product based on the product requirements, manufacturing capabilities and designer preferences. We wanted to learn about material selection so that we could build on what has been done before. The design of functionally graded materials was of interest to us because it is one method of varying the local material properties to improve product performance. The information gathered from both of these sources was useful for us to get started in the right direction, and it is detailed in our Assignment 2.

4.2.2. Simple Example

4 Huang, J., Fadel, G. M., Blouin, V. Y., Grujicic, M., Bi-objective optimization design of functionally gradient materials. Materials and Design 2002; 23:657-666.
Our 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 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.

4.2.3. **Reverse-engineer method**

After completing all three portions of the simple example, we returned to the material design portion to reverse-engineer our method for material design. We began by identifying the steps we took to determine the product and material layout for the cantilever beam. The following steps were identified:

- Research possible methods for varying material properties.
- Select method for varying local material properties.
- Develop material model.
- Develop part model.
- Choose design parameters using part model in a cDSP.

The first step we took was to identify several methods for varying the material properties in the beam. Given the possibilities, we then selected a method for our application. In the example, we chose to alloy metals together at varying volume fractions along the length of the beam. Other possibilities included designing a composite or laminate material or designing the topology or internal structure of the material. It is also possible that more than one method for property variation could be implemented concurrently.

After choosing to alloy metals at varying volume fractions in our beam, we developed the material model. This material model was then incorporated into the part model. Finally, the part model is used in a compromise Decision Support Problem to select the best values for the design parameters.

The material selection portion of the simple example also added value to the material design portion. By systematically selecting the material based on the product requirements, we were aware of other materials that might be useful in our material design beam. We also realize that in many product design...
applications, the material may not need to be designed because the material selection may be good enough. Therefore, we have included the material selection process in our augmented method. If the material that is selected meets the specified requirements, there is no need to proceed to the material design process. A more detailed explanation of the method can be found in our answer to the Question for the Semester.

4.2.4. 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 3.

![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 ME 6101 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.

4.2.5. ME 6101 Lectures

In addition to the development of the examples, we also put together two lectures on material design for our fellow students in ME 6101. 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
came from our example problems, and is covered in detail in this project report. The slides for both of these lectures are included in Appendix 3.

5. Project Results

5.1. Simple Example

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 5.

<table>
<thead>
<tr>
<th>Material(s)</th>
<th>Material-driven Design</th>
<th>Material Selection</th>
<th>Material Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>width (a), m</td>
<td>0.033</td>
<td>0.036</td>
<td>0.027</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>16.92</td>
<td>6.93</td>
<td>6.46</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>1.58</td>
<td>9.14</td>
<td>14.61</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.

5.2. Comprehensive Example

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.

6. Utility

This project has value for many customers. For Hannah and Stephanie, this project is valuable as exploration into material design for future research and as a jumpstart for our graduate studies. For Jitesh Panchal, this project enables him to get assistance adding material design into the curriculum for ME 3180. For Farrokh, Greg, and our fellow ME 6101 students, this project will enable us to incorporate material design and multi-scale design in the ME 6101 lectures. And finally, for the design community, this project is valuable for showing that systematic material design is possible and can be demonstrated for both simple and complex design problems.

Within the context of ME 6101, the outcomes of this project have utility with respect to our AO learning goals, our answer to the Q4S, and our future research goals.

6.1. AO Goals

The lessons learned by undertaking this project have helped us to achieve our AO goals. Learning with respect to each specific goal will be discussed in section 9: Lessons Learned.
6.2. Q4S

With respect to the answer to the Q4S, this project has utility in two areas: reverse engineering our method for material design, and the verification and validation of our method.

6.2.1. Reverse Engineering the Method

Completion of the simple material design example was very useful for reverse engineering our method. Since there was no systematic method for material design that we could personalize and augment, we had to develop the method ourselves. To do so, we tried to design a material for the cantilever beam in the simple example. This process allowed us to explore the complexities of the problem and determine what core transformations must occur.

6.2.2. Verification/Validation

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 section 3.1a-c. 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.

6.3. Future Research

This project was also very useful for focusing our future research. Although we both knew that we were interested in material design when we entered graduate school, we did not yet understand the complexity of the problem and how to go about solving it. By completing this project, we have been able to explore the issues facing material design and now we can begin to address them.

7. Critical Evaluation

We must now ask the question: What really has been achieved by completing this project? Although we have come a long way in this project, many of our conclusions are tenuous due to the limitations of our work, and there is much future work to be done.

7.1. Limitations

There are many limitations to the work we have accomplished. First of all, the simple example that forms the basis of our proposed method is very simple and employed many simplifying assumptions. For example, when modeling the performance of the beam, we assumed that the beam would be made of ten
discrete segments with varying volume fractions of the steel-aluminum alloy. This assumption allowed us to create a part model that we could use within the cDSP to determine our design parameters without requiring a long computation time. However, it would be preferable to continuously vary the volume fraction in the beam, rather than break it up into discrete segments. This brings up another limitation: the material model for the beam does not address the entire processing-structure-property-performance relationship. Consequently, there is no guarantee that this beam can be manufactured. These limitations and others must be addressed in future work.

7.2. Future Work

Besides the completion of the comprehensive example, future work must be completed to address the limitations mentioned above. Although it is useful to show that material design is possible, it will be much more useful to develop a method that can be used to design an actual product. Methods for modeling the processing-structure-property-performance relationship of materials must be explored in order to develop the top-down approach for material design.

8. Lessons Learned

We have learned a great deal by undertaking this project. Our learning applies to the project in general, and specifically to our A0 learning goals.

8.1. Learning associated with semester project

We learned many things while completing this project that will be relevant to our research in the future:

- By planning a design example of a multi-scale ventilation system, we learned that multi-scale design requires knowledge of interactions between scales and within scales, and how these interactions will affect the performance of the system.
- By completing the cantilever beam design using three different methods for incorporating materials, we learned that material selection is a good method for incorporating materials into the product design; however, we also learned that material design opens doors to product performance that may not be achievable with homogenous selected materials.
- By reverse-engineering our method for material design, we learned what steps must be taken to transform material requirements into a material layout.
- Through reverse-engineering the method, we also learned that while our method is intended to be inductive, it still has deductive elements.
- While preparing the simple material design beam example, we realized that many commonly-used engineering equations assume constant material properties throughout the part. This assumption is not valid for designed materials, which is why material and part models are used in simulations to explore the design space.

8.2. Learning associated with A0 learning goals

The learning goals that we identified in our Assignment 0 are listed 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:
Value is defined as benefit divided by time invested. Interpretation of value is defined below:

- 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.

- 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.

- 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.

- 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.

- 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.

Completing this project has helped us to achieve our learning goals in the following ways:

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

   By designing our own semester project, we have indeed framed a question for research. Also, by completing the project, we have learned more about the field of material design, and we have identified challenges that must be addressed in future research. The background information that we gathered for our project will also be valuable for our Master’s research.

2. Learn about current materials design processes in order to build on them for future materials design research
   
   Value > 1

   Through completing the simple example using material-driven design, material selection, and material design, we have learned how materials are currently incorporated into products. We also learned about ways to change the material properties throughout a product by conducting background research.

3. Learn to apply materials design concepts to engineering problems, and vice versa
   
   Value > 1

   Our project directly addresses this learning goal. By completing the project we have applied material design concepts to engineering problems, and by designing the project we learned how to apply engineering problems to material design.

4. Learn to communicate research findings in the academic community via conference and journal papers
   
   Value = 1

   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
   
   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. Completing the project 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.
Appendix 1: Augmented Method for Material Design

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

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
- Elaborate a requirements list
- Publish requirements list on the file sharing system/database

Requirements list
- Design specification

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

Design Alternatives

Most likely to succeed concept

Choose alternative for principal solution:
- Perform selection DSP
- Evaluate against economic and technical criteria
- 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
- Generate best preliminary material and product layouts using DSP
- Evaluate against technical and economic criteria
- Publish all data on the file sharing system/database

Preliminary layout

Define the construction structure:
- Eliminate weak spots
- Check for errors, disturbing influences and minimum costs using computational tools
- Prepare the preliminary parts list and production and assembly information
- Publish all documents

Definitive layout and material

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

Product Documentation

Solution

Incorporate material in product design

Figure 4: Augmented Method Overview
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

Figure 5: Phase 3 of Augmented Method
Appendix 2: Simple Example

Motivation: Why Design Materials?

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 considered an example of the design of a cantilever beam with a fixed load at the free end, and a square cross-section. We employ three design methods in order to determine the dimensions and material of the beam and compare the results.

Example Problem: Cantilever Beam

Consider a solid, square cantilever beam under a constant loading. The beam is subject to a force of 10 N located at the free end. For this particular design problem, the maximum allowable displacement at the free end is $\delta = 0.01$ m. The beam must be 2 m in length to meet the design specifications. In order to reduce the load on the beam caused by the weight of the beam, we wish to design the beam to be as light as possible. The cross-sectional dimensions of the beam and the material that the beam is made from are not constrained, except that the beam must have a square cross-section. A picture of the beam and the governing equations describing the behavior of the beam are displayed in Figure 6.

![Figure 6: Loaded beam](image)

Tables for the deflection of beams under various loading conditions have been created by application of Euler’s beam theory\(^5\). Due to the linear relationship of applied loads to beam deflection, the principle of superposition can be used to develop equations for the deflection of beams under combined loading. In our case, the beam is subjected to two vertically (down) applied loads: the finite load of 10 N at the free end, and the distributed load of the weight of the beam itself. Equation 1 describes the displacement ($\delta$) of the beam at the free end under the given loading conditions, where $\rho$ is the density of the beam material, $g$ is the acceleration due to gravity, and $E$ is the modulus of elasticity of the beam material.

$$\delta_{\text{max}} = -\frac{(8FL^3 + 3\rho ga^2 L^4)}{2Ea^4}$$  \(1\)

The mass ($m$) of the beam can be found using the following equation:

$$m = a^2 \rho$$  \(2\)

---

To compare the results of each design method, we will also calculate the safety factor of the beam. Since our beam is only loaded in one direction (vertically down), the safety factor is defined as the yield stress \( \sigma_y \) divided by the maximum stress in the beam. The maximum stress in the beam will occur at the top of the beam at the fixed end. The equation for safety factor is shown in Equation 3.

\[
S.F. = \frac{\sigma_y}{\left(\frac{6L(F + pg/2)}{a^3}\right)}
\]  

(3)

Material-Driven Design

Method Overview

In material-driven design, the product material is chosen based on the experience of the designer. After successfully implementing a certain material (steel, for example), engineers reason that it is wise to continue implementing this material in future products; however, they often do so without fully analyzing differences in performance requirements across various design problems.

In this traditional practice of design and manufacture, the designer is given a basic form (cantilever beam) of the product and the material it should be made of. The designer then determines the dimensions of the part needed to meet the component performance requirements. The material-driven design model is illustrated in Figure 7.

![Figure 7: Model of material-driven design process.](image)

The loaded beam design problem at the beginning of this section can be solved using material-driven design methods.

In Practice

As designers, we know a lot about working with iron, so we will choose iron for our beam material. The density, elastic modulus, and tensile yield strength of iron\(^6\) are as follows:

- \( \rho = 7870 \text{ kg/m}^3 \)
- \( E = 200 \text{ GPa} \)
- \( \sigma_y = 60 \text{ MPa} \)

Given the applied force \( F \), length \( L \), density \( \rho \), and Elastic Modulus \( E \) of the beam, we are able to calculate the cross-sectional area of the beam.

\[
-0.01m = -\frac{\left(8(10N)(2m)^3 + 3(7870kg/m^3)(9.807m/s^2)a^2(2m)^4\right)}{2(200\times10^5 Pa)a^4}
\]

(4)

---

\(^{\text{6}}\) All properties from www.matweb.com as listed for pure iron.

http://www.matweb.com/search/SpecificMaterial.asp?bassnum=AMEFe00
The mass of the beam was calculated using Equation 2.

\[
m = a^2 L \rho = (0.033 \text{ m})^2 (2 \text{ m}) \left( 7870 \text{ kg/m}^3 \right) = 16.92 \text{ kg}
\]  

(5)

The safety factor of the beam, calculated using Equation 3, is as follows.

\[
S.F. = \frac{60 \times 10^6 \text{ Pa}}{6(2 \text{ m})(10 \text{ N}) + (7870 \text{ kg/m}^3)(9.807 \text{ m/s}^2)(2)}
\]  

(6)

Since the safety factor is greater than one, the iron beam will not fail under the applied loads.

**Material Selection**

**Method Overview**

Material selection involves selecting a material and part dimensions that meet the load requirements and objective of the design problem. Engineers are provided with an extensive data base characterizing most materials available for manufacturing applications. A system of equations and tables has been developed in order to guide the designer’s decisions. Materials can be selected based on a wide variety of objective functions such as minimizing or maximizing component strength, cost, weight, thermal conductivity, and environmental impact. The material selection method analyzed for this project was created by Michael F. Ashby and detailed in his textbook, *Materials Selection in Mechanical Design*.7

In design problems involving material selection, the designer begins the material selection process with an idea of the basic form of the product (for example, a beam, flywheel, or gear) and an extensive material properties database. After completing the materials selection process, the designer has determined the product dimensions and material that should be implemented in the component design. A flowchart representing the input and output values in the material selection process is shown below in Figure 8.

![Figure 8: Model of material selection process](image-url)

The loaded beam design problem at the beginning of this section can be solved using material selection methods.

**In Practice**

A diagram of the material selection process, as determined by Ashby is shown in Figure 9.

As shown in the figure, we start by considering all available materials. To reduce the number of possible material choices, we first screen the materials by applying property limits. Property limits are determined from the product requirements that are constraints and that affect the properties of the selected material. For example, if a product must operate in an environment where the temperature ranges from 50-150°C, the temperature range would limit the properties of the final material selection. Property limits are applied first because they must be obeyed for the success of the design. In our beam example, no property limits are specified, so they will not be applied.

The remaining materials then are ranked on the basis of material indices. Material indices reflect the product requirements that are objectives rather than constraints. A material index is “a combination of material properties which characterizes the performance of a material in a given application”[8]. Several material indices are identified for various objectives and constraints in Ashby’s book, and charts are provided to assist the designer in ranking the material on the basis of these material indices.

In the beam example, we wish to minimize the weight — and hence, the mass — of the beam. We also wish to select a material that will adequately support the applied load and weight placed on the beam. The length of the beam must remain constant at 2 meters and the cross-section must remain square.

The objective function of this problem is given in Equation 7.

\[ m = AL\rho \] (7)

This is the equation that we wish to minimize. We can minimize the mass of the beam by either reducing the cross-sectional area \( A \) or choosing a material with a low density \( \rho \). Ideally, we would like to choose a high-strength material with low density. Therefore, the cross-sectional area of the beam would not have to increase significantly to sustain the load on the beam.

---

In order to use the material tables provided in *Material Selection in Mechanical Design* textbook, material indices were calculated for the example problem. The derivation of the material index is given below in Equations 8 – 11.

\[
S = \frac{F}{\delta} \geq \frac{C_1 EI}{l^3} \tag{8}
\]

Where, \( S \) is the stiffness of the beam and \( C_1 \) is a constant which depends on the distribution of the load.

\[
I = \frac{a^4}{12} = \frac{A^2}{12} \tag{9}
\]

Combining Equations 7-9:

\[
m \geq \left( \frac{12S}{C_1 I} \right)^{\frac{1}{2}} \left( \frac{\rho}{E^{\frac{1}{2}}} \right) \tag{10}
\]

We wish to maximize the follow material index (\( M \)) for the beam example problem. That is, beams with low mass (\( m \)) will have a high material index

\[
M = \frac{E^{\frac{1}{2}}}{\rho} \tag{11}
\]

Materials are plotted on a graph of elastic modulus versus density, shown in Figure 10. The line representing the equation for the material index is highlighted at the bottom of the graph. Since we wish to maximize the material index (and decrease component mass) it is best to choose a material above the material index line. Our subset of materials now consists of all materials above the material index line. This subset includes many materials; therefore, we should consider additional material requirements in the material selection process.

---

9 *Ashby, pp 71-74*
We will now use supporting information such as handbooks, specialized software, expert systems and the internet to reduce this large subset of materials to a few prime candidates. Since the pool of potential materials is still quite large, we have narrowed the pool to a few categories of materials for further exploration. These categories are woods (parallel to grain), carbon fiber laminates, beryllium alloys, ceramics, and engineering alloys (steel, aluminum, etc.). These categories were chosen because of their location on the chart in Figure 10; more specifically, these categories lie furthest away from the material index line.

After consulting supporting material, the pros and cons of each category of materials were identified and are displayed in Table 6.

Table 6: Pros and Cons of Material Categories

---

Figure 10: Elastic Modulus vs. density for a variety of materials

10 Ashby, pg. 419
<table>
<thead>
<tr>
<th>Category</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood (parallel to grain)</td>
<td>low density, inexpensive</td>
<td>highly variable, degrades quickly (rots)</td>
</tr>
<tr>
<td>Ceramics</td>
<td>very high strength</td>
<td>brittle</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>high strength-to-weight</td>
<td>expensive, directional properties</td>
</tr>
<tr>
<td>Beryllium Alloys</td>
<td>high strength-to-weight</td>
<td>health hazards, expensive</td>
</tr>
<tr>
<td>Aluminum</td>
<td>well known and readily available</td>
<td>none</td>
</tr>
</tbody>
</table>

Several of the categories of materials were found to be very expensive as compared to more readily available engineering materials such as steel or aluminum. Since cost was not a requirement in the problem formulation, this should not make a difference for our selection. Other disadvantages that were identified include rapid degradation, high variability, brittleness and environmental and health impacts. Similar to high cost, the problem formulation does not specifically forbid these assumed disadvantages. Without revising the formulation of the example problem, none of the categories of materials can be eliminated at this point, and these five categories become our prime candidates. This realization reinforces the importance of the requirements list. To be consistent, all true limits and objectives must be included in the requirements list for the product design to satisfy the customer.

The last step in the material selection process is to consider the prime candidate materials within the local conditions of the design. This means that the expertise of the designers and fabricators must be considered as well as the eventual manufacturing capabilities. This part of the procedure is not systematic because it is driven by the experience of the designers and the process capabilities in manufacturing. In our case, as designers, we are only familiar with designing for ductile materials, specifically the traditional engineering alloys such as steel and aluminum. Since aluminum is much less dense than steel, and we are interested in reducing weight, our final material choice is aluminum. However, aluminum is certainly not the only material that could be successfully implemented in this example. The role of the design engineer is to analyze the material data charts and select a material that best meets the design requirements. For the purpose of this example, we will assume that the beam manufacturer recommends Al 6005-T1, so this is the chosen aluminum alloy.

Once the material has been selected, the remainder of the beam design is conducted in the same manner as for material-driven design. The material properties for Al 6005-T1\(^1\) are as follows:

\[
\begin{align*}
\rho &= 2700 \text{ kg/m}^3 \\
E &= 69 \text{ GPa} \\
\sigma_y &= 105 \text{ MPa}
\end{align*}
\]

Equations 1-3 were used to determine the characteristic length, mass and safety factor of the aluminum beam. These computations have been listed below in Equations 12 – 14.

\[
-a \cdot m = -\left(\frac{8(10 \text{ N})(2 \text{ m})^3 + 3(2700 \text{ kg/m}^3)(9.807 \text{ m/s}^2) a^2 (2 \text{ m})^4}{2(105 \times 10^9 \text{ Pa}) a^4}\right)
\]

\[
\Rightarrow a = 0.036 \text{ m} = 3.6 \text{ cm}
\]

\(^1\) http://www.matweb.com/search/SpecificMaterial.asp?bassnum=MA6005T1
\[ m = a^2 L \rho = (0.036 \ m)^2 (2 \ m ) \left( 2700 \ \frac{\text{kg}}{\text{m}^3} \right) = 6.93 \ \text{kg} \quad (13) \]

\[ \text{S.F.} = \frac{105 \times 10^6 \ \text{Pa}}{\sqrt{6(2 \ m)(10 \ \text{N}) + \left( 2700 \ \frac{\text{kg}}{\text{m}^3} \right) \left( \frac{9.807 \ \text{m/s}^2}{2} \right)}} = 9.14 \quad (14) \]

Since the safety factor is greater than one, the aluminum beam will not fail under the applied loads.

**Material Design**

**Method Overview**

Material design is the process of tailoring material properties to meet the requirements of specific design problems\textsuperscript{12}. Scientists, engineers, and blacksmiths have been practicing material design for centuries by creating materials such as steel and plywood. As we achieve a greater understanding of material behavior, material design moves from a game of chance to a formulated science.

At the beginning of the material design process, designers have an idea of the product form and may have constraints on the dimensions of the product. Designers also know the loading conditions of the product, which are driven by the product requirements. The output of the materials design process is a material that has been designed to meet the specific requirements of the product. A schematic illustrating the material design process is given below in Figure 11. Dashed lines around “Product Layout/Dimensions” are used to show that dimensions can be either an input or an output of the material design process. This is because there is a weak coupling between the product dimensions and the product material. If product dimensions are driving the design, they will be an input to the process; otherwise, they are determined during the design process.

![Figure 11: Model of material design process](image)

**In Practice**

Material design techniques can be applied to our beam design example. The first step is to determine the manner in which we intend to vary the material properties within the beam. There are several options. We can vary the material composition of the beam by alloying metals or designing a composite beam. We can vary the internal structure, or topology, of the beam to use less material while maintaining strength. We can also design a processing path composed of thermal and/or surface treatments to

\textsuperscript{12} Seepersad, C. C., 2004, "A Robust Topological Preliminary Design Exploration Method with Materials Design Applications," Ph.D. Dissertation, G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.
change the material properties of the beam. The key here is that the material properties of the resultant beam will not be homogeneous throughout the beam. Consider the beam in Figure 12. The elastic modulus of this beam is some function of the distance, \( x \), along the beam. The properties of the resultant beam could be a function of one, two, or three dimensions depending on the complexity of the design.

![Figure 12: A cantilever beam with elastic modulus as a function of \( x \)](image)

Once we have selected a method (or methods) for varying the material properties, we will use computer models to explore the design space. Since we know we will have to create computer models, we will select the property variation method for this example based on the ease of modeling.

For our cantilever beam example, we have chosen to alloy two metals to obtain our product material. We have assumed the material properties of the product material to be linear in volume fraction (\( v_f \)). This relation is shown in Equation 15, and can be used for all of the material properties required for our calculations: \( E, \rho, \) and \( \sigma_{yield} \), where \( X_A \) and \( X_B \) are the material properties of alloy component A and alloy component B, respectively.

\[
X_{alloy} = (v_f)X_A + (1-v_f)X_B
\]  

(15)

This relation is our material model for the beam. Now we need an interaction model to simulate the effects of the material on the performance of the beam itself.

Creation of the interaction model begins with the realization that the beam equations that we have been using for the two previous examples no longer apply. Specifically, the beam deflection equations developed by Euler by integration of the bending-moment equations have assumed homogeneous material properties throughout the beam. This assumption does not apply to our example. We could return to the bending-moment equation and repeat the integration without assuming constant properties; however, for the sake of time constraints, we chose to use finite element software to model the beam performance.

To enable heterogeneous material properties in the resultant beam, the beam was modeled in COMSOL in ten discrete segments. COMSOL was chosen because it is compatible with MATLAB. The volume fraction in each of the segments could be assigned independently, with the only restraint being that the volume fraction had to be greater than or equal to zero and less than or equal to one. The inputs to the interaction model (COMSOL model) are the characteristic dimension, \( a \), and the volume fraction in each segment. The characteristic dimension is held constant for all sections to avoid stress concentrations. The outputs of the interaction model are the maximum deflection of the beam, the maximum stress, and the location of maximum stress. A simple script to calculate the weight of the beam was also created in MATLAB by summing the weight of the individual segments based on the volume fractions in each segment and the densities of the alloy components.
Once the material and interaction models were created, a compromise Decision Support Problem (cDSP) was formulated to choose the best values for the characteristic dimension, a, of the resultant beam and the volume fraction in each discrete beam segment. The formulation of the cDSP is shown in Figure 13. The minimization was implemented in MATLAB using the fmincon function.

Given:
- Material property relation
- Loading conditions
- Beam length (L)
- Alloying metal properties

Find:
- Volume fraction (vf) in each segment
- Beam width (a)

Satisfy:
- Constraints:
  - \( \delta \leq 1 \text{ cm} \)
  - S.F. > 1
- Bounds:
  - \( 0 \leq vf \leq 1 \)
  - \( 0.005 \leq a \leq 0.25 \text{ m} \)
- Goals:
  - minimize weight

Minimize:
- Deviation from target weight

Figure 13: Formulation of the cDSP

The properties of alloying materials were also needed as inputs to the cDSP. Since aluminum was used in the material selection design, we decided to try to alloy aluminum with a stronger material. We chose steel for the stronger material. The material properties of aluminum were listed above in the material selection example and are reprinted below. The material properties of AISI 1108\(^{13}\) steel are also listed.

\[
\begin{align*}
\text{Aluminum 6005-T1} & & \text{AISI 1108 Steel} \\
\rho & = 2700 \text{ kg/m}^3 & \rho & = 7850 \text{ kg/m}^3 \\
E & = 69 \text{ GPa} & E & = 205 \text{ GPa} \\
\sigma_y & = 105 \text{ MPa} & \sigma_y & = 325 \text{ MPa}
\end{align*}
\]

The volume fractions found by solving the cDSP are shown in Figure 14. A volume fraction of one indicates pure steel and a volume fraction of zero indicates pure Al 6005-T1.

\(^{13}\) http://www.matweb.com/search/SpecificMaterial.asp?bassnum=M1108A
Alloy composition in each segment

The volume fractions reflect the expectation that the stronger material (steel) would dominate the alloy at the base of the cantilever, while the lighter material (aluminum) would dominate the alloy at the free end of the beam. This is expected because the maximum stress of a cantilever beam is located at the base of the beam, because that is where the maximum bending-moment is applied.

By solving the cDSP, the characteristic length, \( a \), was found to be 0.027 m, and the safety factor was found to be 14.61. In this case, the safety factor was calculated by comparing the maximum stress in each segment to the yield strength in each segment. The minimum safety factor is the safety factor of the beam as a whole. This safety factor assumes that the beam will not fail at the connections between the discrete beam segments.

Comparing the methods

A comparison of the data calculated in the beam design examples is shown below 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>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>

Material Selection vs. Material-Driven Design

As shown in the comparison, the aluminum beam is superior to the iron beam because it has a smaller mass. In addition, the safety factor is larger for aluminum, indicating that the iron beam will fail under a smaller applied load than the aluminum beam. The aluminum beam is slightly wider than the iron beam, but has a smaller mass because the density of aluminum is so much smaller than the density of iron. These benefits are possible with material selection, because the designer is able to choose materials that meet the specific goals of the design problem. Material selection also provides designers with a systematic way of choosing materials, rather than approaching this aspect of design in a trial-and-error fashion. The large database of material information associated with material selection is one valuable design tool that has emerged from the development of the material selection process.
Material Design vs. Material Selection

Although material selection yielded a much better design as compared to material-driven design, it is possible to achieve a less massive beam using material design techniques. By alloying steel with aluminum only in the places and amounts necessary, the beam width was reduced from 3.6 cm to 2.7 cm with a savings of 0.47 kg. In addition, the safety factor of the beam was increased from 9.14 to 14.61.

Conclusions

In this example, we have demonstrated that it is possible to achieve a smaller, lighter beam design by designing the material in conjunction with the product geometry; however, there are many limitations to this simplified problem that must be addressed in future work. To more rigorously compare material design to material selection, a design problem with more requirements should be considered. In the material selection process, there were not enough constraints and objectives to lead us to any particular material, and consequently, the material was chosen on the basis of the experience of the designers. Also, the material design process must address the processing of the designed material in addition to the structure, properties and performance, because the designed material is of no use unless it can be manufactured.
Appendix 3: ME 6101 Lectures on Material Design