My Answer to the Question for the Semester

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A Final Submission for ME 6101
Orchestrated by Dr. Farrokh Mistree and Matt Chamberlain
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Chapter 1. Setting the Context

The course orchestrators for ME 6101 for the Fall 2003 semester, Farrokh Mistree and Matt Chamberlain, have presented me with a learning opportunity by offering an individual course in a group setting. They have built scaffolding for me to learn how to keep learning and to help me define and reach my goals.

Farrokh and Matt have posed a question for the semester (Q4S), and they began the course by asking me to define my goals. In this introductory section, I provide their suggested question for the semester and the context in which they have asked the question. I then articulate my goals—which I adapted during the first half of the course. After stating my goals, I describe my mindset for answering the question for the semester, which can be summarized as the future is place for me to define. I also explain my view of knowledge as the core of engineering design, which becomes a recurring and guiding theme. Finally, I modify the Q4S to match my goals and perspective of design.

The systematic approach to engineering design presented by Pahl and Beitz (Pahl and Beitz 1996) is featured prominently in my answer to the question for the semester (A2Q4S). In this A2Q4S, I used “Pahl and Beitz” and “P&B” to refer to the process and method they develop in Engineering Design (Pahl and Beitz 1996).

1.1. The Question for the Semester

The course orchestrators Dr. Farrokh Mistree and Matt Chamberlain present following context:

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.

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

In this context, they have proposed the following question:

How should the Pahl and Beitz (Pahl and Beitz 1996) systematic design method be augmented and personalized to support the realization of technical products and processes for a global marketplace?

Motivation for formatting from Steve Rekuc
1.2. My A0 Goals

At the very beginning of the semester, the course orchestrators asked me to outline my goals for the course. Through the first few weeks, my goals evolved. I have presented my final articulation of my goals as follows:

Primary Goal:
1. Create the basis for a paper to submit for the American Society of Mechanical Engineering Design Engineering Technical Conferences (ASME DETC) 2004 Conference

Secondary Goal:
2. Augment the P&B process to incorporate modern tools such as computer simulations, knowledge representations, CAD, and other computer-aided engineering tools and mathematical models, as well as identify opportunities to create new tools

Other Goals:
3. Improve my skills at deep reading
4. Work in a group using a systematic approach to design and collaboration. I’d like the project to have a clear use beyond the assignment itself
5. Develop insight into engineering and business in the year 2020

Minimal Goal:
6. Prepare for the Design qualifying exam

The notion of a primary goal is that that goal is central to everything I do in the course. I have captured my primary goal as creating the basis for a DETC 2004 paper for several reasons.

First, I would like to start publishing and presenting my work in order to gain experience and recognition, so the paper is a goal in itself. What is more important is the assumption underlying my choice of the presentation of a paper at DETC as my primary goal. My assumption is that if the paper is accepted for DETC, the content of the paper has some value to the design community. Another assumption is that if the content is valuable to the design community, then my research for the paper also has value, which is a signal that I am moving in a valuable research direction as I craft the scope of my Ph.D. dissertation.

These assumptions may not always hold, but I believe that capturing my goals in something concrete is more valuable than stating an amorphous goal such as “Create the basis for future research.” The specificity required for a paper will help direct my attention towards actually formulating and synthesizing my thoughts in a consistent and presentable manner.

My second goal is an attempt to relate my individual goals to the course; the Pahl and Beitz process can become the context in which I set my research contributions.

My third goal relates to one of the course orchestrators’ hope of helping me learn to keep learning. Deep reading is a skill that will help me in my Ph.D. research and my career, as
the ability to understand, challenge, and apply the claims and ideas of others is a prerequisite for leveraging their work and succeeding in a research community.

My fourth goal really has three parts, all of which relate to the project. The first part is to work in a group, since this is the way engineering design is done today and will be done in 2020. The second part is to employ a systematic approach to design; this will help me understand both the P&B process and the value of using a systematic approach. The third part is to make the project useful beyond just completing the project. This means that I should make a strong effort to relate the project to my long-term goals, as well as my A0 goals for this course.

My fifth goal is related to my creation of a vision for 2020. This goal relates to the Wayne Gretsky quote the Farrokh presented in lecture. His recipe for success was, “I skate to where the puck is going to be, not where it’s been.” Despite the challenge in anticipating the future, it is a valuable skill to have, and one that I am currently not good at.

Finally, my minimal goal is to help me prepare for the design qualifying exam. If I get nothing else out of the course, I must understand the P&B approach to design enough to pass the qualifier.

1.3. Mindset in Answering the Q4S

In order to explain my mindset in answer the Q4S, I borrow a quote that Steve Rekuc presented in his ME6102 Question for the Semester (Rekuc 2003).

“The future is not a result of choices among alternative paths offered by the present, but a place that is created--created first in the mind and will, created next in activity. The future is not some place we are going to, but one we are creating. The paths are not to be found, but made, and the activity of making them, changes both the maker and the destination.”

-John Schaar

The point that I latch on to is that I am creating a prescriptive process. I am creating the process that my company will follow in the year 2020. The design process that I create now will not just be dropping into 2020. By proposing it now, I can also work to incorporate existing tools and create new supporting tools. I embrace a decision-based view of design. In this view, engineering design is a sequence of decisions made by human engineers. The role of tools such as the computer, models, or attention directing tools is to support these human efforts. This relationship leads to the notion of a human computer cyborg, which I discuss more in Section 7.2. At the heart of my research is desire to support human decision makers as they make decisions.

I also see adopt notion of the future as a place; I explore this place via a frontier analogy in more detail in Section 2.1. My main point is that if I position my company as one of the earliest settlers of this frontier, then the company can shape this frontier. If I wait for other organizations to settle the frontier, then I will have to live with the world they create.
I believe that defining a design process alone is insufficient to realize technical products in the year 2020. Paradigm shifts in corporate structure and the approach to design must also occur. I have developed a corporate philosophy for 2020, including specific policies regarding hiring, employee evaluation, layoffs, intellectual property rights, and the role of the company in society. This philosophy creates an environment that fosters my design process for 2020 by unifying the employees in a single purpose. The shared philosophy will be the glue that holds together design teams across disciplines and cultural boundaries.

Finally, I recognize that I will never be able to control all the aspects of the future. For example, a single company has limited influence over the behavior of competitors, customers, and political and legal policies. Consequently, to succeed in the future, a company will need to adopt a strategic approach.

1.4. Knowledge in an engineering design firm

A company’s employees are the key to company’s success; it is the knowledge of employees and their willingness and ability to share their knowledge with their coworkers and to apply their knowledge to their work that creates value for the company. I feel that it is important to emphasize that it isn’t enough for the employees to have knowledge. It is also insufficient to just have mechanisms for sharing this knowledge. The employees must also have an interest in sharing their knowledge and applying it to projects. I illustrate my view of the role of management in capitalizing on employee knowledge in Figure 1.

I have divided the flow of information into four stages. In the following, I describe the four stages and present a broad view on how to enable the flow of information and knowledge in a company in 2020. These notions form the primary motivation for the corporate philosophy that I develop in Chapter 4.

1. Get knowledge to engineers. This can be achieved through several avenues:
   • Continuing education and professional development, including helping engineers to learn to keep learning
   • Opportunities to provide original ideas for projects, processes, or policies
   • Opportunities to learn from other employees

2. Unlock the knowledge in the workforce. Many employees will feel an internal, self-defense pressure to withhold some knowledge from their coworkers. If an employee could literally “upload” his or her knowledge to someone or something else, the employee’s value to the company would be reduced. One key to unlocking the workforce’s knowledge is job security. If someone is relatively certain that if they perform adequately then they will retain their job, they should not feel as hesistant to share their knowledge.

3. Provide means to communicate knowledge. This involves the company providing opportunities for knowledge exchange and providing charge codes for these activities. This might be done via weekly meetings in which employees present aspects of their current or past work to a particular team or group. It might be as simple as providing a simple way to create knowledge sharing sites on an intranet.
4. **Encourage others to listen**  It isn’t enough to encourage people to share information. There has to be someone there to listen. This partly requires hiring employees who want to keep learning and get excited listening to how other people have solved problems. By providing meetings and charge codes for knowledge sharing sessions, employees will be willing to use their time to engage in such activities. It may even be worth making a requirement for a certain number of hours or meetings per month.

![Figure 1: Managing Employee Knowledge](image)

Given this view of the flow of information, my next task will be to think of ways to augment the human ability to store and access information. For example, knowledge management systems can support these human activities. There is also room for continual improvement in methods of communicating knowledge. The willingness and ability of engineers to share information is a prerequisite for effective knowledge management systems. My corporate policies seek to create an environment encourage these activities.

### 1.5. Product Proposal: My Personalized Question for the Semester

The motivation for my research is the question:

> How can human decision-making in the engineering design process be improved?

Building from this research question, the context of the course, the ideas presented in the previous section (1.4), and my goals, I propose the following personalized question for the semester:
There are five modifications of the question:

- Risk assessments
- Simulations
- Reuse of knowledge
- Distributed design environment
- Year 2020

The first three relate to my framing research question, as they are all possible ways to support human decision making. The fourth recognizes the fact that the environment in which engineers design is frequently broken into teams that are distributed across geographic and interdisciplinary borders. As this should affect the way design decisions are made, I choose to focus on this aspect of the “global marketplace” as opposed to the consumer side. My assumption underlying this transition is that in order to support a global marketplace, companies will position their engineers at locations around the world, either because labor is more available and affordable, or to have engineers closer to customers.

Finally, the course orchestrators have fixated their examples on the year 2020, and I have so far followed their lead. I feel that it is essential to identify in the question that I am looking towards the future. It is also valuable to fix a target year, so that my context clearly excludes the distant future (for example 2100), which is even harder to anticipate.

1.6. Approach to answering my Q4S

My approach from the beginning has been the following:

(1) Develop my vision for 2020
(2) Augment Pahl and Beitz for 2020
(3) Personalize Pahl and Beitz to my application area

Farrokh Mistree repeated in lecture on October 9, 2003, that he believes that one should really “personalize” and then “augment” P&B, although the lecture slides still imply the opposite order—which guided my initial approach.

I have decided to stick with my initial approach, which I justified in A3 by writing, “I prefer my approach to answering the Q4S because it keeps the design approach general as it is augmented for 2020, and then personalizes it to my company and task.” One of the reasons that I augment and then personalize is that I am not adapting P&B to a new domain. My initial focus is on systems that are similar to the mechanical engineering design tasks that P&B originally addressed. I recognize that if the process were being
transferred to a domain such as software design, it may be necessary to personalize it to that domain and then augment it for the year 2020.

In the end, nearly all of my changes to P&B are in augmentations. Even in my team project, there was little need to personalize P&B in order to answer our research questions. This does not mean that P&B does not need to be personalized for space system design. It means that I have not considered these aspects because they were not central to my goals.

I recognize that I cannot address every valuable augmentation to Pahl and Beitz during this semester. I will address some augmentations at a higher and motivational level but not a detailed level. I will prioritize augmentations based on my goals and constraints later in this paper, once I develop the requirements for a design methodology in 2020. Before I can create a requirements list for an augmented P&B design method for 2020, I must develop a vision for 2020, which I express in the next chapter.
Chapter 2. My Vision for the Year 2020

I approached developing my vision for the year 2020 by three methods.

1. Explore the world of 2020 and the technological frontier via an analogy with the geographic frontier in the history of American westward expansion
2. Expand and abstract from The Engineer of 2020, a prospectus by the National Academy of engineering Committee on Engineering Education
3. Direct my thinking on 4 aspects of 2020

2.1. Exploration by Analogy

2.1.1. Motivation for analogy

My approach to creating my vision for 2020 is motivated by a sentence from the introduction to Arnd Rothe’s master’s thesis (Rothe 1994). He writes,

“Unfortunately, the Western way of life is characterized by steady dissatisfaction and the creation of new desires and wishes.”

I’ve presented this in bold because I think it is very thought provoking and probably could serve as the subject of a thousand page learning essay.

I have tried to think deeply about this sentence, and I’ve formed the following opinion. First, I agree with all but one word in this sentence; I object to Mr. Rothe’s use of the conjunction “unfortunately.” I challenge that this Western character is in no way unfortunate. It is instead the very core of the technological progress that has been made in the past few centuries.

I believe that it is this dissatisfaction that creates new desires and wishes, and that these desires and wishes in turn foment the curiosity that sustains the creativity and innovation that give birth to the new ideas that advance society. Without a tendency towards dissatisfaction, society will stagnate.

It is this desire for something new that will drive the world of 2020 to evolve into something different from what we live in today. From this motivation, I seek to explore the engineering world of 2020 by making analogies to the advancement and settlement of the American Frontier.

2.1.2. The fortunate proliferation of new desires

If everyone is satisfied, who will push the envelope? Without dissatisfaction, from where will the urge arise to improve one’s lot in life, and the quality of life in general? My opinion is clearly biased because I have been raised in this Western culture, and in particular an American culture.

Europeans had their own time of grand expansion, exploration, and colonization. The way in which these countries handled these activities was clearly devastating to the native people in those lands, and they suffered greatly as Europeans sought new gems, metals, labor, and land. Nevertheless, I see this exploration as leading to the formation of the United States.
The first Europeans to form true settlements in what is now the United States came here in order to better their lot in life. In some cases they were not satisfied to adopt the state imposed religion or to suffer persecution for rejecting it. They came here with the hope of living the American dream before there was an America. Some settlers were quite dissatisfied with their lot in these new colonies, and they quickly moved again in an effort to improve their lives. Rogers Williams’s desire for a colony with a true freedom of religion drove him to lead followers to Road Island.

Throughout history, immigrants have come to the United States seeking to improve their lives. Once here, people steadily moved westward, always seeking a better life. At the expense of the Native Americans and the millions of buffalo that once roamed the plains, Americans pushed westward; at times they sought gold, at times at times they sought jobs picking fruit in the Napa Valley. Recently they sought to reap the harvests of Silicon Valley. Americans are on the move; if things aren’t getting better, then they must be getting worse. The bar is always being raised, and everyone wants to clear it.

2.1.3. The Frontier Thesis

Frederick J. Turner was the first historian to expound a frontier thesis of American culture. A collection of essays is available online.\(^2\) Turner writes in “The Significance of the Frontier in American History” (Turner 1893).

The United States lies like a huge page in the history of society. Line by line as we read this continental page from West to East we find the record of social evolution. It begins with the Indian and the hunter; it goes on to tell of the disintegration of savagery by the entrance of the trader, the pathfinder of civilization; we read the annals of the pastoral stage in ranch life; the exploitation of the soil by the raising of unrotated crops of corn and wheat in sparsely settled farming communities; the intensive culture of the denser farm settlement; and finally the manufacturing organization with city and factory system.

In following his frontier thesis, he analyzed American society. For example, he argues that as frontier states were admitted to the union with democratic suffrage, existing states had no choice but to extend suffrage. The expansion also forced the slavery issue and shifting power to the brink; in the end, slavery was eliminated. These changes were the eventual result of the American Dream to continually improve one’s standard of living. The lesson here is that the frontier was shaping not only the leading edge of advance, it was also changing engrained notions in the core of society.

I highly recommend reading “The Significance of the Frontier in American History”, but this is not the place to analyze Turner’s thesis in depth. I merely provide an introduction.

\(^2\) [http://xroads.virginia.edu/~HYPER/TURNER/](http://xroads.virginia.edu/~HYPER/TURNER/) There is also some biographical information is available at [http://www.pbs.org/weta/thewest/people/s_z/turner.htm](http://www.pbs.org/weta/thewest/people/s_z/turner.htm).
here because his work is part of my inspiration for attempting to describe the frontier that pushes forward to 2020.

[Frontier in engineering/technology; in crafting my vision for 2020 and strategically positioning my company, I am settling a new frontier.]

2.1.4. Where is the frontier?
I claim that although the geographical frontier closed in 1890 according to the Superintendent of the Census for 1890, a new frontier opened. This technological frontier took over. I can’t fully analyze when or where it began, but it did. After 100 years of geographic expansion, the country actually began to shrink as the technological frontier pushed outwards.

Railroads and the telegraph began to shrink the geography of North America during the American Civil War. Suddenly the logistics and intelligence of war could move at unseen speeds. In 1858, England and the United States were linked by the telegraph, and instant communication across thousands of miles and multiple cultures was a reality. Globalization had begun. American interests were enmeshed with European interests, as demonstrated in the bloodshed of two world wars; political and business concerns no longer ended at the countries shores.

2.1.5. Milestones on the Technological Frontier
I choose three identifiable milestones along the advance of the technological frontier that were crossed in the 113 years since the geographical frontier closed. The first was powered flight, a race which the Wright brothers won. The second was space exploration, which either Sputnik or Yuri Gagarin crossed first. The third was the landing people on the moon, which Neil Armstrong and Buzz Aldrin crossed first.

All three of these received a lot of media attention at the time, generating mixtures of excitement and fear depending on where you lived. They are still exciting, and young children dream of being pilots or astronauts. However, I claim that these frontiers are not as important as their byproducts and the culture that drove them.

2.1.6. Globalization
The airplane shrunk geography even more that trains and instant communication had. Businessmen in New York not only could know what was happening in Chicago minute by minute, but—with deep enough pockets—they could fly out and visit the grain elevators and stockyards in a matter of hours. Suddenly a company’s business center could be removed from other operations. Just as new ways of life had to be created to survive in the log cabins of the American frontier, new modes of business had to be developed survive economically on the technological frontier. And just as economic and logistical systems existed behind the American frontier to profit from it and push it forward, new systems developed behind the technological frontier.
2.1.7. Complexity of Technology and Goals

The element of space travel that I focus on is the complexity of the Saturn V Rocket, Apollo orbiter, and the lunar module. These systems had a greater scale and scope than any previous manmade system, at least to the best of my knowledge. There were built under the pressure of Cold War politics, which meant that the budget was almost bottomless, and the goal was clear. As President Kennedy announced on May 25, 1961, "First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the Earth." (About 2003).

In the commercial world of 2003, not to mention 2020, things are not so simple. Today, things need to be done cheap, quick, and well. The financial constraints and the definition of “well” are the big changes from Apollo. Products have complicated goals; they have many dimensions to their objectives. The question to answer for design in 2020 is how to meet these goals and trade between the multiple objectives.

2.1.8. Frontier Lessons

People, specifically Americans, tend to be dissatisfied. They maintain a living document of goals and wishes that regenerates itself by adding a new one—or maybe two—as soon as one is crossed off the list. For the first 100 years of American history, people migrated west looking for riches, property, or a chance to start over. This wanderlust is an integral part of American culture, and it shows itself today in different ways.

More and more parents are sending their children off to college, much as they may have been sent off to the frontier settlements in the past. These parents seek a better life for their children than they themselves enjoyed. They recognize that the requisite for success in today’s technological frontier are not bulging biceps and skill with an ax or shotgun (as they were on the geographic frontier), but rather an education and intellectual abilities.

In nature and society, it is those who can anticipate, react, and adapt quickly to changing conditions that survive. As frontiers advance, life changes not only at the boundaries but also behind the lines. The way things were done in the past must be adapted or reinvented to keep pace with the push forward. Otherwise, the frontier will move too far and die, cutoff from the core strengths of established towns and the proven ways of life.

The frontier challenges are no longer fighting off Native Americans, mountain lions, starvation, or dysentery, but rather position your product in a market when people want it and at a price that they will pay for it. Just as rifle-toting squatters ruled in the Oklahoma Territory, it this first one to market with the firepower to keep it who profits and holds its share.

People will always seek to move farther into the frontier, in the process pushing the frontier farther with them. Geographic expansion is constrained; the world is only so big. In nearly all cases, geographic expansion of one people was at the cost—and usually destruction—of another people. Market share can be increased by similar hostile moves, but the beauty of looking towards 2020 is that it doesn’t have to happen that way.
Unlike open land, new markets can be created and existing markets expanded without hostile takeovers. Technological research pushes the frontier outwards without destroying someone else’s domain. The responsibility increasingly placed upon companies is to do their research and build their products in ways that don’t destroy our environment. The geographic frontier is closed, so we can’t find new land, air, water, forests, etc. to replace the ones we destroy. We must expand, grow, and settle the technological frontier responsibly.

In the following section (2.1.9), I abstract these lessons into laws of the frontier.

### 2.1.9. Laws of the Frontier

I summarize the previous section by defining the following laws of the frontier; these laws apply to both the geographic frontier and the technological frontier.

1. People strive to move to something newer and better
2. You must bring the proper tools to the table
3. Those who flourish are able to anticipate, react, and adapt quickly
4. The people behind the frontier must also adapt and progress in order to keep pace or the frontier will die
5. The first and strongest will win, as long as he/she/it remains the strongest
6. The technological frontier is constrained only by human creativity and innovation
7. The geographic frontier is closed, so we must protect the world we have

### 2.1.10. Strategic Positioning and Agility in 2020

I would like to focus on Frontier Law 5. Notice that the law has two parts

1. The first will win
2. if it remains strongest

Strategic positioning relates to the first part. The goal of strategic positioning for a company is to prepare a company for future market needs and technological capabilities. If a company succeeds at strategic positioning and they have a strong design process and quality, happy employees, it has a great chance of being first to market. However, this alone does not guarantee long-term success and sustainability.

After getting to market first, the company must adapt its processes, policies, and product portfolio to react to fluctuations in market conditions, including varying consumer preferences, or it will lose its advantage. This requires agility, which can be defined as the capability or ability to move quickly and easily [adapted from dictionary.com].

Combined, strategic positioning and agility will help a company achieve a sustainable success, which is important in a company that seeks to establish long-term relationships with its customers and employees, as my company of 2020 will.

### 2.2. The Engineer of 2020

My ultimate goal for this paper is to look ahead and speculate on the future. Eventually I will develop a prescriptive model of how design should be done. One basis for this
future vision is *descriptive* models of the past and present. One approach that I have not carried out would be to examine what people predicted 20 years ago for today. What was right and what was wrong about their vision? How can we learn from and improve on their forecasting abilities? What I have done here is looked at what a panel of engineers, who I presume are experts, has identified about engineering today.

The content and motivation for this section is drawn from a project prospectus for the National Academy of Engineering Committee on Engineering Education (NAE 2003), which is available online. What I really like about this document is that it identifies current trends in engineering. These can help guide my thoughts on the future.

I have reproduced here, without permission, the following two sections of this prospectus. Please keep this in mind should you choose to redistribute this paper. As an editorial note, I have changed the format of bulleted lists in the original to numbered lists for easier reference here.

### 2.2.1. Current Trends in Engineering

**CONTEXT: OPPORTUNITIES AND CHALLENGES FOR THE 21ST CENTURY**

As we enter the new millennium, we can already identify trends that are likely to redefine the boundaries of engineering and the composition of the engineering workforce. Some of the most salient trends are listed below:

1. a global population approaching 10 billion with a steadily aging demographic and a growing demand for diversity in the engineering workforce
2. an imperative for “sustainability” in the face of global population growth, industrialization, urbanization, and environmental degradation
3. an increased focus on managed risk and assessment with a view on public privacy, safety and security
4. the globalization of economic systems and the interconnectedness of its component parts
5. the accelerating pace of technological advances, including the increasing importance of information technology, communications science, and biological materials and processes in engineering
6. growing concerns about the social and political implications of rapid technological advances and their uneven application among different constituent groups (e.g., the digital divide, medical ethics, etc.)
7. the diminishing half-life of engineering knowledge in many fields
8. the growing complexity, uncertainty, and interdisciplinary foundations of engineered systems
9. the growth of the “services-based” component of the economy
10. the increasing number of engineers working in nontraditional areas that require technological
competence and/or fluency (e.g., management, finance, marketing, public policy, etc.)

11. the shift in engineering employment from large companies to small and medium sized companies and the growing emphasis on entrepreneurialism

12. increasing opportunities for incorporating technology into the education and work life of engineers

In the coming decade, other conditions may become “trends,” or even disruptions of established technological priorities in certain nations or around the world. We can be certain that current complexities will create tremendous engineering challenges, only some of which are foreseeable. It is incumbent upon us to gather our best thinkers and to exercise our best judgment in laying out a bold and thoughtful plan, to both manage the challenges that lie ahead and influence the changes we want to create. The Engineer of 2020 is a thoughtful approach to preparing for the challenges of early 21st century engineering.

2.2.2. Framing Questions

The following questions will inform both phases of the project. The questions are intended to stimulate ideas for changing the content and delivery of engineering education:

1. What kinds of work might, or should, engineers be involved in by 2020? How should "engineering work" and an "engineer" be defined in 2020? What will be the boundaries of engineering in 2020?

2. Who should perform engineering work in 2020? What should the composition of the engineering workforce be in 2020 (e.g., gender, ethnicity, disciplinary backgrounds, etc.)?

3. How and where will people be recruited into the engineering profession in 2020?

4. How and where might the engineer of 2020 be educated?

5. How might new technologies effect [sic] an engineer's area of control and responsibility?

6. What fundamental engineering and nonengineering skills will an engineer need in 2020?

7. What should constitute the foundations of engineering ethics in 2020?

8. How should the engineer of 2020 be prepared to address the societal impacts and policy dimensions of engineering work?

2.3. The Engineer of 2020 Analyzed

I now provide my opinion and ideas about The Engineer of 2020.
2.3.1. Trends

For the most part I agree with this list; I have even stated some of them already. I am not sure what is meant by “the diminishing half-life of engineering knowledge in many fields.” Does this mean that we are losing knowledge, and we are losing it faster than ever before? Does this mean that knowledge becomes obsolete faster than ever? The first implies that we need to do more to preserve, store, and manage information. The latter implies that we don’t need to store it because it becomes obsolete quickly; maybe we even need to purge our memory stores. When something becomes obsolete, something about it is no longer useful; it has either been replaced by something better, or the function is just no longer needed. What makes knowledge obsolete?

I am skeptical on item 11. I know that during the internet boom there was a significant proliferation of small companies. These small companies received a much larger geographic exposure than small companies of the past because the internet is global. Using the internet they could reach customers in countries their employees didn’t even know existed. However, I’m not convinced this is true across the board. My impression was that companies continue to merge and grow bigger, incorporating new subsidiaries in different countries and markets.

The key words from the trends identified in the prospectus are

- diversity
- sustainability
- environmental
- risk
- privacy
- safety
- security
- globalization
- accelerating pace and rapid technological advances
- ethics
- knowledge
- complexity
- uncertainty
- interconnectedness
- interdisciplinary
- services
- entrepreneurialism
- opportunities

Of these key works, the last—opportunities—is the most important. The most important lesson to take away from speculating on 2020 is that the trends we see today and imagine for tomorrow present opportunities to do things better. The organizations and individuals who best embrace their opportunities, plan for the future, and adopt systematic approaches will most likely enjoy the most success in business and happiness in life.

For now, I add the following keywords of my own:

- collaboration
- multilingual

2.3.2. Framing Questions

I really like the question put forth in the prospectus. I propose to add the following:

- Will the Pahl and Beitz systematic design process still be reasonable in 2020 given the widespread use and functionality of computers? If so, how should the Pahl and Beitz systematic design method be personalized and augmented to
support the realization of technical products and processes for a particular product in a global marketplace?

- What new tools or management practices will be needed to keep distributed collaborators from multiple cultures on the same page?
- What roles with a human serve and what roles will computers serve in engineering design in 2020?
- How will engineers be able to identify the problem correctly in the 2020?
- How will engineers determine what customers really want in 2020, and who will these customers be?

I seek to answer the first three of these in my answer to my Q4S.

2.4. My personal vision for 2020

I organize this section into four main sections, each of which explores a particular aspect of design in the year 2020. The four aspects that I chose to direct my attention are:

- Knowledge Management
- Leadership
- Tinkering and modeling
- The Pace of Technological Advance

2.4.1. Knowledge Management

I have discussed the role of knowledge in an engineering firm in Section 1.4. By the year 2020, there will be new methods for capture, storage, retrieval. For example, I expect:

- less document based
- multiple original languages
- computer interpretable knowledge
- explicit semantics
- better visualizations
- faster search

All of these things will enable greater reuse of knowledge, which in turn enables:

- more opportunities for adaptive design
- more opportunities for morphological methods
- use of a repository as source for forced relationships and attribute-listing, or other ideation methods
- automated combination of solutions

Finally, the increased and simplified reuse should enable engineers to meet more goals better since successful past solutions can be adapted, adopted, and extended to new problems.

2.4.2. Leadership

Who will be leading companies in the year 2020? Where will these leaders be located, and what traits will they need?

2.4.2.1. Nationality

I’ve decided to consider this after I noticed I was biased towards thinking someone like me—a natural born and raised American—will be leading companies in 2020. I’d like to
consider this more. Who will be leading global companies in the future? Will it matter? What will their cultural background be? What country will they be from? If I can predict that, then I can better predict other characteristics. More likely, leaders will be more diverse. I present in Table 1 the results of my brainstorming and analysis process. After generating as many ideas as I could, I eliminated some completely farfetched ideas and then categorized the influences and applied them to speculating on there will be a trend towards more non-American leaders.

Table 1. What contributes to nationality of leaders?

<table>
<thead>
<tr>
<th></th>
<th>Non-American</th>
<th>American</th>
</tr>
</thead>
<tbody>
<tr>
<td>More experience</td>
<td>+</td>
<td>✓</td>
</tr>
<tr>
<td>interacting with</td>
<td></td>
<td></td>
</tr>
<tr>
<td>different cultures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>and languages</td>
<td></td>
<td></td>
</tr>
<tr>
<td>More patience</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>More open-minded to</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>existence of</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>differences</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multilingual</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Increasing centrality, influence of EU</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Economic opening of China</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Concentrated technical education</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ease of study abroad</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Adherence to own culture</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

I speculate that leadership will be multinational. No company will draw all of its upper management from one country, because they will be operating in a global marketplace. The engineering teams will be distributed geographically. American companies will need to broaden their horizons and incorporate international talent.

2.4.2.2. Training

In a collaborative, distributed design team, the organization and process of design will be of foremost importance. Therefore, leaders will need to be trained in design processes and not technical details.

Such training will need to be developed and expanded, as it does not seem to be prevalent in engineering curricula. The ME6101 and ME6102 courses offered at Georgia Tech are definitely a step in the right direction. The management, business, decision theory, and engineering programs will need to be synthesized into a curriculum for engineering design management. My undergraduate program—specifically my program in
Engineering and Management Systems\textsuperscript{3}—was another step in this direction, but it was incomplete.

2.4.2.3. Job Responsibilities

What will a leader’s job responsibilities be in the year 2020? In my LE2 I went into more details, but in the end I abstracted the following higher level skills, which can be summarized as the ability to:

- Clarify
- Abstract
- Ideate
- Evaluate
  - Qualitatively when necessary
  - Quantitatively as much as possible
- Decide
- Coordinate
  - People
  - Resources
  - Information and knowledge. The leaders have ultimate responsibility for the seamless integration of knowledge from different types of stakeholders, and different locations, cultures, and technical disciplines
- Prioritize

All of these activities remain uniquely human, and I believe they will still be human activities in 2020. However, computer tools with increasingly support these activities. It is this integration that leads to the notion of a human-computer cyborg, which I discuss more in Section 7.2.

A very important thing for decision makers to realize is that tools are not making the decisions. The ultimate responsibility still lies with the human, or at least it should in the year 2020. The military is very concerned with human-in-the-loop procedures for effectiveness and political reasons. As long as the ultimate responsibility lies with a human, the scary science fiction notion of a cyborg taking over the world, such as in the Terminator movies, is impossible.

Once the cyborg notion is adopted, it is easy to see that leaders should organize their teams to make humans and computers work in a symbiotic relationship such that the benefits of the synergy are maximized. This would be a relationship in which the computer extends and augments human abilities, and the human extends and augments the computer’s capabilities.

\textsuperscript{3} More information on this program is available at http://www.orfe.princeton.edu/undergraduate/EMSCertificate.html
2.4.3. Tinkering and modeling

Innovation has often resulted from tinkering, at least in the romanticized version of history. Certainly there are other routes to innovation, but this is one. I pose the question, how will tinkering be done in the future, or what will replace it?

According to Merriam-Webster, to tinker means, “to repair, adjust, or work with something in an unskilled or experimental manner” (M-W 2003). In my mind the word “unskilled” is somewhat misplaced. I choose to focus on the “experimental” part and use the word “unskilled” as a qualifier that really distinguishes this informal trial and error experimentation from the rigorous scientific method.

My vision of 2020 is that models and simulations will take the place of the gears, springs, wood, and nails that earlier tinkers used as their building blocks. When imagining the past, I picture a large garage or shed, or maybe even a laboratory in someone like Edison’s case, littered with piles of spare parts, and I ask what the analogous thing will be in 2020.

First, it will not be the same. Even today’s systems are too complex to be designed and built with old-fashioned tinkering. There may still be an occasional success, but I doubt they are common. The options are too many and the availability of composable parts too small. A design team in 2020 will certainly need to pursue a more guided and systematic approach in the future.

Second, I recognize that some tinkering does still happen today, specifically in the area of prototyping. According to Merriam-Webster, one definition of a prototype is, “an individual that exhibits the essential features of a later type” (M-W 2003). This prototype can be used as a proof of concept or for refinement of design. For example, the wing sweep angle of a prototype aircraft can be “tinkered” with through variation in wind tunnel experiments.

Next, my vision is that this type of tinkering can be expanded through the use of computer models and simulations. Naturally, this is done today in engineering design, but it should me more tightly integrated into the design process. As a repository of models and simulations is created, either within a company or by a standards committee, it will become the new pile of spare parts that is ripe for tinkering.

A major advantage that computer models have over physical entities is that because duplication of software is trivial in time and cost, all parts are spare parts and become part of the repository. Therefore, they are always available. A disadvantage of this is that there will be more to sift through in the 2020 version of Junkyard Wars or engineering design. An enhanced knowledge management system that contains computer interpretable semantics about the models and simulations could assist in this sifting, or maybe even perform the sifting one day.

Finally, in the year 2020 tinkering will be more common in the conceptual design phase because a larger set of models—including simulations—will be gathered in a repository
that contains sufficient context and semantics for reuse. These models will support the
decision process during conceptual design, possibly allowing a better assessment of
things such as risk and cost much earlier in the design process than today.

I expect that their will be a long way to go even in 2020 to make model reuse and
composition automatic. There will still be an important human role. However, I do
expect that significant progress will have been made in the first step, which is to find a
way for humans to express the semantics and context of their models explicitly in a
human interpretable form.

2.4.4. The Pace of Technological Advance
I was originally trying to ideate on product lifecycle changes by the year 2020, which led
me to extensibility. This is turn led my to a consideration of the pace of technology; it is
spreading and evolving faster than ever before. In this section I explore the ramifications
of this in the context of computers and the internet.

2.4.4.1. People don’t yet know how to use computers effectively
It is clear to me that computers can be put to a myriad of uses that provide value, and that
they have a significant amount of unrealized potential. In some cases this is because the
supporting infrastructure—such as computer interpretable knowledge representations—is
still being developed. A successful company in 2020 must realize the full potential of
existing technology in addition to anticipating and incorporating emergent technologies.
One important obstacle to achieving this is that people don’t know how to use computers
effectively.

I am not trying to insult any individuals or class of people with this statement. People
don't know how to use computers effectively for two main reasons

1. Computers have been adopted widely in society sooner than a deep understanding of
   how to use them effectively could be formed
2. Most people—including engineers and scientists—are not trained formally in how to
   use computers as tools. Consequently they often don’t know
   • what is possible to do using a computer
   • what is valuable to do using a computer
   • how to do something valuable using a computer, for example how to choose the
     proper software to complete a task with the most value

As people learn how to use computers more effectively, the computer will become a
more powerful tool. This might lead the realization of a human-computer cyborg. As
progress is made on understanding how to use computers effectively, formal training will
need to be formulated and incorporated into academic or corporate programs. Designers
must be taught to use computers, and they must learn to keep learning how to use
computers.
2.4.4.2. Technology spreading faster than we can cope

One sign of the rapid increase in the rate of technological advance is the faster adoption of new technology by a large segment of the population. For example, the internet has spread more quickly than legal standards and security methods can keep pace. A new product such as Windows XP becomes so widespread so quickly, that there is less and less time for testing and refining the product with the first customers to settle the new frontier.

If a smaller community of users adopted a piece of software such as Windows XP in the first months or even years of its existence, then security flaws such as those exploited by the recent Blaster worm may not have affected as many people. I am making some assumptions here, such as that the worm would have been unleashed in the smaller community or that security watchdogs would still actively seek such vulnerabilities even with a small market to hurt or help respectively.

However, Windows XP has been widely adopted very quickly, so bugs, viruses, and worms affect so many individuals and organizations that they literally can bring the whole economy of the United States (as well as the entire industrialized world) to a halt. There is no reason to think that this will change in a global marketplace, especially as more countries come online.

My company can do little to prevent the above problems with commercial off the shelf software tools. Our primary concern will be to prevent similar problems with our products. We will need to resolve the tension between longer safety testing timelines and the need to reduce time to market.

There are two main factors I consider now. First, the rapid and widespread deployment of a product such as Windows XP is a large departure from previous technologies. In other technologies, the large segment of the market did not adopt the same new model or new product every year. Second, even revolutionary technologies such as the telegraph did not spread as quickly as the internet. My perspective is only considering the internet explosion in the last 10-15 years and not going all the way back to the initial DARPANet, which may not be totally fair.

The common thread in my examples is that safety nets existed to cushion the falls from early failures. Certainly some individuals and companies suffered, but society as a whole never ground to a halt.

For example, when the first airmail service began, it was between a limited number of cities. The previous system (mainly train service for long haul) still existed, so there was a backup. The existing infrastructure was sufficient to sustain the continuing activities, such as mail service that predated the new technology. However, new technology breeds new demands and activities, and there is often no backup for these new demands. For example, when the internet goes down, people come close to panic, asking everyone on their network, “Do you have email?”.
For example, air transportation quickly created a new market for long distance leisure and business travel since it took less time to get between places. However, the new technology was not so widespread or integral to the economy that failures of the new technology—and consequently the temporary cessation of new activities—impeded progress in the country. Certainly growing pains might have been felt when such figures as Knute Rockne or Will Rogers were killed in early plane crashes, but these losses were tangential to societal advance.

### 2.4.4.3. Coping with this pace

I see three main things that will need to be done by 2020, if not already:

1. Reduce the number of errors and oversights in new products
2. Provide better safety nets to product failure
3. Fix problems more quickly (and maybe even automatically at some point in the future)

The three factors will translate to requirements for a design methodology in the year 2020.

All of these endeavors can be supported by a systematic design process. A systematic design process takes the designers through a variety of perspectives and levels of abstractions and can include formal techniques for ideation and failure analysis. These planned efforts should reduce the number of problems in design and production of new products.

A systematic process can also help in budgeting resources, including time, to providing safety nets to failures. It is difficult to identify what a factor of safety (common in structural design) would be in an information system. Tools will need to be created an adapted safety engineering process incorporated into the design methodology.

Finally, a following a systematic design process should provide a more complete and structured body of knowledge about the design than an ad-hoc approach. If this knowledge is captured in some form of context rich repository, the impact of problems may be mitigated and corrections made expediently.

I specifically see a knowledge repository as assisting in fixing problems by speeding the corrective actions. This body of knowledge will be valuable because:

1. The original design team may not be easily assembled due to its distributed nature
2. People leave their positions and jobs quickly and may not be available at all
3. People forget
4. It is usually people on the bottom of the totem pole get assigned to fixing bugs. These are probably not the original designers, so they will need knowledge about the original design process and decisions
Chapter 3. Requirements List for an Augmented Design Process in 2020

Before a product is created, the requirements should be clear. A requirements list is the output of the product planning and clarification of task phase of the P&B process.

Therefore, before personalizing and augmenting the method presented by Pahl and Beitz in *Engineering Design: A Systematic Approach* (Pahl and Beitz 1996), I plan my product and develop a requirements list for design methodologies in the year 2020.

3.1. Pahl and Beitz Requirements for a Design Methodology

3.1.1. Presentation of Requirements

Pahl and Beitz write on page 10 that a design methodology must, directly quoting:

- encourage a problem-directed approach; ie it must be applicable to every type of design activity, no matter in what specialist field
- foster inventiveness and understanding; ie facilitate the search for optimum solutions
- be compatible with the concepts, methods, and findings of other disciplines
- not rely on finding solutions by chance
- facilitate the application of known solutions to related tasks
- be compatible with electronic data processing
- be easily taught and learned
- reflect the findings of cognitive psychology and modern ergonomics; ie reduce workload, save time, prevent human error, and help to maintain active interest

In their surrounding discussion they also note that the design methodology must

- recognize the importance of intuition and experience
- foster and guide the abilities of designers
- encourage creativity
- emphasize the need for objective evaluation
- support reuse of knowledge
- provide an effective way to rationalize the design and production processes

It also must be simultaneously

- flexible
- capable of being
  - planned
  - optimized
  - verified

3.1.2. Discussion of Pahl and Beitz Requirements

In their words, “Systematic procedures merely try to steer the efforts of designers from unconscious into conscious and more purposeful paths.” I think that this should be interpreted as the overall goal of systematic procedures.

By steering the efforts into conscious paths, they can be recorded, analyzed, adapted, improved, taught, and automated. Because the path is delineated, responsibility can be assigned and tasks divided. Once the process is made explicit, tools can be developed to support specific aspects of the systematic approach. Pahl and Beitz recognize that a
systematic design methodology is “a prerequisite for flexible and continuous computer support of the design process using product models stored in the computer.”

I infer from the word “steer”—which is different from “constrain”—that the procedures must be well-structured but general; the specific steps should be presented clearly by means of identifying the crux of the step. This main purpose should be generally applicable. The procedures should also be adaptable. The procedure must allow for iteration, the skipping of steps, and the incorporation of new steps. If the procedures are clearly defined, then the designers will be able to identify which ones are relevant to their task and where they need additional steps not included in the existing framework.

3.1.3. Organization of P&B Requirements

In this section I list requirements for an engineering design methodology derived from Pahl and Beitz, and I group them into categories. This is motivated by the use of an affinity diagram, shown in Figure 2. I have supplemented it with one category that there was no value in adding to the actual diagram. I did consider whether this belonged under “management” but found no strong motivation to do so.

Design Goals:

• Support multiple objectives of design process
  o Design for cost
  o Design for manufacturing
  o Design for risk
  o Design for reliability
  o Design for the environment
### Figure 2: Affinity Diagram, Pahl and Beitz Requirements

#### 3.2. Organization of My Requirements

I now present my own requirements, which are derived from my vision for 2020 in Chapter 2. These are grouped into categories, as motivated by an affinity diagram. I do
not believe it is valuable to create another diagram, as that took over one hour for the previous with almost no benefit. I believe that the act of creating one affinity diagram taught me its power. I see the actual poster-board and sticky-note group process as a valuable attention directing tool for a group, but no more powerful in presentation than a bulleted list.

Knowledge Management
- Support the capture of knowledge, information, and decisions
- Encourage the capture of knowledge, information, and decisions
- Encourage the use of the computer to store knowledge
  - easier distribution
  - faster search
  - visualization tools
- Incorporate searches of repository into solution finding
- Use documentation as summary of repository or as procedural directions
- Check for consistency of final design and knowledge repository
- Check for consistency between repository and documentation

Leadership
- Encourage explicit discussion and agreement about process (reduce implicit assumptions)
- Help cross linguistic boundaries
- Provide a framework for each of the following tasks
  - Clarify
  - Abstract
  - Ideate
  - Evaluate
    - Qualitative
    - Quantitative
  - Decide
  - Coordinate
    - People
    - Resources
    - Information and knowledge
  - Prioritize

Exploration
- Support the search of knowledge repositories
- Encourage and support tinkering
  - Incorporate the use of prototypes early in design
  - Integrate the use of modeling and simulation at multiple levels of abstraction, from the system view down to component analysis

Computer Use
- Direct consideration of what is possible to do using a computer
- Support evaluation of what is valuable do using a computer
• Support selection of how to use the computer

Systematic
• Easily taught and discussed across cultures and languages
• Structure the tasks and responsibilities
• Makes knowledge repository more structured and aligned with tasks
• Make iteration loops smaller and less frequent

3.3. Design Process Principles
In addition to design methodology requirements, I propose the following guiding principles for a design methodology, some of which are motivated by my frontier lessons from Sections 2.1.8 and 2.1.9.

• Help designers bring the correct tools to the table
• Help designers anticipate, react, and adapt quickly
• Encourage process support structures to develop
• Help designers reduce time to market
• Help designers deliver a quality product and keep pace with changing demands and requirements and future customer desires
• Stretch the bounds of creativity and innovation
• Protect the natural and corporate resources
• Facilitate consideration of multiple objectives

These principles should be reviewed whenever an augmentation to the process is considered, or a new tool is used to execute the process.

While browsing some best practices, I found one category that relates to my thoughts in Section 2.4.4.3. Here it is, taken directly from Kevin Klein’s A2Q4S (Klein 2003).

Deal with Failure
• Increase quality
• Effectively and efficiently react to failures
• Identify and predict failures and pose solutions
• Allow for efficient elimination of weak ideas
• Reduce size of repeated step when reach failure

3.4. Clarifying the task: Demands of the future

3.4.1. Review of trends
I have now presented requirements explicitly stated by Pahl and Beitz, requirements I’ve derived from reading Pahl and Beitz, and requirements that I’ve created or compiled based on my vision for 2020. The next step in creating the requirements list for my personalized and augmented Pahl and Beitz systematic approach to engineering design is to determine which requirements are relevant to my vision of 2020 and then to prioritize which ones I want to focus on.
In order to accomplish this relevancy check, I use the keywords from the trends that I identified in Section 2.3.1. I now add my own keywords identifying current and future trends and qualify them with what is motivating the move towards them

- collaboration complexity of systems leads to multidisciplinary teams and different teams for different phases of the process
- multilingual globally distributed engineers
- reuse of knowledge, materials, infrastructure equals cost savings
- repository need to keep everything in one place as engineers move to new jobs or different locations
- computerization computers are great! computing power is cheap! (are they?)
- simulation why can’t prototyping, verification, and testing be done with simulations instead of needing to actual produce an item?
- quick information moves more quickly, why can’t it be generated more quickly?
- cheap hey, the bottom line is still monetary in most organizations
- quality with all this technology and trained engineers, why can’t you make things that work better and last longer?
- automated computers and robots faster and tire less than humans
- verify show you did everything that should have been done according to you contract (legal motivation)
- validate show how great your product or model is; computers give us numbers, now show us that they mean something!

### 3.4.2. Synthesis of Trends

I now take the key words presented in the preceding section and in Section 2.3.1, seek their essence, and group them into a smaller set of terms that I feel are related. This is again motivated by an affinity diagram, only here I have omitted titling the groupings.

- globalization, diversity (cross cultural), multilingual, and interdisciplinary collaboration seem to have the same main challenge: communication, both expression and transmission
- security is one form of safety
- privacy is one thing that a code of ethics must address
- accelerating pace
- environmental is one aspect of sustainability
- risk is caused by uncertainty
- complexity and interconnectedness of both products and markets
- knowledge must be stored (repository), managed, and reused
- simulation and automation are two aspect of computerization
- quick and cheap often go hand in hand
- quality should be designed for, but must also be able to verified; validation of models used also is with the aim towards quality of the final product
3.4.3. Relevance Analysis using Matrix Diagram
I have created a list of potential requirements and motivation in the form of trends. I now create a matrix diagram to see how the requirements that I’ve proposed fit with the trends. This matrix is attached in Appendix A.

Of the requirements that I’ve proposed so far, I believe that some are not requirements of a design process, but of the tools that are used to execute the process. I’ve included an a column in the matrix to represent whether a requirement is for the method or the tools.

The difference is in some ways subtle, but I believe it is necessary in order to keep the process general. The process should force the designers to explore certain aspects of the design at a certain time, and direct them to structuring their efforts appropriately. For example, the design process should prescribe “seek solution variants” using ideation techniques. It should not say “employ lateral thinking”. A supplement to the process can recommend specific tools. I discuss this more in my Assignment 3 Part I.

3.5. Lessons Learned from using Matrix Diagram
The first thing that I discovered using the matrix diagram was that there were a lot of cells to consider. Often it was hard to distinguish whether or not there was a strong connection between a trend and a requirement. I considered using a variable scale of relevance, but I could not assess any different levels of relevancy; every time I’d look at a cell I’d have a different opinion. I reconsidered my goal of using the matrix diagram. I wanted to use it as a qualitative tool to make sure that
1. There was at least one requirement relevant to each trend
2. There was at least one trend relevant to each requirement
If there were a requirement that did not have relevant to a trend, then I had to consider
- Is the requirement superfluous?
- Is the requirement inherent to the general design process?

Even if the requirement is not relevant to a trend, it may be important. For example, I did not identify any trend as relevant to original design. Clearly the design process must support this. My identification of trends was mostly an effort to consider what needed to be changed in the process, so core requirements may not be addressed by trends.

3.6. Reduction of Requirements
Some of the requirements in the matrix diagram strongly overlap with other requirements in their relevance to trends. Such overlap was used to guide the process of bringing the requirements to a higher level and reducing the overall number. For my coursework to be manageable, I need to reduce the number of augmentations to the Pahl and Beitz methods that I seek to include and explore in my project. I have presented in Table 1 a condensed list of requirements and their relevancy to the trends that I identified.

One requirement, “support original design” is not marked as relevant to any trend. Nevertheless, it is clear that a general design methodology must support original design. The relevancy of the trends in the matrix to adaptive and variant design is that adaptive design and variant design will become more important in the future. This is especially
true in the area of *mass customization*, which is one area that I will not address in my A2Q4S. If you are interested in this aspect of design, I suggest reading Mark Wills’s A2Q4S, which is available on the course website.

The question mark “?” in the matrix reminds me of an important issue that Farrokh Mistree and Rich Malak have mentioned in various discussion, that a design repository raises issues of intellectual property rights and privacy issues. It could be a record of individual actions as well as a way for a company to infinitely store the expertise of employees. Why would an employee turn his ideas over to a permanent record? That might make the employee obsolete. It was this question that first motivated me to try to develop an intellectual property rights policy for my company and to create a corporate philosophy that encourages long-term commitments between the company and its employees, as I have done in Section 4.5.

The requirements presented in Table 2 do not yet form a requirements list. Responsibility has not been assigned, and the difference between demands and wishes is not made. There are also still too many requirements to consider in this course, so the list will need to be reduced even more and then prioritized.
Table 2: Relevancy Matrix

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Globalization, diversification, multicultural, interdisciplinary</th>
<th>Safety, security</th>
<th>Privacy, ethics</th>
<th>Accelerating pace of technology</th>
<th>Environmental sustainability</th>
<th>Complexity, interconnectedness</th>
<th>Knowledge management, reuse, repository</th>
<th>Computerized, simulation, automated</th>
<th>Quick, cheap</th>
<th>Quality, verification, validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compatibility with current technology and electronic data processing</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Compatibility with management constructs</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Compatibility with cognitive psychology</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Compatibility with legal regulations and ethical standards</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Compatibility with industry standards</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Generality: applicability to design in different fields</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Support original design</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Support adaptive design</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Support variant design</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Be easily taught and learned</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Facilitate creation of support tools, especially computerized tools</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<tr>
<td>Capable of being planned</td>
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<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Capable of being improved/optimized</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Capable of being verified</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Structure the tasks and responsibilities (subdivide)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Encourage explicit discussion and agreement about process (reduce assumptions, cross linguistic and cultural boundaries)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Make knowledge repository more structured and aligned with tasks</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Apply known solutions to new tasks / support and encourage the reuse of knowledge / search repository</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Evaluate progress: have identifiable decision points and milestones, framework for knowing when to quit</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Effectively and efficiently react to failures (Make iteration loops smaller and less frequent)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Encourage the capture of knowledge, information, and decisions</td>
<td>+</td>
<td>?</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Use documentation as summary of repository or as procedural directions</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Check for consistency of final design and knowledge repository</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
3.7. Reducing and Prioritizing the Requirements

The requirements list in Table 2 is still pretty large. Based on my reviews of former answers to the Q4S, I concluded that the requirements need to be limited in number because I did not see how they could meet or verify a requirements list that long.

At the least, I need to prioritize my requirements list for a design methodology in 2020 before I begin to augment P&B (see reference Pahl and Beitz 1996). In this learning essay I explore each of the requirements. I talk to why they are important and in what ways. The motivation for this is to capture my thinking for review and as the context for prioritizing my requirements. In order to prioritize them, I need to assess them in several dimensions. I must prioritize my requirements, before I can start to augment P&B and schedule the other work that I need to complete.

3.8. Description of my Analysis

The first way I distinguish my requirements is by separating them into two categories—demands and wishes, which in this case is in some ways a subjective assessment.

The second way I separate the requirements is by stating if I think that an augmentation is needed in the existing P&B approach. For example, P&B clearly supports original design, but on the other hand, there is plenty of room for improvement in rationalizing the decision process.

The third measure is related to my work this semester. For each requirement that I believe necessitates an improvement to P&B, I qualitatively assess how much effort I think that I would need to invest to effect that improvement this semester. The scale is set up as follows:

- **Low**: should require only a few structural changes in the process and will not require me to acquire or generate a great deal of new knowledge.
- **Medium**: certain aspects of the improvement will require new knowledge to be acquired or developed in order to understand how to best complete the step.
- **High**: will require new research and insight into how to address a sub problem; items in this category are potential research topics for graduate students.

In this rating system, the “medium” category is the most unclear. When I use that rating I basically mean that the change is not trivial to achieve, but the process can be improved without revolutionary new research contributions. For example, “make knowledge repository more structured and aligned with tasks” is medium because I’m not really familiar with how knowledge repositories are structured, but I doubt that this is a revolutionary approach to knowledge management.

The fourth rating I use a qualitative measure of the effort required to create tools to support the augmentations to the process. I use the same scale as for the previous rating. I present the following example to contrast with my previous example. The requirement to “apply known solutions to new tasks” and its related requirements “support and encourage the reuse of knowledge and search the knowledge repository” probably require...
a medium amount of effort to bring them into the process. P&B already include these to some extent, but there is room for improvement. The development of tools to really support these augmentations—such as repositories of context rich semantic and computer interpretable knowledge—is a major research and development project.

**Requirements for a Design Methodology for the year 2020**

<table>
<thead>
<tr>
<th>Very new requirement?</th>
<th>Demand or wish?</th>
<th>Improvement necessary?</th>
<th>Estimate of effort to augment process</th>
<th>Estimate of effort to create support tools</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>low</td>
<td>1. Compatibility with current technology and electronic data processing</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>low</td>
<td>2. Compatibility with management constructs</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>medium</td>
<td>low</td>
<td>medium</td>
<td>3. Compatibility with cognitive psychology</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>medium</td>
<td>high</td>
<td>low</td>
<td>4. Compatibility with legal regulations and ethical standards</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>5. Compatibility with industry standards</td>
</tr>
<tr>
<td>W</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>6. Generality: applicability to design in different fields</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>7. Support original design</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>8. Support adaptive design</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>9. Support variant design</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>10. Support contracting and subcontracting</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>11. Be easily taught and learned</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>12. Facilitate creation of support tools, especially computerized tools</td>
</tr>
<tr>
<td>W</td>
<td>yes</td>
<td>medium</td>
<td>low</td>
<td>medium</td>
<td>13. Capable of being planned</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>medium</td>
<td>14. Capable of being improved/optimized</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>medium</td>
<td>medium</td>
<td>high</td>
<td>15. Capable of being verified</td>
</tr>
<tr>
<td>W</td>
<td>yes</td>
<td>medium</td>
<td>low</td>
<td>medium</td>
<td>16. Structure and subdivide the tasks</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>17. Encourage explicit discussion and agreement about process (reduce assumptions, cross linguistic and cultural boundaries)</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>18. Make knowledge repository more structured and aligned with tasks</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>19. Apply known solutions to new tasks / support and encourage the reuse of knowledge / search repository</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>medium</td>
<td>20. Evaluate progress: have identifiable decision points and milestones, framework for knowing when to quit</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>21. Effectively and efficiently react to failures (Make iteration loops smaller and less frequent)</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>22. Encourage the capture of knowledge, information, and decisions</td>
</tr>
<tr>
<td>W</td>
<td>yes</td>
<td>medium</td>
<td>low</td>
<td>medium</td>
<td>23. Use documentation as summary of repository or as procedural directions</td>
</tr>
<tr>
<td>W</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>24. Check for consistency of final design and knowledge repository</td>
</tr>
<tr>
<td>W</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>high</td>
<td>25. Check for consistency between repository and documentation</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>medium</td>
<td>high</td>
<td>low</td>
<td>26. Provide a framework for each decision task; rationalize the decision process</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>high</td>
<td>high</td>
<td>low</td>
<td>27. Integrate the use of prototypes, modeling, and simulation at multiple levels of abstraction, from the system view down to component analysis (tinkering)</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>high</td>
<td>high</td>
<td>low</td>
<td>28. Guide what can and should be done valuably on the computer</td>
</tr>
</tbody>
</table>

**Figure 3: Analyzing the Requirements**
3.9. Discussing Requirements

I have numbered the requirements in Figure 3 for convenience. I will now speak to each of the requirements in either a small group or individually, and I will therefore explain my reduction of the requirements for my work in this course.

3.9.1. Requirements 1-5 and Requirements 11-15

I begin by lumping requirements 1-5 and 11-15 together. I believe that the Pahl and Beitz method adequately meets these requirements. Most of them are requirements taken directly from Pahl and Beitz. They stand as requirements for 2020 because any augmentations made to the process will still need to meet these requirements. I view these requirements with an extension of the rule “if it ain’t broke, don’t fix it.” Certain parts of P&B aren’t broken; meeting these requirements ensures that I don’t break P&B while trying to make it better.

3.9.2. Requirement 6: Generality: applicability to design in different fields

Please notice that I have qualified “generality: applicability to design in different fields” as a wish. The argument for making it a demand is that the power of the process increases immensely if it is kept general. The argument for making it a wish is that I may benefit greatly from a sacrifice of some generality for the purposes of this course. There is no reason that my design process needs to be directly applicable to a task such as designing a student’s graduate studies. If I make this requirement a wish, then I can more readily make tradeoffs in my approach that will allow me to incorporate issues more directly related to my research, such as including simulations, even if they limit the generality of the approach slightly. Essentially, I’m allowing for personalization to creep into the augmentation phase.

3.9.3. Requirements 7-10: Supporting various types of design

I believe that the P&B approach can address adaptive design and variant design better than it does now. It must also address subcontracting and supply chains.

The bulk of their work deals with original design. I doubt that this augmentation will require much effort. I see it as a matter of modifying the process such that there is an explicit decision point when adaptive or variant design is chosen, and then that design process re-enters the core original design process at a later point. There might also be a variation on product planning and clarification of task to better implement the extension of product families, but much of the augmentations alone these lines are best left until ME 6102.

I believe it is important to recognize that the first phase of engineering design as presented by P&B is not necessarily followed by the same company that will design the product. For example, one company might identify a market and make a requirements list, and then contract the development out to a company with greater knowledge in that area.
A very common example of this is when the Department of Defense or a scientific exploration organization such as NASA declares the need for a particular product or tool. The actual changes to the process will not be substantial, but there is a lot of room for new tools to help bridge the gap. For example, the conveyance of requirements between organizations is not easy. Even more difficult is the conveyance of preferences for tradeoffs across any boundaries.

This type of issue will also arise in supply chain management. If suppliers are not dominated by the company they are supplying, they might not work to the same standards, ethics, and societal goals.

3.9.4. Requirement 16-17: Structure and subdivide the tasks

Originally this requirement read, “structure the tasks and responsibilities (subdivide)”, and it was classified as a wish. In retrospect, I think this is primarily because it isn’t clear what I meant by “responsibilities.” The method cannot really structure responsibilities—meaning who must do what. The method can help managers structure the tasks; the scaffolding that supports this results from the process being systematic. I propose to make this a demand and rewrite it as “structure and subdivide the tasks.” By breaking the design process into small and bounded steps, the efforts of designs are concentrated on a particular task. If anywhere, the structure of responsibilities is relevant to the realization of Requirement 17.

There needs to be a step in the design process for project or process management. This needs to happen not only at the beginning of design, but at least during each phase because the teams of designers often change as design moves from one phase to another.

During this process management step, the process to be followed and design teams is made explicit. An analogy to what I’m thinking of would be an NFL football team agreeing that they will all use the same playbook. Another analogy would be to make sure that all the assistant chefs on Iron Chef are actually following the same recipe. This will be important in 2020 because I expect that design teams will be geographically distributed and interdisciplinary. In government projects, several organizations and companies are often involved. The room for misunderstandings on the process is plentiful.

With distributed design teams, the opportunity for confusions is increased. With different work schedules and locations, scheduling meetings between teams will be more burdensome and extensive. Current remote collaboration tools still lack the capacity for teams to really interact with each other over distance. Although I expect improvements by 2020, I think people will still be learning how to work and learn from each other using these tools.

3.9.5. Requirement 18-19, 22: Facilitate knowledge reuse

My motivation here is that a company should leverage its existing knowledge. One way to facilitate knowledge reuse would be to capture and store it according to the design process. In other words, knowledge generated during conceptual design, such as working
principles, will probably be useful in future conceptual design activities, but it will also be relevant downstream in the same design process. It must be readily available for both uses.

I claim that this augmentation to the process will take medium effort because the additional steps are not trivial. At the same time, I doubt that significant developments need to be made in knowledge management to realize it. It is something that I am not prepared to tackle in depth at this time. I also suspect that most tools supporting knowledge management have some facility for incorporating where the knowledge originated. The more difficult question to answer is how to minimize the obstructions to the design process while the knowledge and information is captured for the design repository. Again, this is outside the scope of my augmentation this semester. Fortunately, such alignment is only a wish. Requirement 19 is the important one.

P&B include the reuse of knowledge in their systematic approach to engineering design. Their process takes designers through tasks from cognitive psychology that support ideation, and P&B also discuss searching design catalogues. I think that their approach is off to a great start. My task is to speculate on how it might be improved with current and 2020 technology.

I categorize this augmentation as taking a medium amount of effort to include in the process. The approximate areas where knowledge reuse should be sought do not change much, or at least I do not expect them to. However, the exact way in which they should be folded into the process are not yet clear to me. The role of the human will not disappear by 2020. Therefore, ideation methods involving humans will still be valuable. However, they can be complemented with knowledge capture and repository searching.

The tools and technologies that support these activities are active research areas. This field is mostly outside of my research goals, intersecting only in the theory of reusing models and simulations and needing to capture information such as the context and accuracy of those models.

The design process, including the corporate philosophy, must encourage the capture of knowledge, information, and decision rational. For example, how was a decision taken? Using what information and method? Without this capture of knowledge, design knowledge cannot be reused. As design teams become more distributed and fluid, the knowledge in one engineer’s head will not be available to the other designers.

The captured decision rationale could be valuable for troubleshooting, downstream design space trades, and trades between teams of designers, not to mention during future design tasks. My corporate philosophy will encourage the engineers to capture and share this knowledge, but they still need a mechanism to do so.

I is not entirely clear to me how the design process can be augmented to facilitate knowledge capture. One way is to use DSP templates and the DSP technique (Marston, Allen et al. 2000) to support human decision makers. I see that these tools might be
developed to support capturing more knowledge, but as far as I know, there is a lot more research to be done into how to actually capture knowledge in a conveniently accessible manner. This is outside the scope of my work in the foreseeable future.

3.9.6. Requirement 20: Evaluate Progress

The process should encourage the use of evaluation points where a decision could be taken to terminate the project. These do not have to be the only places in the process that the project could be terminated, but the process should ensure that a conscious decision is made to move forward in the design process. The motivation for such reviews is to reduce the size of the iteration cycles by catching a problem in an earlier design step. These reviews, as I will call them, also serve as the point where the requirements will be explicitly considered in comparison with the current state of the design.

It will not be difficult to include review points in the process. I’m not yet sure how to decide where to place them, but the real challenge is in formulating methods for actually evaluating the process. This is extremely important with contract completion; how will a company measure if they or their contractual partner are actually progressing as they should? How will they know at the end if and when the contract has been fulfilled? At least given my knowledge, there is research to be done into how the qualitative judgment of whether the progress towards the goals is satisfactory.

3.9.7. Requirement 21: Effectively and efficiently react to failure

This requirement is related to two things that I discovered and discussed early in this paper, for example in Section 2.4.4.3 and in Kevin Klein’s A2Q4S (Klein 2003). My company’s philosophy is that failures are inevitable and should serve as learning activities. Designers may not even know that there has been a failure until they evaluate their progress and compare their design with the requirements. No matter how the failure is discovered, the question arises about what to do next. Designers should be encouraged to question things and to discover and report possible problems, concerns, or failures.

If Requirement 20 is met, then failures will be identified relatively quickly, before many additional resources are invested in the faulty design. Also, the systematic approach to design mitigates against risk. If an ad hoc approach is used, designers are more likely to subconsciously cut corners, which increases risk.

If a depository of the design process and decisions has been adequately kept (Requirement 22), then the design fault can be traced backwards to see when it was made, under what assumptions it was made, and what other decisions might be affected by correcting the failure. However, this traceability needs to be triggered by the identification of the problem in the first place.

Given that Requirement 20 is present, I think that this requirement is almost outside of the process of engineering design and is more related to a company’s corporate philosophy. If the company can create an environment in which the inevitability of design failures is accepted, then engineers might be more willing to draw attention to a potential failure earlier, thus diminishing the cost of failure to the design team and company. I imagine that some management cultures tend to “shoot the messenger” who
brings the bad news of a failure, instead of thanking them for suggesting an avenue to investigate in more detail.

One way to reduce failure may be to explicitly consider risk in the design process. For example, early design decisions are made under uncertainty: among other uncertainties, there is no knowledge about future design decisions that will affect the system performance. There is also uncertainty in the models used to support decisions.

3.9.8. Requirements 23-25: Knowledge repositories, Documentation, and Consistency checking

These potential requirements are not essential to a design methodology. I have also received feedback from Farrokh that they are not clearly defined. I have decided to eliminate most of these requirements from my scope of concern in this course, but I would like to recognize one idea. This is the notion that human involvement in detail design could nearly disappear from the engineering design process in knowledge is captured formally and in a computer interpretable manner throughout the entire design process. If things are documented properly throughout the process and the proper and complete set of evaluation criteria are used, then almost everything should have been specified at the completion of embodiment design. As an example of this possibility, P&B note on page 402 that with respect to detailed drawings and parts lists that “These activities are increasingly supported, and in some cases automated, by CAD software”

3.9.9. Requirement 26: Rationalize the decision process

I see a huge opportunity for improvement in P&B here. The amount of effort involved in augmenting the process to meet this requirement might be just as big. Given the interest of the SRL family in decision support, I’m confident that there is a lot of material available from which I can leverage these augmentations. The aspect that I seek to bring into the decision process is an explicit consideration of risk.

Uncertainty is a major concern in all design. There are two flavors of uncertainty. One is that the final design is uncertain as decisions are taken earlier in the process. The second flavor of uncertainty involves things such as operating environment, production tolerances, and reliability. I need to develop this argument farther in the context of my project and the NASA research opportunities that motivate my current research. I discuss the different types of uncertainty in Section 8.8.

3.9.10. Requirement 27: Integrate modeling (including prototyping and simulation) into the process

The P&B approach was formulated before the average engineer had access to anything approaching the power and convenience of today’s personal computers. Today there are many more models and simulations available, and I imagine that custom software available at a higher standard for a lower price. Therefore, the use of such computer tools needs to be integrated into the process.

I suggest one place to include them is in the evaluation of solution variants at different stages in the process. In the later stages of embodiment design, this integration is fairly
straightforward. For example, a CAD model of the form of a part, or a modal-analysis of vibrations in an element. The computer models merely take the place of a physical model or experiment.

I propose that modeling can be taken farther. For example, if model creation can be made inexpensive (by means such as facilitating reuse), then more exploration and evaluation can be done. I also propose that modeling be brought into conceptual design, beginning by simulating the systems perspective based on the function structure.

I believe that both incorporating these into the process and developing the tools—such as reusable models like composable simulations—require a significant investment in research.

3.9.11. Requirement 28: Guide computer use

I’m not sure how this requirement will fit in to the process. I think it is a bit of an umbrella for including knowledge capture and simulation. At the same time, if it could be integrated into the process, then managers will not have to spend time deciding what to do on a computer and how. They might be able to pick and choose. I am leaning towards removing this requirement; it is more of a guiding principle for developing the other requirements.

3.10. Prioritizing my requirements

In the previous section, I have reduced my list of requirements (that I present in Figure 3) to a smaller set, which I show in Figure 4. I have included in Figure 4 only those requirements that are demands. I have also synthesized some requirements from Figure 3 into a more general requirement. I now seek to prioritize my requirements. My prioritization is developed in the next section and also shown in Figure 4.

Requirements for a Design Methodology for the year 2020

<table>
<thead>
<tr>
<th>Demand or wish?</th>
<th>Improvement necessary?</th>
<th>Estimate of effort to augment process</th>
<th>Estimate of effort to create support tools</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>i. Support various type of design including contracting</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>low</td>
<td>ii. Encourage explicit discussion and agreement about process (reduce assumptions, cross linguistic and cultural boundaries)</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>iii. Evaluate progress: have identifiable decision points and milestones, framework for knowing when to quit</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>low</td>
<td>medium</td>
<td>iv. Effectively and efficiently react to failures (Make iteration loops smaller and less frequent)</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>medium</td>
<td>medium to high</td>
<td>v. Encourage the capture and reuse of knowledge, information, and decision rationale</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>medium</td>
<td>high</td>
<td>vi. Provide a framework for each decision task; rationalize the decision process</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>high</td>
<td>high</td>
<td>vii. Integrate the use of prototypes, modeling, and simulation at multiple levels of abstraction, from the system view down to component analysis (tinkering)</td>
</tr>
<tr>
<td>D</td>
<td>yes</td>
<td>high</td>
<td>high</td>
<td>viii. Guide what can and should be done valuably on the computer</td>
</tr>
</tbody>
</table>

Figure 4: Priority requirements
As I review Figure 4, I decide that Requirements i-ii will be met first in my augmentation of P&B. Requirement iii will also be addressed in the process, although I will not go far towards developing quantitative measures of progress.

Requirement iv will be met by encouraging iteration and exploration earlier in the design process, with the aim of reducing iteration later in the design process when design freedom has been closed and resources irrevocably committed. I will try to expand the ways in which P&B suggest seeking existing solutions. In addition to ideation and catalogue searching, knowledge repositories will need to be searched; I can include this in my prescriptive process even if I do not yet know how they will be embodied.

In requirement v, my emphasis is really on decisions. In decision based design, which I discuss in Chapter 7, decisions are the heart of the engineering design process. Knowledge and information are applied by designers to help form judgments and make decisions. This should be the driver for knowledge capture, although the captured knowledge can also support maintenance and documentation as well.

It is necessary to formalize the decision process (requirement vi) in a way that facilitates decision rationale capture, just as it is important to capture design knowledge in a way that does not obstruct the creative design process. The decision process can be rationalized in many ways. In this project, I focus this requirement by concentrating on the explicit incorporation of risk assessments into the design process. However, for the more general course setting I will need to incorporate decision support tools that include multiple objectives.

Requirement vii is very challenging and exciting. It is in this category that I see the greatest potential for revolutionizing engineering design. Therefore, it is within this context that I will meet Requirement x, where the “x” might as well stand for “eliminated” instead of “ten” as it can be subsumed by requirement ix.

A company in 2020 must devote resources to teaching people what they can do with computers, what they should do with computers, and how they can best execute it using a computer. However, I cannot address all of the issues related to computer usage; I will focus on the use of modeling and simulation.
Chapter 4. My Company in 2020

Before I begin to augment the Pahl and Beitz process, I first present a view of my company in the year 2020. This is valuable, because the nature of a successful company in the year 2020 will need to be different than it is today. If the company wants to capitalize to the fullest on the knowledge of its employees, it will have to treat them different that employees are treated today. It will also need to hire employees who share the corporate philosophy and believe in the corporate policies, which I present in this chapter.

4.1. Introduction

As described in Section 1.4, I believe that the heart of an engineering design company is knowledge. Design is the creation and application of knowledge to make decisions that lead to a product with the goal of meeting requirements. Better knowledge enables humans to make better decisions. My company will need policies, tools, and a philosophy that support the generation and reuse of knowledge. One piece of my question for the semester seeks to achieve “better reuse of knowledge.” Currently the source and repository of most of this knowledge is the company’s employees. Therefore, the company must foster an environment in which knowledge is shared and built on.

I begin to develop my philosophy from this personal bias that employees are important; they and their knowledge are the core of the company. I will also consider intellectual property rights, since intellectual property is knowledge in the form of a marketable company asset. Finally, I will build off of parts of Bjoern Avak’s LE 10 and look at the role of the company in society.

I begin my discussion of corporate philosophy from a somewhat naïve perspective, a perspective that, like my other core beliefs, is biased by my experiences and even irrational factors. My ideal philosophy may not be feasible, but there is no law that can prove ahead of time whether it will succeed or not. My approach is to try to establish policies that embrace this philosophy. From this start, I may later bolster or adapt it to increase the likelihood of success.

4.2. Theme and goals of my corporate philosophy

Employees and their collective are the core of a company; it is therefore essential to foster an environment in which the employees feel loyal to their coworkers, their projects, and the company. Only in this environment can the company access and capitalize on the knowledge of its employees; in any other environment, the company is underutilizing its most precious resource.

In keeping with this theme, I have identified the following goals for my ideal corporate philosophy:

1. Employees are content with their jobs, responsibilities, and co-workers
2. Employees and shareholders are proud of the role their company plays society
3. Employees can sustain their families in a secure and pleasant lifestyle
4.3. Mode of Operation
In my set of goals, I notice one possible failure. There is no direct financial incentive for shareholders to invest in the corporation. I doubt that enough investors will sign-up to float a company based merely on their shared belief that a company with happy employees and social responsibilities will succeed and be profitable in the long-term.

As I proceed in this paper, I will not occupy myself too much with the question of how to replace dividend payments with an alternative incentive, and I will naively believe that investors of some kind will fund such a company.

One way to realize this is to structure the company such that the employees are also the owners, such that they share common interests. Their long-term interests as employees might balance their short-term interests as owners seeking to make a quick profit at social or future corporate costs.

Another mechanism would be to organize my company as a not-for-profit or non-profit organization [note: I use the terms interchangeable, although in some jurisdictions I believe there are subtle legal differences]. According to the SCORE (SCORE 2003) (a nonprofit association dedicated to entrepreneur education and the formation), non-profits serve a function in society. They augment and, in many cases, replace the role of government by responding to society’s problems, and in some cases preventing society’s problems. Many non-profit organizations are in the field of human social services, performing a service for the social good, and so the government offer benefits in returns.

The purpose of a non-profit is consistent with my corporate goals. This is probably the only way that I can organize my company, although I again admit to not knowing all of the details.

4.4. Employee policies
My employee policies are based upon the goals listed in the introduction and my view of knowledge in an engineering firm which I present in Section 1.4. The goal of the policies is to hire and retain employees who contribute to the generation, communication, and application of knowledge in the firm.

4.4.1. Hiring Practices
As Bjoern Avak writes in his LE 10, I believe that “permanent employment constitutes a long-term commitment for both the employer and employee.” As Mr. Avak suggests, “Before making this commitment, one should carefully examine whether there really is a match between the new employee and the team.”

For my job search after my undergraduate, my contacts at MITRE seemed to think that it was crazy of me to ask if I could come visit their site a second time—after they had made a job offer—to talk with more employees, even though I offered to cover all of my own
expenses. I should have realized at that time that they were not interested in hiring to fill a team, but were hiring to fill a desk. This became very clear after several weeks in the company.

In the end, my time at MITRE was a short-term waste in many aspects for both the company and me. I was able to take several lessons away from my experience, and I had a great time outside of work during my year there. However, there is no doubt in my mind that we both would have been much better off during that year if I had gone to work with a different firm. I don’t want my company in 2020 to suffer similar problems.

As Bjoern suggests, internships and temporary employment are excellent possibilities for both parties to get to know each other. Consequently, I believe that my company must recognize the importance of internships and make a strong effort to give interns real projects that are integrated into the larger purposes of the company. My two internships with Exxon Research and Engineering were perfect in this respect. Unfortunately, I knew other interns there (and at other companies) who had experiences that were not as productive.

Interns in my company will not be viewed as cheap hires to perform mundane tasks; internships will be an opportunity to challenge interns so that they and the company can learn how they can rise to these challenges and create value.

If potential hires are located near the company, I believe that they should be encouraged to interact with the current employees as much as possible. For example, the potential hire could be invited to lunch on several occasions with the same people so that he or she can start to develop a relationship with the current employees.

Regular corporate team building events, especially of the younger employees, provide an excellent opportunity for not only those employees but also potential employees to socialize together and really grasp the personalities of those people who are hired by the company.

Both of these policies seem to avoid the problems with security that my original idea—short two week internships or career shadowing programs—may have. These types of short term contact in the work place may open the company to espionage or abuse. However, it may be possible, especially for hires directly from college who have a low probability of being associated with a competitor in a professional relationship. If feasible, such a program would really allow a potential employee to see how the company operates on the inside.

### 4.4.2. Layoff Policy

As I noted above, I agree with Bjoern Avak that “permanent employment constitutes a long-term commitment for both employer and employee.” Therefore, my goal for my company is to achieve a no layoff policy.
When employees are confident that they will not be laid off, it should reduce competition between individuals. In turn, this should encourage sharing of knowledge between employees; there will be little benefit in withholding knowledge because there is no incentive to hold onto to nuggets of knowledge that might help place you behind someone else in a lay-off.

This long-term commitment will not be enforced legally. The two parties may still part ways unilaterally. There is no sense in keeping an unhappy employee, and there is no value in keeping an unproductive employee. Hopefully an open environment of bilateral discussions can avoid such unilateral actions, but they may happen.

As Bjoern notes in his LE 10, “Humans evolve over time and their objectives change.” Bjoern continues, “Having worked for a particular department for several years, an employee and his/her colleagues might realize that the interests of both parties no longer match. In that case, the employee should switch to another department.” I would add that the either party may be better off leaving the company completely.

In cases where employees are not performing adequately, they can still be fired or asked to resign. The first option will be to work with the employee to better match his or her abilities and interests with projects. If an interest match is found but an employee lacks particular skills to be successful at that task, the company will arrange training.

I’m not yet prepared to answer exactly how such poor performance would be measured, but in extreme cases it may become obvious over time that an employee is no longer valuable to the company. Hopefully this will be minimized by effective hiring practices, but again, people change over time, and sometimes the changes will not be consistent with a simultaneously evolving company and team.

One open question is how to fund the company when money is tight. Most companies will layoff employees when their revenues fall too far below a sustainable level. Perhaps my company could sell off other assets before resorting to layoffs. The risk is that avoiding layoffs may ruin the company financially, resulting in the company folding and all employees losing their jobs.

If a for-profit mode of operation is chosen, then in less extreme circumstances, corporate policy will state that no dividends or other distributions of profit to owners will occur when the company is operating at levels that cannot sustain the current work force. Profits will also not be distributed for at least one year after a layoff. By having these policies, the company shows that employees come before profit. Reductions in force will never happen in order to boost profits; layoffs will only be used to salvage the company’s existence.

The next course of action is suggested in Bjoern Avak’s LE 10. He writes, “In times of crisis, [department heads] will award fewer contracts to external contractors and concentrate on the company’s permanent employees. In a way the company sacrifices the employment of some external contractors to ensure the survival of the entire
company.” From a utilitarian perspective, this means that the company’s ethical scope of concern is weighted more towards those people to whom the company has made the commitment of permanent employment.

In cases where layoffs of permanent employees absolutely can’t be prevented, I propose the following policy. First, the company should ask for volunteers to work reduced hours at reduced pay, but at full-time benefits. I believe that there will be some takers as some people are eager to have more time to spend with children, hobbies, or other income generating activities.

Second, before employees are laid-off completely, they should be asked individually if they would accept a reduced hour schedule for a period of time. I think this is the shakiest proposition, because employees may be insulted that they were selected for a reduction in force over others. If they remain at the company, their morale and commitment to the firm may be damaged.

Third, anyone who does accept reduced hours should be allowed to do so for a set time period. For example, a limit of six months would allow the two parties to reassess what is best for them. During this time, the company will allow the employee to actively seek a new job and provide assistance, much as companies now do with normal layoffs. After five months, both parties should discuss with each other what they plan to do at the end of the sixth month. Natural options are an end of employment, a return to full time, or a continued or modified reduced schedule.

Fourth, any victim of a reduction in force will be informed that as long as he or she maintains current contact information with the company, he or she will be informed of all future openings in the firm. They will also have the first opportunity to fill positions and will be hired before new employees are hired. This may be slightly inefficient in the sense that a new employee may be a better fit for the job, but the cost is hopefully repaid by the culture and loyalty demonstrated in the policy.

Finally, a lay-off package will include one month of full pay for anyone, plus several other months of reduced pay for people ineligible for pensions or other retirement benefits, in which case a more complicated arrangement is necessary. The company will also hire a placement agency to help the employee find a new job. The company supports these policies because it does not want to abandon its employees even in the worst circumstances.

4.4.3. Training and Education

My corporation will commit itself to enabling and encouraging employees to continue their educations. As Bjoern Avak writes in his LE 10, “[It] is the right and responsibility of every single employee to work on his professional and personal weaknesses.” He also notes that this is in keeping with the third canon of the ASME (American Society of Mechanical Engineering) code of ethics (ASME 2003).
One way to help employees work on their weaknesses and to develop new strengths is through education. This can be in the form of peer knowledge sharing sessions and tutorials, onsite training, computer based training, and formal university education programs, including the National Technical University and other distance learning programs, such as those offered by Georgia Tech and Columbia University. The corporation will grant people company time and charge numbers for these training activities.

Each employee will be given a time budget per month (or other convenient unit) to spend on training. Employees who are actively seeking degrees can apply for an accelerated degree program in which they are given even more company time to pursue their degree. This will not be available to everyone, as the company cannot afford to have its entire workforce pursuing advanced degrees on company time. To compensate for this restriction, the company will compensate all employees for tuition and fees expended on courses taken in the pursuit of a specific accredited degree or otherwise approved by the management.

I’ve seen such an accelerated degree program work effectively at the MITRE corporation and have heard good things about them at other organizations such as Exxon Research and Engineering, and also the MIT Lincoln Laboratory. My company will base its program on these programs.

I expect that by the year 2020 distance learning programs will be more mature than today, and more options will be available. Employees will also be more accepting and comfortable with distance learning because they will have been exposed to it during their standard education.

In addition to providing funding and time for distance learning, my company will locate its main offices near large universities or a collection of smaller, more specialized universities so that employees can take pursue advanced courses or degrees part-time in a traditional university setting. This assumes that such opportunities will not have been replaced entirely by distance learning. I imagine there will be a demand in 2020 for face-to-face education; based on my experience taking a video course at Georgia Tech Lorraine, the system is far inferior to a face-to-face classroom setting. Although distance learning technology, management, and policies will improve by 2020, “old-timers” like me will probably still prefer the “old-fashioned” education.

### 4.4.4. Performance Feedback

Employees, especially young ones, need feedback from coworkers and management. This will help employees and managers discover an employee’s weaknesses. The employee can focus his or her efforts on improving in these areas, and the management can arrange educational opportunities that may help the employee improve. I propose the following feedback system.

First, management reviews should be performed every six months for every employee. It may be sufficient to have two types, a partial and full review, with the partial primarily
serving to help the employee improve, and the full review serving both to help the employee and to reassess that employee’s compensation and work assignments.

The second part of my policy is more original. I believe that during the course of a project, peer reviews be conducted by the team members of their own performance and their coworkers. These peer reviews will be strictly confidential. In no case will they be used in a person’s compensation or continuation of employment reviews—for negative or positive reviews. In this way, the reviews are strictly a means for the group to help itself get stronger. If my company’s employee hiring practices as successful, the team will want to help each other succeed.

When employees are provided with feedback, care will be put into not only what is said but how it is presented. In my LE4 I explored the process of providing feedback. Because my company maintains a long-term relationship with its employees, we are interested in them in the long-term. The best way to help someone improve is to point out what they need to do next; what is the next step that they can take. Everyone can always improve a lot, but if an individual is presented with too many suggestions or criticism, that person will become defensive and un receptive. Managers will also try to keep the employees receptive to feedback by demonstrating that they are trying to help the employee. Just as Farrokh uses a green pen to provide feedback in ME 6101, managers must show the employees that they are given them the green light for success.

### 4.4.5. Compensation

Employee compensation is very difficult to plan. In most professions it is difficult to fairly and accurately assess a person’s value and contribution to the company. I really don’t have many insights to provide here. In general, my company will follow practices similar to existing companies. In other words, we won’t seek out pay or underpay compared to our competitors.

Employee compensation will be reviewed at a minimum annually. Promotions can be granted at any time in the cycle, and promotion may entail a raise, but will normally occur at the same time as the annual compensation review.

Compensation reviews will be based on managerial review. Managers will be able to interview an employee’s coworkers as part of the review process. However, the employee will not know who was asked to evaluate him. The people asked to make evaluations will be asked questions that focus on an employee’s positive characteristics. The goal of this peer review—which occurs separate from the peer review aimed at helping an employee improve—is to give coworkers an opportunity to identify significant contributions that an employee has made to a project or team that may have escaped a manager’s knowledge.

The company’s full compensation packages will be generous. For example, we will offer new college hires a full 15 days of vacation during their first year, accrued weekly. This will allow them to have personal time during their first year and as soon as two weeks
into their career. I believe that this will make them happier and show them that the company respects that they have other interests and commitments in life besides their job.

At the end of every calendar year, employees will be allowed to “cash-in” up to five days of vacation time for full pay. This will provide employees the flexibility to earn some extra cash instead of vacation time if they need it. Assuming that there are no legal restrictions, these days can also be donated to other employees via an emergency leave fund. Vacation can accrue up to a limit of 20 days in an employee’s “vacation bank.” I do not want to force people to use or lose vacation on a calendar basis, but it is not feasible for the company’s accounting to allow infinite accruals.

4.4.6. Teams

Engineering projects will consist of teams in the year 2020. These teams may be distributed over significant geographic distances and even in separate organizations or companies. In general, I believe that this will pose a large challenge to effective engineering because the team members will not know each other at a personal level. It is also more likely that a tight nit and collocated group will have similar work schedules, since they will be in the same time zone (work day) and country (holidays).

In order to introduce my idea for team selection, I must first present my view of design as two systems—a human system and a product system. The human system is divided into teams, and the product system is divided into subsystems. I discuss this idea more in Section 7.6.

In order to mitigate the problems with distributed teams, the project must be carefully subdivided into tasks that are each assigned to teams, with the members of one team coming from as few locations as possible—preferably one. This will allow the project interfaces to match the geographic interfaces, something that I believe will smooth the design process. Naturally this may not always be possible due to the location of an expert who may be needed. However, if the core of a team is in one location, then the expert could be flown in as needed at a lower cost than uniting people from a larger number of locations. This will increase the opportunities to work together, as well as freeing travel money for other activities, such as teambuilding events outside of work.

By assigning teams in this manner, I believe that teams will have a tendency to recur; the same people will tend to form teams. These people will learn each others work and communication styles, which should lead to increased efficiency. Also, personality differences will become known and can be avoided in future team assignments. There is need to mix up the teams occasionally to increase the spread of knowledge throughout the company, and it will be up to managers (using feedback from the team members) to balance these two factors.

Finally, an important aspect of managing a successful team is getting all the members to share and believe in a common sense of purpose. For example, sports teams often pull together the best when facing the fiercest adversity.
Near the beginning of this season, one of the Atlanta Thrashers hockey players was killed in a car crash, and the driver of the car was another teammate. This event might have torn apart the soul of the team, especially as the driver—who was severely injured physically, faces severe emotional trauma and guilt, and may face criminal charges—was the team’s best player last year and brightest hope this season. Instead of falling apart, the team got off to by far its best start of the season, including an emotional overtime win in Toronto in front of the deceased player’s family.

The lesson here is that a shared purpose—in this case wanting to win in order to honor their fallen friend—helped the team to coalesce. Differences were set aside as they pursued what to them was a noble goal. Individuals came forward and carried a load that they probably didn’t even know they could carry.

I hope that my company never faces such a tragic event, but a lesson can be learned. If a team feels a shared and noble purpose or goal and are bound together as a family, they can do great things; they can exceed everyone else’s, and maybe even their own expectations.

In my company of 2020, this shared purpose is the company philosophy. Each employee is working to prove that this business model can work. They will be working on projects that they believe in—projects that help people and society, that are environmentally friendly, and are reliable.

4.5. Intellectual Property Rights

[Note: My background in this area is not strong. I am basing most of this section on the presentation made by Steven P. Wigmore, Esq. to the Atlanta section of the ASME on October 13, 2003 (Wigmore 2003)]

4.5.1. Patent Protection

The motivation for a government to create a patent system is to encourage the sharing of knowledge. According to Mr. Wigmore, a patent is “the legal right to exclude others from making, using or selling a patented invention for limited period of time” (Wigmore 2003). This period of exclusivity is the patent holder’s reward for sharing knowledge. Without patent protection, many more ideas would remain trade secrets, which have the opposite purpose of a patent; a trade secret tries to prevent competitors from gaining knowledge so that the holder of the trade secret can maintain an infinite monopoly on the knowledge. For example, the recipe for Coca-Cola is a trade secret.

My company in 2020 will pursue patent protection for all applicable (patentable) inventions and ideas. The company’s knowledge will be available for others to build from. This is in keeping with the company’s interest in serving the public. There may be exceptions when company may choose to make certain things publicly available without patent protection, but most things will require patent protection; as much as the company might want to be altruistic, it must also protect its own existence.
For example, if my company invents a new way to make LCD displays with non-toxic components, we would want to share this with other firms, because the net result will be less damage to the environment. However, if we give this away for free, the company will sacrifice a revenue source. With patent protection, the company can license that technology to other firms. By sharing this knowledge, other researchers or developers may find other uses for the technology or be able to improve it, further benefiting the environment and society.

As this example suggests, patents can be a source of income. According to Mr. Wigmore (Wigmore 2003), IBM’s patent portfolio generates more than $2 billion per year. My company’s policy will be to increase the number of patents that we license out, as opposed to a goal of increasing the amount of income per patent that is licensed. My untested theory is that this will create a more consistent and diverse flow of royalty income that might help to sustain the company during periods when other cash flows are reduced.

I want my company of 2020 to be seen as a leader and an innovator, and patents are often used as a proxy for evaluating innovation. Maintaining a large portfolio of patents is one way to bolster the company’s reputation. The company will be conservative in defending its patents. I do not want my company to be seen as a litigation machine; however, there may be times when companies ignorantly or maliciously violate patents in ways that damage my company. If the company did not protect its future, it would be violating its long term commitment to its employees.

4.5.2. Patent Ownership

The final issue I address in intellectual property is ownership of patents. My company will walk a fine line here. As in most companies, employees will have to assign to the company ownership of any patents that have resulted from the use of company time, facilities, or other resources. However, the corporate agreement will also state that the inventor maintains what I call “inventor rights,” a form of “inverse shop rights.”

Farrokh Mistree is uncomfortable with this idea, asking “What if the inventor does sell the patent to competition?” I admit that this system is a bit risky, and maybe should only be done on a trial basis, if that is possible. My main objective of this was to solidify the company’s commitment to the employees, by leaving the rights with the employee if the employee is laid off.

“Shop rights” refers to the situation when an inventor’s rights are not formally transferred to the company by a written agreement. In this case, most rights remain with the inventor. However, if the invention was created on company time, or at a company facility, or with company funds, the company retains a license to keep using the invention even if the inventor leaves the company.

My idea of “inventor rights” is that the inventor maintains a license to keep using the invention even if he or she leaves the company. As with a company maintaining “shop rights”, the inventor cannot sell the license to the patent to any outside party. They would not be able to use the patent if they take a job with another company either. However, the
inventor would be allowed to start his own company and use the patent. I don’t see this happening often, so the cost should be low to my company.

However, I feel that it is important for the inventor to maintain some rights to the invention. As a policy, it signals that we respect the engineer’s freedom and knowledge; they maintain some ownership over their contributions. Unfortunately, we cannot give them full ownership because it would be too risky for the company. There must be some penalty for an employee breaking their long term commitment to the company.

At the same time, if the company breaks its commitment to the employee by laying that person off, the person has some ownership over his or her patent. They would have something to show for their work that they can use to signal prospective employers or with which to start their own company.

4.6. The Role of the company in society

Companies do not exist in isolation. The company interfaces with four stakeholders

1. Shareholders (in a for profit company)
2. Customers
3. Employees
4. The rest of society and the environment

This section looks at the company’s relationship with its customers and society.

4.6.1. Product Safety

In his LE 10, Bjoern Avak has framed safety as a conflict between the company and its customers. He notes that engineers face a conflict of interests between maximizing corporate profits and ensuring the safety of others, because safer products often cost more. In keeping with the third canon of the ASME code of ethics, “Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties” (ASME 2003).

Mr. Avak proposes two resolutions of this conflict of interest. First, he suggests that issues of safety be dealt with at a higher level in management.

First, the Chief Developers have to decide what extent of safety is needed in different components. The decision has to take account of ethical aspects. The decisions should then be laid down in the requirements list of the product, e.g. ‘the airbag deployment circuitry has to pass the testing procedure XY.’ There are two reasons why these decisions have to be laid down in [writing]. On the one hand, the designer for the airbag deployment circuitry gets an ethical guideline for his work. On the other hand, through signing off the requirements list, the Chief Developer makes it a legally binding document. He can hold the designer responsible for fulfilling the requirements list. Besides, he
can be held responsible if the requirements list [is] untenable from a safety point of view.

I appreciate the notion of holding engineers accountable for their decisions to the extent that it encourages them to make better decisions. However, I am a bit concerned of the legal consequences of such a rigid assignment of responsibility. Gross negligence must be punished, but honest errors should not result in a multi-millionaire lawsuit against an individual that will ruin his family. I recognize my ignorance in this area; I am not sure what legal barriers and assessments can be used. These will need to be explored by my company’s legal department between now and 2020.

Mr. Avak’s second recommendation is to support technical inspection agencies. My company will employ independent inspection agencies to evaluate designs for safety, reliability, environmental impact, and other externalities that they may impart on society. Our contracts with these inspection agencies should make it clear that their future relationship with my company is in no way contingency on the nature of their assessments. We will encourage them to ask questions and challenge our designs.

**4.6.2. Ethical Concerns with Knowledge Availability**

The goal of utilizing outside inspection agencies and encouraging employees to challenge designs raises ethical issues that must be confronted. For example, if they question an aspect of the design and we do not address it, do we become negligent? More specifically, how do we distinguish between hypothetical conjectures, hunches, and legitimate objections? These types of questions have been raised during the investigation of the Columbia Space Shuttle loss.

[Gene Kranz, former NASA flight director] contends the NASA of yesteryear would not have allowed the Columbia accident. The system would have fixed the recurring launch problem of breakaway fuel-tank foam, he says.

Midlevel management -- gutted during the 1990s to save money -- is where Kranz would turn to hear about workers' gut feelings. If two or three workers had the same hunch -- even without data to back it up -- then that would be enough for Kranz to call a halt and investigate, and to collect more data.

The framed plaque from that era still hangs in the Mission Evaluation Room at Johnson Space Center, downstairs from Mission Control:

"In God we trust, all others bring data."

With Columbia, engineers had no data, just a sick, sinking feeling when they saw the video and film images of the chunk of foam smacking the ship's left wing during liftoff in January. Their repeated requests for spy satellite pictures were ignored or overruled, so no one knew Columbia had a mortal gash that would let in
scorching atmospheric gases when the spacecraft headed home.

To his everlasting regret, [Wayne] Hale -- who initially pursued the request for satellite photos -- ultimately came down on the side of mission management team leader Linda Ham, who nixed the pictures.

Hale grows quiet when asked if the episode was a good lesson in his new role as Ham's replacement: "It's a lesson that was too dear to learn ... the price was too high." (CNN 2003)

Is NASA or are certain employees negligent for ignoring hunches? I contend that they are not. Engineers have hunches all the time, and many do not pan out. However, as Kranz says, “if two or three workers had the same hunch”, then the issue should be investigated. This is also true if one employee asserts his hunch strongly.

This discussion has revealed a third way that that a company should promote the design of safe products. I believe that the main thing that the corporate culture must do is to encourage people to state their concerns and hunches in open forums with their teams and managers. Only after a hunch is articulated can others assess its validity and consequences. As Kranz says of the engineers, “Look, these people are professionals. They're being paid a professional wage. If they have a problem, I expect them to stand up and speak up. Period”(CNN 2003). Such openness will not only help to identify and resolve safety issues, but it can promote the identification of cheaper, more robust, and sustainable designs. The firm cannot capitalize on employee knowledge unless employees are encouraged to go out on a limb once and a while to share their insights.

### 4.6.3. Environmental policies

Bjoern Avak contends in his LE 10 that, “Any technical device represents an intervention into natural ecosystems. It is just a question of degree.” This is a very interesting perspective to take, and I embrace it. Much as a decision can be thought of as an irrevocable allocation of resources, the production of any device or product is an irrevocable allocation of natural resources.

Environmental sustainability might be thought of as a measure of how many resources allocated in a product cannot be recouped for other uses. Environmentally conscious design and design for recyclability seek to reduce the impact of a product on the environment. As Mr. Avak notes, “Environmental sustainability is a conflict between the company and society.” Unlike a conflict between the company and customer, the negative impact to society is external to the agreement between the two parties involved in the exchange. These externalities to society are not priced into the product; a pure profit seeking company will have no interest in reducing negative externalities.

My company seeks to be friendly to society. Our employees will be more passionate about their work when they are designing with a goal to reduce negative externalities.

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4 ME 6101 Lecture 18, “Aggregation Paradoxes.” Slide 8.
This assumes that our hiring practice has succeeded in hiring employees with similar values.

As Mr. Avak writes, “…in a deregulated market, it is not in the direct interest of a company to offer environmentally sustainable products. Doing that would not result in an improvement of the company’s market position.” This conclusion results from two unstated premises.

First, he assumes that environmentally conscious design results in higher costs. In many cases, he is correct. However, in other cases, he may be wrong. Companies that have dumped industrial waste at their sites have been held liable for remediation and waste removal to the costs of millions of dollars.

Mr. Avak’s second premise centers on his definition of the word “deregulated.” According to Merriam-Webster, deregulation is “the act or process of removing restrictions and regulations” (M-W 2003). Based on this definition, it is hard to argue with his point. Certainly, if restrictions on pollution are removed from all companies, an environmentally conscious company will have trouble competing (in the short term) in the main marketplace due to increased present costs. However, I contend that this type of deregulation is not occurring.

As Mr. Avak discusses, a completely free market does not result in the most ideal market. As he notes, humans still operate the system, and they can modify the market reward function—normally business profits—through taxes, including taxes that are penalties on negative business practices such as polluting. Mr. Avak states the relationship beautifully as, “Taxes establish a connection between the company’s objectives and concerns of society as a whole.”

In general, I believe environmental regulations and concerns in the United States and Europe are becoming stronger. I cite as an example of this trend a recent agreement by mobile phone manufacturers to make their phones more recyclable (BBC 2003). My company will strive to make our products truly recyclable. We will support initiatives for the reuse of products such as those discussed in this article in which mobile phones are refurbished for use in developing nations. However, we look beyond such extensions of product life cycles to the final end of a product’s life. We are interested in having products that are recyclable; we want to reprocess the material, not just condemn our products to less expensive, Third World landfills.

As more consumers and voters around the world recognize the importance of environmental sustainability, they will shape the market reward function through tougher taxes and regulations on environmental sustainability. Consequently, my company’s role in the marketplace will increase because we will position ourselves as an environmental leader. As government regulations on pollution tighten, our environmentally friendly practices will be marketable to larger audiences and will be in line with the market reward function.
4.6.4. Closing thoughts on the role of my company within society

As Mr. Avak writes, “Democracy is the free competition of concepts and ideas.” In addition to advancing my corporate philosophy by operating my company as a proof of concept, the company can take a larger role in shaping policy. My company will embrace Mr. Avak’s corporate philosophy:

…[My] company will use all methods admissible in an open and democratic society to shape social and political developments in the interest of its stakeholders (employees, shareholders, clients). Company representatives will however recognize that their organization is only a part within the framework of a larger social system. The company may [attempt to influence] the decision making within the social system in any lawful manner. Yet, once the decision has been made, the company will comply with the rules and regulations imposed by society.

My company will stop short of endorsing particular political candidates, as I believe this will create tension between the company and employees. For example, a candidate that the company may favor based on his or her environmental policies might take a strong stand on an issues that employees are strongly split on, such as abortion.

Instead of endorsing specific candidates in elections, the company can lobby governments and support or oppose particular bills or policies. Employees will be encouraged to present lectures, presentation, and tutorials at professional society meetings and local universities. The company will also support their efforts to serve as expert witnesses in open hearings.

The company can form coalitions with other companies to promote common philosophies. The company will also fund academic research in areas consistent with the corporate philosophy. This will help to advance technology and educate the next generation of engineers in these areas.

4.7. Value of Considering a Corporate Philosophy

My question for the semester is:

How should the Pahl & Beitz[see reference x] systematic design method be personalized and augmented to include risk assessments, simulations, and better reuse of knowledge while supporting the realization of technical products and processes for a distributed design environment in the year 2020?

In recognizing the importance of the employees to a company, I have proposed what might constitute a new business model. I’m sure other firms have emphasized their employees, but my perspective really looks at the employees as the core of the company.
It is the knowledge of the employees that makes the company. The company can best capitalize on this knowledge by making each employee feel important and integral to the company. With enhanced job security and reduced competition among coworkers, knowledge will be shared and built upon. This is a prerequisite for extensive knowledge management systems and knowledge reuse. In this sense, I have helped to answer a key part of my question for the semester.

Another aspect of my question for the semester is “distributed design environment.” The shared corporate philosophy will be the glue that binds the employees together over geographic and departmental boundaries. Employees come from different religious, cultural, and linguistic backgrounds. My company needs to offer something special to bring them together. Diversity can be valuable, but it can also create tension [see Section 6.2.1 for more information]. If tomorrow’s pay check is the only motivation for coming to work, employees will not make the commitments to each other or the firm that are necessary to overcome these other differences.

In this chapter, I have described specific policies. I believe this is more important than just stating, “the company will make the employees feel important,” or, “the company will help society.” Naturally I couldn’t address every aspect of a company, so there were some places that my suggestions are superficial. However, I took many of my thoughts to the next level. I can’t promise that these policies will work, but if I had not suggested a policy, there would not have been anything to test.
Chapter 5. The Base Method for Augmentation

5.1. Engineering Design: A Systematic Approach by Pahl and Beitz

I would like to acknowledge that a large portion of the content of this section has been taken and adapted this past summer for a special problems course at Georgia Tech (Aughenbaugh 2003).

5.1.1. Introduction

Pahl and Beitz begin their discussion by dividing the design process into four high-level steps, as follows, taken from Steve Rekuc’s ME6102 A2Q4S (Rekuc 2003).

| Planning and clarifying the task: | Involves an investigation into the economic and technical viability of creating a given product and the definition of the exact requirements of a system and the criteria surrounding its functioning. |
| Conceptual design: | Requires an abstraction of the essence of the problem to be solved and the evaluation of different solution variants to this problem. |
| Embodiment design: | Conversion of a conceptual working structure to a specification of layout. |
| Detail design: | Brings together the individual parts of a design (and their properties) to create and confirm a specification of production. Final check of design. |

They have illustrated their process as a flow chart, which I have reproduced here using an image from Steve Rekuc in Figure 5. The remainder of the book describes each of these phases and the related methods for accomplishing each. Before these steps are explained in more detail, a general synopsis of the beginning of the book is presented.

It is important to acknowledge that at the time Engineering Design was first published, Pahl and Beitz had spent the majority of their careers focused on the heavy machinery industry. Consequently, many of their detailed examples, primarily in the embodiment and detail design phases, are narrowly focused on that domain. However, their basic approach is applicable to a much wider range of engineering and systems design projects.

In their first chapter, Pahl and Beitz identify trends in design and provide a historical setting. They observe that German designer traditional focus on the functional structure—deriving sub-functions by decomposing the high-level functions. They contrast this with their observations of the emphasis in other geographic regions. The approach they present tries to incorporate the advantage of these different approaches.
Figure 5: Pahl and Beitz Systematic Design Process from Figure 3.3 in P&B
5.1.2. Design Fundamentals

Chapter 2 is split into two parts, “Fundamentals of Technical Systems” and “Fundamentals of the Systematic Approach.” They begin the latter section by discussing the “Psychology of Problem Solving.” They note on page 46 that:

The results of [cognitive psychology] research have to be taken into account in engineering design so that the procedures and methods recommended match the way humans think; and so that the thinking processes of designers are supported in ways that help them find solutions more easily.

5.1.3. The Process of Product Development

While it is impossible to define a specific sequence of actions that are applicable to all design processes, a general framework can be outlined. The process must be somewhat flexible and not only accommodate but encourage and complement cognitive problem solving activities. Every individual problem will call for purposeful thinking, analysis, abstraction, and synthesis as defined in Chapter 3. This is true in each of the different phases, and it is therefore a consideration for all design tools.

The four phases of the design process mentioned earlier are now clarified as follows in Table 3. The boundaries between these phases are often fuzzy, and iteration between them will usually occur. Pahl and Beitz explain with an example that such “backtracking” may occur when auxiliary functions are discovered during embodiment design for which a principle solution must be defined. [page 65]

Table 3: Phases of the Design Process

<table>
<thead>
<tr>
<th>Phase</th>
<th>Result is a specification of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product planning and clarification of the task</td>
<td>Information and requirements</td>
</tr>
<tr>
<td>Conceptual Design</td>
<td>Principle</td>
</tr>
<tr>
<td>Embodiment Design</td>
<td>Layout and construction</td>
</tr>
<tr>
<td>Detail Design</td>
<td>Production</td>
</tr>
</tbody>
</table>

Pahl and Beitz devote three chapters to these phases. They present a very lengthy discussion on embodiment design that concludes with a very brief treatment of detail design. The following four sections (5.1.4 through 5.1.7) of this paper summarize these chapters with a focus on the areas relevant to this study.

5.1.4. Phase I: Product Planning and Clarification of Task

According to Pahl and Beitz, “To start product development, a product idea is needed that looks promising given the current market situation, company needs and economic outlook.” I claim this can be expanded or adapted for other domains to include tests such as consistency with enterprise goals and policies, legal constraints, government demands, etc. The point is that during the product planning phase, ideas need to be generated. Once a promising idea is selected, the task must be clarified. This involves collecting information about the requirements that the product must fulfill, preexisting constraints,
and the relative importance of the constraints and requirements. The result of this stage is a requirement list. The two sub-phases, or stages in this phase of the development process are elaborated on in the following sub-sections.

5.1.4.1. Product Planning

Product planning is divided into five steps, as presented on page 122 of Pahl and Beitz:

1. **Analyzing the situation** of the company, its products, and using knowledge from market and other sources. The result is a *situation analysis*.

2. **Formulating search strategies** while taking into account the goals, strengths, and weaknesses of the company, consider market niches and needs. The result is a set of promising *search fields*.

3. **Finding product ideas**: Searching within each field for new functions, working principles or geometries. The result is a set of *product ideas*.

4. **Selecting product ideas**. Use a selection procedure that takes into account company’s goals, strengths, and weaknesses. The result is one *product idea*.

5. **Defining products**. Elaborating and evaluating product ideas, for example through the formulation of a first requirements list. The result is a *product proposal*.

5.1.4.2. Clarifying the task

This stage seeks to refine the product proposal and generate a more detailed description, namely a requirements list. According to Pahl and Beitz, this stage must answer the following questions, with only minor adaptations from page 131.

- What is the problem really about?
- What implicit stakeholder wishes and expectations are involved?
- Do the specified constraints really exist?
- What paths are open for development?
- Are the functions specified necessary and appropriate at the start?
- What objectives is the intended solution expected to satisfy?
- What properties must the solution have?
- What properties must the solution not have?

5.1.4.3. Developing the Requirements List

Pahl and Beitz recommend the following method of compiling requirements, adapted from pages 134-135

- Identify the requirements
  - Pay attention to main heading of the checklist (presented in Figure 5.7 on page 133 in Pahl and Beitz 1996)
    - Determine quantitative data
    - Determine qualitative data
  - Ask
    - What objectives must the solution satisfy
    - What properties must it have
    - What properties must it not have
  - Collect further information
  - Specify demands and wishes clearly
If possible, rank wishes as being of major, medium, or minor importance.

- Arrange the requirements in a clear order
  - Define the main objective and the main characteristics
  - Split into identifiable sub-systems, functions, assemblies, etc. in accordance with the main headings of the checklist
- Enter the requirements list on standard forms and circulate among interested departments, licensees, directors, etc. Examine objections and amendments, and if necessary, incorporate them in the requirements list

According to Pahl and Beitz, this requirements list, once compiled, becomes an invaluable store of information.

### 5.1.4.4. Importance of Clarifying the Task

The importance of this stage cannot be overstated. While this importance may at first appear obvious, it is widely accepted in the field of systems engineering that poor requirements definition is the leading cause of project failure. The requirements definition process, or as Pahl and Beitz would say, the “clarification of the task” requires that all stakeholders express their needs, desires, and expectations clearly. The requirements must then be stated unambiguously, which can be a challenge considering that the requirements become the vehicle of communication from the planners to the engineers and between parties (developers and client, for example), each of which can have different cultures, languages, assumptions, and domain knowledge.

### 5.1.5. Phase II: Conceptual Design

The conceptual design phase takes the requirements list and determines the principle solution to be pursued in embodiment design. Pahl and Beitz divide this into four steps:

1. Abstracting the essential problems
2. Establishing function structures
3. Development of working principles
   a. Identification/Generation
   b. Combination
   c. Selection
4. Evaluation of principle solution variants

These steps are explained in the following subsections.

#### 5.1.5.1. Abstraction

The aim of abstraction is to avoid the problems of reliance on traditional methods and fixation by emphasizing what is general and essential. The process should ask, “What is really necessary? What is the main task?”

#### 5.1.5.2. Function Structure

The establishment of the function structures begins by indicating an overall function, which should be directly related to the main task identified via abstraction. A block diagram can be used to express the relationships of inputs and outputs independently of an implementation. The main functions of a system can be broken down into sub-functions. The function structure should be developed in a manner as independent of
implementation as possible. Abstraction will need to be maintained even while decomposing these functions, with adjustments to the relevant level of abstraction for that stage of the decomposition.

5.1.5.3. Working Principles

According to Pahl and Beitz, “A working principle must reflect the physical effect needed for the fulfillment of a given function and also its geometrical and material characteristics.” [page 161] In other words, the process of generating working principles is akin to generating ideas for how a defined function (or sub-function) can be performed by a physical implementation.

Since there are multiple functions and sub-functions, working principles will be generated for each. These separate principles must then be combined. In some cases, a working principle for one function may be incompatible with a working principle for another function. Such conflicts can be diagnosed using a matrix to combine working principles for two functions. Pahl and Beitz provide an example on page 172 in Figure 6.24.

This process may lead to multiple solution variants (combinations of working principles) that appear viable at this stage of the design process. These will need to be evaluated and the most promising variant (or possibly variants) chosen.

5.1.5.4. Evaluation of Principle Solution Variants

Once the working principles are generated, combined, selected, and detailed, there may be more than one solution variant. A list of criteria by which to evaluate them must be identified. These criteria should include economic, ergonomic, and environmental factors as well as extensibility, flexibility, performance, maintenance, and other measures of effectiveness. In the end, it is preferable to select one principle solution with which to begin embodiment design, but in some situations multiple solution variants will have to be carried forward and developed in more detail before a final decision can be made.

5.1.6. Phase III: Embodiment Design

According to Pahl and Beitz, “Embodiment design is that part of the design process in which, starting from the working structure or concept of a technical product, the design is developed in accordance with technical and economic criteria and in the light of further information, to the point where subsequent detail design can lead directly to production.” The design phase actually receives the most consideration in Engineering Design, including examples with significant levels of details. I have taken the following description of embodiment design from Steve Rekuc’s A2Q4S for ME 6102 (Rekuc 2003). I have set this section with different margins and font to make clear Steve’s contribution.

This phase uses the working principles and concepts developed in phase II to develop an actual design to the point where detailed design can take over to lead directly
into production. There several steps involved in embodiment
design, that can be classified as follows:

1. **Starting from the Concept:**

   1. Identification of requirements that are critical in
determining the embodiment of the design.
   2. Production of scaled drawings embodying spatial constraints.
   3. Identification of main function carriers (i.e. assemblies and components fulfills the main function) and creation of rough layout based on them.
   4. Development of preliminary layouts and form designs that define general arrangement, component shapes and materials used in the design.
   5. Selection of one or more suitable preliminary layouts.
   6. Further development of preliminary layouts for function carriers that have not yet been taken into consideration.
   7. Determination of auxiliar functions, exploiting known solutions wherever possible.
   8. Development of detailed layouts for main functional carriers and then auxiliary functions.
   9. Evaluation of layouts against technical and economic criteria.

2. **Results in a preliminary layout, from which the following tasks occur:**

   10. Optimization of form layout by elimination of weak points identified through evaluation of layout.
   11. Check layout design for design faults. Achievement of goals with respect to cost and quality must be established here.
   12. Creation of preliminary parts list and preliminary production/assembly documentation.

3. **Having arrived at a definitive layout, the next task is to**
13. Fix definitive layout design and move on to detail design phase.

P&B provide principles of embodiment design for division of tasks, transformation of force, fault free design, stability and self-help, which discusses the arrangement of system elements such that their supportive interaction improves the fulfillment of a function. As with all other phases of systematic design, the individual steps for embodiment design should be adapted to a given problem, keeping in mind the above mentioned principles.

The authors also present general guidelines to follow while conducting embodiment design, which include design that allow creep and relaxation and design against corrosion damage. These guidelines are rather specific in nature and apply only to the design of those products where corrosion, thermal changes and electricity are issues. They do not apply to the design of software, for example. Other guidelines that P&B provide are more general in nature, such as design for aesthetics, ergonomics, ease of assembly, standardization, maintainability, and reduction of risk.

Embodiment Design concludes with a definitive layout for the design; the definitive layout is checked and documented in the next phase, Detail Design.

5.1.7. Phase IV: Detail Design

According to Pahl and Beitz, “[Detail design] is the phase of the design process in which the arrangements, forms, dimensions and surface properties of all the individual parts are finally laid down, the materials specified, production possibilities assessed, costs estimated and all the drawings and other product documents produced.” [page 69] One point to consider is how good specification management and documentation in the early phases of design may aid this fourth phase.

I have again borrowed this section from Steve Rekuc’s A2Q4S from ME 6101 (Rekuc 2003).

Detail design is aptly defined by P&B as “that part of the design process which completes the embodiment of technical products with final instructions about the layout, forms, dimensions and surface properties of all individual components, the definitive selection of materials and a final scrutiny of the production methods, operation procedures and costs”. (P&B, pg 400)

If any errors in the basic design are uncovered ensuring the embodiment design phase, it is important to rectify these errors before embarking on the detail design phase,
else it might not be feasible to do so, with regards to cost, time and resources.

Detail design is composed of the following:

1. Definitive layout: Finalize the definitive layout, in terms of all drawings and optimization.
2. Integration of drawings and parts lists.
3. Documentation: Complete all documents and check all documents for standards, completeness and correctness.

Detail design often calls for technical knowledge that is particular to the product being designed. Hence it a good practice for designers to refer to design catalogues and technical handbooks when conducting this phase of systematic design.

Finally, the quality of detail design is reflected in the quality and production cost of the product itself. Thus, one should never overlook any aspect of detail design or try to cut corners during this phase.

5.2. The Value of the Pahl and Beitz Approach to Design

I have based this section on Chapter 3 of Engineering Design, although it incorporates my experience to date with the entire Pahl and Beitz Design Process. Pahl and Beitz have titled Chapter 3 as “The Process of Planning and Designing.” I believe that they have captured their main message and principal points in this chapter.

5.2.1. The Main Message of Pahl and Beitz

The main message that P&B present in Chapter 3 is the need for a systematic approach to engineering design and more generally to decision making. Without adoption of one systematic approach, there will be too many possible approaches to pursue. Similarly, without any systematic approach, there are too many directions in which to start your journey. The main goal of an engineering design methodology should be to guide the designers down the correct path. Without a systematic approach, it is unlikely that designers will choose the correct path, and without the correct path, it is unlikely that the correct solution will be found.

5.2.2. The Principal Points of Pahl and Beitz

The Principal points of Pahl and Beitz are summarized as:
1. Repetition of Process
2. Designers take these steps already
3. Complex problems best solved in small steps

I briefly explain these points, including to what degree I accept them, in the following subsections.
5.2.2.1. Repetition of Process
The formulation of a systematic approach to design has allowed designers to recognize that the design process is really a sequence of decisions. The question in 2020 will be how distributed teams of designers can coordinate their decisions. Each of these decisions is summarized by the following sequence
- Abstract (identify crux of problem)
- Search for solutions
- Combine solution variants
- Evaluate solution variants
- Choose a solution
This same procedure recurs throughout the design process, beginning in the clarification of task, and continuing in conceptual design, embodiment design, and detail design. Naturally, the level of abstraction and problem changes, but the process is the same. Therefore, tools and methods that support this decision process—including facilitating collaboration between distributed design teams—will be very valuable in engineering design.

This point did not emerge immediately; I did not discover and accept this point until I attempted a deep-reading of Chapter 3. I also doubt that I would have recognized it without external stimuli such as discussions with current and former ME6101 students, and most importantly my reflection on the Three Little Pigs game and my summer work. I really had to reflect a lot on this and try to relate my experiences and the examples and methods from different chapters of the book and other publications back to this claim.

5.2.2.2. Designers take these steps already
P&B claim that most of the steps in their systematic approach are already taken by designers. They argue that they are often taken unconsciously and too quickly, resulting in weaker designs than could be created by following a systematic approach.

I also accept that most of the steps outlined by P&B are taken in engineering design. They certainly are not entirely “off the wall” or revolutionary. At first I doubted this claim, but I came to accept it as I realized that my doubts were caused by two things
1. People often do not perform the steps explicitly or completely
2. People do not perform them in the same sequence
3. Responsibilities are not always clear in absence of a systematic approach.

With a systematic approach, everyone can know approximately what should be happening when and by whom it should it be performed. The systematic approach becomes a checklist where completion of the tasks can be monitored, so that before one tasks is started there is confirmation that the exit criteria of the previous step are met.

I would like to set this observation in the context of the learning square presented by Farrokh in several ME 6101 lectures. I have shown the learning square in Error! Reference source not found. A systematic approach helps move the design process from the unconscious layer to the conscious layer. By completing a systematic process
and checklist, the design can learn what the know—the questions that have been answered and the tasks that have been completed—as well as learn what they don’t know—the questions that are still open and the tasks that are unfinished.

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Figure 6: The Learning Square

One problem I identified in my job at MITRE was that on several projects, the participants—especially I—did not understand where my piece of the puzzle fit into the whole. Sometimes it wasn’t even clear what my responsibilities were. A systematic approach should help give all participants a vision of a more unified and shared purpose, because the tasks and their sequence will be explicit.

There is still a missing link—the engineers need to share a common goal and purpose. A systematic approach alone cannot get engineers to cooperate or feel passionate about their job and coworkers. The systematic approach is scaffolding that helps a group of similarly motivated engineers to work together towards a common purpose. The company—including its policies and philosophies—must provide the environment in which an approach can succeed.

5.2.2.3. Complex problems best solved in small steps

Complex problems can rarely—if ever—be solved intuitively or globally from the beginning. The problem must be broken down into smaller chunks, which can be solved via a combination of intuitive and discursive thinking methods. These solutions can then be synthesized into a solution for the larger and more complex system.

I readily agreed with P&B that complex things are best solved in small steps—assuming that the problem is partitioned in a productive manner. Products are getting more and more complex, and there is no way that one engineer or even engineers from one discipline can study and solve all decisions and problems. The open question in my mind is how can plans be created and information and knowledge communicated, managed, and stored to enable a complex problem to be broken into smaller pieces, the small pieces solves, and the solutions synthesized into an overall solution.

5.2.3. Evaluation of other P&B Claims

In addition to their principal points, Pahl and Beitz have made other general claims.
5.2.3.1. **Intuition in systematic processes**
Pahl and Beitz assert that a systematic process stimulates creativity and intuitive thinking. My first impression is that these activities would flourish in a free environment. If people are constrained as to when and about what they can think and how they can represent their ideas, how can then be truly innovative and think outside the box?

I remember that on a tour of Walt Disney World that the Imagineers and animators were the only employees not governed by the corporate and theme-park dress codes; the idea was that they would be more productive and creative if they could create their own environment, including clothing, workspace, and to some extent hours.

However, there is a competing notion from cognitive psychology. Herbert Simon (Simon 1947) has suggested the notion of *bounded rationality*. In is in this context, which I discuss more in Section 7.3.1, that attention directing tools and ideation techniques—such as the six thinking hats—become valuable. Through my work and reflection in this course, I have learned that creativity and intuition can flourish in a systematic approach, and that the systematic framing of the thought process can actually assist the creative process.

5.2.3.2. **Scheduling more accurate in systematic approach**
At one level, it seems obvious that scheduling would have to be more accurate when a systematic approach is used than when no structure is given to the process. However, I question how substantial the difference will be. A systematic approach will define the steps that need to be taken, and the sequence of these activities. However, it will not specify how many iterations of each steps will be required or how long each iteration will take.

I do believe that the use of a systematic approach allows managers to develop process-based deadlines and schedule reviews based on phases of the process. In this way, managers can evaluate progress and expenditures such that too much money is not dumped into later design phases (such as embodiment and detail design) before a panel of experts and stakeholders has verified the design concept.

A systematic approach also states the sequence of tasks (outside of iteration), and it will facilitate the division of tasks into subtasks, which can then be assigned to distributed teams of designers. The creation of a schedule for a systematic process will make it more likely that the schedule will be met than if a sequence of milestones in an ad hoc process is set. In the ad hoc process, it will not even be clear how things are progressing.

5.2.3.3. **Systematic approach (never) ensures success**
In fairness, P&B don’t go as far I suggest with this sub-section’s heading. However, on page 70 they write that, “the deliberate step-by-step procedure…ensures that nothing essential has been overlooked or ignored….” The design process cannot ensure anything. It can facilitate, support, and guide, but it does not guarantee completeness or success. I doubt that P&B really believe this statement, and it may even be an artifact of the translation from German.
Regardless of its origin, the statement helps to reveal an important aspect of a systematic approach. However generic and complete it is, it must still be carried out by *humans*. Humans must customize the process to their projects and organizations without losing any of the indispensable components. During this *personalization* [Farrokh’s terminology] the designers must avoid any ambiguities or errors in translation. They need to exercise similar diligence in how they choose to augment it to incorporate new technology, tools, methods, or problem classes. Finally, even a “perfect” method needs to be followed completely by error-prone humans.

### 5.2.4. Design is a recursive process

I’ve had a feeling since my first exposure to P&B’s systematic approach, which is that the whole process could be expressed recursively. It seems that as you move from one phase to another, you will really repeat the previous phase, but at a different level of detail and on a small part of the system or product. This is clearest to me in the functional decomposition. As sub-functions are found, the crux of their main function must be identified via abstraction, and so on until a leaf is found.

This recursive nature is reflected in the repetition of the decision process that I have described in Section 5.2.2.1. However, it goes farther than that. Consider the following example which is related to my ME 6101 project. I have illustrated in Figure 7 the hierarchical decomposition of the systems in a space mission design. For example, the torque actuators are a subsystem of the attitude determination and control system (ADCS), and the ADCS is a subsystem of the satellite.

As the P&B design process of the satellite proceeds, at some point near the beginning of embodiment design, the ADCS subsystem design task will be handed off to a specific design team. This design team must follow a P&B approach to their subtask in order to understand their task and its requirements. After they arrive at a principal solution or concept, for example 3-axis control using reaction wheels, they still need to embody this concept. The task may be handed off to specialists in reaction wheel design. This new team will need to understand their task, requirements, and complete their design. I have illustrated this recursive P&B process in Figure 8.
5.3. The Shortcomings of the Pahl and Beitz Systematic Design Process

The Pahl and Beitz design process is amazingly flexible and relevant to design now and in the year 2020. However, it does not meet all of the requirements to be a powerful approach in the year 2020 according to my visions. In this section, I summarize some of the requirements developed in Chapter 3 at a high level with the purpose of explaining my motivation for augmenting the P&B method.
• **Knowledge management not adequately addressed.** According to my view of design, knowledge plays an important role and is a design company’s key asset. As more complex designs are addressed in the future, there will be inherently more information and knowledge created and used in the design process. Due to the limits of human cognition, tools will be needed to augment human abilities. This issue will become more important as decision tasks, teams, and decisions become more distributed across geography, disciplines, and time.

• **The process doesn’t incorporate available computer resources, including modeling and simulation tools.** The Pahl and Beitz process was created before the universal availability of computers in engineering design. The design process needs to be integrated with the computer tools of the present and future. These computers tools support the human decision maker; this relationship leads to the notion of a human-computer cyborg.

• **The process does not account for distributed design teams and concurrent engineering.** Engineering is increasingly practiced by teams, and these teams are no longer co-located. As the global marketplace grows in importance, teams will be distributed over larger distances. The Pahl and Beitz process works in a linear manner, and assumes that there is only one design team working on the one design project. The process needs to be adapted to support concurrent processes carried out by distributed teams. In such situations, the division and coordination of tasks will be challenging.

• **The process does not explicitly handle the types of uncertainty encountered in design.** When designers need to make decisions, they do not always have all the information that they would like to have. The Pahl and Beitz process does not address this aspect of design. I would like to look at the role that uncertainty plays in the design process by looking at risk and robust design.
Chapter 6. Initial Augmentations for Design in 2020

6.1. Introduction
In this chapter, I present some of my augmentations to the P&B process. The augmentations in this chapter are specific alterations to the steps of the process. I will present my more important ideas in subsequent chapters. These subsequent chapters propose a change in mindset and paradigm to design. Those chapters are most relevant to my future research and goals. However, this chapter ties my A2Q4S most tightly to Pahl and Beitz.

6.2. Process Management
Corporate managers will have to evolve by the year 2020. Some of these changes are captured in Chapter 4 where I express my corporate philosophy. As I noted in Section 5.3, P&B assume a linear process of a single team. In the year 2020, at least certain phases of design will be done concurrently by distributed teams.

Management of these teams, from selection to interactions in decisions, will become key to the success of companies in the year 2020. In order to meet these demands, process management will become a specific and indispensable step in the augmented P&B process. The process management step should occur at the start of every phase, as well as any other time that work is divided into teams or subcontracted to outside parties, as I have shown in Figure 11, Figure 12, and Figure 13.

6.2.1. The Role of Diversity in Design Teams
In addition to having satisfied employees who share a common corporate philosophy, the employees must be grouped into appropriate teams. Although there are not specific positions that can be stated for all design projects, managers should build a team from the perspective of filling particular roles. For example, no matter how talented and united a football team is, the team will not be successful if the offensive team is fielded with defensive specialists.

From the perspective of a sports team, the individual positions represent diversity. Each player has a role, with unique characteristics that make that player valuable to the team. The notion of diversity that I present here does not refer to the type of diversity frequently referred to in university admissions policies or political debates. There are dimensions of diversity that go beyond superficial differences in appearance, and even beyond differences in religion and culture.

6.2.1.1. Diversity of Mind
The type of diversity that should be considered when forming a successful design team is what Steve Rekuc has referred to as diversity of the mind. He writes in his ME 6102 A2Q4S (Rekuc 2003), “Problem solving in design is made easier when the problem is attacked from different mindsets; the best way to see a problem through multiple mindsets is to have a design team composed of intelligent designers that think
differently.” I fully agree, extending this claim by adding that the best individual engineers are ones who can act with a diversity of mind on their own. Attention directing tools such as role-playing can help engineers—as individuals or as a team—to achieve diversity of mind. For example, this is the role of the six thinking hats attention directing tool.

Steve Rekuc has developed his notion of diversity of mind into the following primary characteristics

- Educational Background
- Cultural Background
- Problem solving technique/perspective
- Synthesist vs. analyst

In the following discussion, I present his explanation (Rekuc 2003) of these characteristics and then provide my comments.

1. Educational Background. The educational background of members in a design team will have a huge affect on the manner in which they approach a design problem. A company should look to compose a design team from a mixture of academic backgrounds. This includes their specific area of study, such as Mechanical Engineering and Industrial Engineering, as well as their place of education such as Georgia Tech or M.I.T. To this end I would consider previous job experience as educational background because potential candidates would hopefully have learned from their previous experience.

I agree with this characteristic because it is easily implemented. However, I caution this need not be a requirement. All of these notions of diversity are guidelines and things that managers will want to consider in the context of individuals that they will know fairly well. Just because someone went to Georgia Tech doesn’t mean that they think like Georgia Tech. However, I do believe that the company should seek to hire people from a variety of school in different regions of the country and world.

2. Cultural Background. By cultural background I do not mean what type of music a person listens to or what activities they do for fun – that is certainly a component of culture, but not the most important component when forming a design team. Really the cultural diversity that we are looking for here is based on values of the person and maybe is more appropriately termed ethics. I am not saying that companies should hire ethically questionable people; on the contrary I suggest that companies look for people with different ethical drivers. For example one person might consider technological advancement of prime importance, whereas another person sees environmental protection as their paramount concern. The inclusion of individuals with different values will allow a combination of different mindsets that every design team needs.

I strongly caution managers from focusing on culture at a shallow level. Cultural diversity in the general sense raises the likelihood of conflicts in processes, values,
communication, and coordination. At one level, I think that team members should be similar in cultural background.

For example, in one of my job experiences I saw one team trying to operate with two members who rarely saw eye-to-eye. One was a devout Jew and strong supporter of Israel. The other was a Muslim who strongly sympathized with the Palestinians and opposed the existence of Israel. By one definition, they were diverse. Additionally, they appeared to be fairly accepting of people of different cultures. They even seemed to share similar ethics. The conflict arose because of their differing premises. The one believed that the Jews had a natural right to “their land”, and the other believed that the Palestinians had a natural right to “their land.” Unfortunately, both “their lands” were the same land. Given their starting premises, each side reasoned that all means were acceptable to remove the other people from the land.

This example illustrates the need to express care in forming teams, and a prerequisite for this is knowing the employees at an individual level. It also illustrates the danger inherent in forming teams that cross cultures. Managers must walk a thin line; I do not advocate all white-male-Protestant teams in any way, nor any other singly dimensioned sorting. However, cultural diversity for the sake of cultural diversity is risky. The result of including diversity—different decision perspectives—should drive the inclusion of cultural diverse team members.

3. Problem Solving Perspective/Technique. Although closely tied with the educational background of individual there is still significant difference and significant importance of this aspect. Problem solving plays a huge role in design because design is problem solving. Companies should therefore consider the manner in which the potential designer attacks problem, the way in which they organize their solution methods, and the steps they take to get to a solution. I believe this is one of the crucial aspects that require diversity, as those individuals with different problem solving skills will allow difficult problems to be attacked from different angles.

I object slightly to the statement that “design is problem solving.” I prefer to word this relationship as, “Design is a sequence of decisions taken by humans with the goal of implementing a solution to a proposed task.” Design is problem solving at a high level, in that it can be captured in the discourse, “We would like to achieve x. How do you do that? Let’s generate a solution.” However, strictly stating that design is problem solving understates the role of decisions in engineering design.

4. Synthesist vs. Analyst. [In a talk that Steve Rekuc attended last year] Dr. Leifer [of Stanford University] pointed out that the most successful design teams were the team that had asked the most combination of reasoning and creative questions throughout their design process....This means that design team need to be both thinking creatively and analytically in order to be successful, therefore the design team needs intellectuals to fulfill both roles. Ideally, design team members should be equally balanced in creative and analytical skills, but that
doesn’t always happen; the company must therefore ensure that there is an equal amount of analytical and creative talent on a design team.

Steve’s main point is that in the future, design teams will need analytical and creative abilities, and since individuals have varying skills in these areas, the managers who assign team membership must choose people to balance these abilities.

6.2.1.2. Closure on Diversity

My final comments on this view of diversity focus on what is not included. First, there is nothing that states that team members should be located diversely. Second, there is nothing that emphasizes the importance of including members from different societal cultures.

On the first point, I see a significant disadvantage to locating team members in different places. I firmly believe that a team can work its best when the members share similar schedules, know each other at a personal level, can work together in person. In the future, there may be ways to achieve this feeling of a family across distributed team members, but at least for me, this is not realized by current or emergent technology.

The second point reinforces the first, because geographical distributed engineers will often work in very different cultures. Even co-located engineers can be from different cultures, and this can create inefficiencies as miscommunication and larger misunderstandings can result. I have had roommates from Pakistan, India, Mauritania, Tanzania, France, and the United States, and I have always had the best understanding with the other Americans. Sharing an environment with people from a very different culture from my own has helped me to grow and improve myself as a person by broadening my horizons, but I have also been involved in or seen many conflicts arise. I do not believe that these activities are efficient for a company that needs to be agile and succeed in short timelines.

6.2.2. Contracts

Even before a team is formed and assigned to a specific design task, a contract should be drawn up by management that states not only the team composition, but also its mode of operation and—most importantly—its responsibilities. A team’s responsibilities will dictate the types of engineers that should be included on the team. After the team is formed, the team contract will help guide smooth function of the team as a whole, and to the system level goals. Contracts are important even within one company, because (for example) in many projects, the conceptual design is performed by a different team than the embodiment design.

Steve Rekuc (Rekuc 2003) has proposed the that a team contract define the following:

1. **Code of Conduct.** The basic operation of the team including times of team meetings and expected work/office hours for team members.

2. **Primary and Secondary responsibilities/expectations of members.** The role that each team member plays in the team should be defined here. The design team, having explicitly stated
responsibilities of each team member, should operate smoothly. All responsibility should be accounted for.

3. **Communication standards.** The team should establish their means of communicating with each other; this will include information about when the communication will occur. Established communication practices will hopefully avoid miscommunication and the lack of communication in the design process.

4. **Knowledge and information representation standards.** The company should record information and knowledge about the design in a consistent format; the exchange and reuse of the knowledge and information will be made much easier by doing so. A company does not need an individual recording knowledge or information that only the individual can interpret. Standard representation should alleviate this problem.

5. **Protection of proprietary material.** Design teams of the future will not always consist of long-term employees. Teams will often be composed of consultants and experts from other companies. A company should therefore clearly state, in the team contract, what the company considers to be ‘proprietary’; doing so shall avoid controversy over who retains ownership after the design project is over.

I endorse his first items fully. I believe that his fourth item (knowledge and information representation standards) will become important in the future, but it does not yet make sense because there are no standards with supporting tools that are easily accessible to most engineers. This is one challenge for knowledge management systems in the future—there needs to be a way to unobtrusively capture the knowledge generated and used during design.

The motivation for Steve’s fifth point (protection of proprietary material) is incorrectly motivated for my company, because my company will focus on retaining long-term employees. As we will encourage our engineers to share their knowledge via patents and in some cases academic publications, it will be necessary to establish responsibility for these issues in the team, so I accept Steve’s inclusion of item five into the contract, but for different reasons than he has proposed.

In addition to these five items, I believe that the team contract should articulate

6. Tasks
7. Schedules
8. (Penalties—in certain situations)

The inclusion of a specific list of tasks and a schedule for completing these tasks will serve several functions. First, they both serve as attention directing tools for forming the team, because they help to answer the sequence of questions:

1. What will this team need to do?
2. How quickly does it need to be done?
3. Who can best do this?”

The answers to these questions will help managers decide both the size and then composition of the team.
The second use of the list of tasks and schedule is to keep the team progressing both on-time with regard to the system schedule, and on-track with regard to the tasks that the other teams are expecting the team to complete. The task list can serve as a checklist for the team completing its responsibilities.

A possible eighth item—penalties—will probably not be necessary in my company because there is a larger corporate setting, with a specific corporate reward structure. When a team is formed without the superceding shared corporate structure, then penalties for failing to meet responsibilities and expectation should be made explicit in a contract.

6.3. Checklists and checkpoints

The Pahl and Beitz process is divided into four main phases, and six total phases (product planning, clarification of tasks, conceptual design, preliminary embodiment design, definitive embodiment design, and detail design). I believe that is necessary to explicitly evaluate whether one phase is completed before moving to the next.

This is especially important given my assumption that the teams working on the design change as it moves from one phase to another. Given this assumption, it will be even more expensive to iterate between phases, since a team has to be reassembled.

In order to reduce the iteration between phases, a specific checkpoint should be placed at the end of each phase, as I have added to the P&B process in Figure 10, Figure 11, Figure 12, and Figure 13. At this checkpoint, the design is reviewed and an explicit decision is taken as to whether to proceed to the next phase.

One tool that will help this review process is a simple checklist of the goals and requirements for a design phase. The checklist should require a brief explanation of how the requirements were met. This proved to be useful in my team’s design of our design project. It is impossible to keep in mind all of a project’s requirements and to simultaneously analyze whether each one was met. A checklist is an attention directing tool that systematically helps a designer consider whether something is complete.

This augmentation is related to process management because the process management step organizes the teams and establishes the responsibilities and contracts. These contracts either contain or form the basis for the checklists used to examine whether the phase is complete.

6.4. Variant design and subcontracting

As I noted in Section 3.9.3, I believe that the P&B approach can address adaptive design variant design, subcontracting, and supply chains better than it does now. I have augmented the P&B process such that there is an explicit decision point when either original or variant/adaptive design is chosen. In these cases, especially with variant design, and the design process re-enters the core original design process after a concept is chosen, as I have illustrated in Figure 11. I have not addressed the product planning and clarification of task augmentation, because I believe that these will involve the planning.
of product families, open engineering systems, and other subjects that are covered in ME 6102.

My augmentation is shaky from the view of adaptive design. It seems to me a goal of knowledge reuse is to make as much of design as possible an adaptive design. I have specifically separated variant and original design because they seem to be opposite ends of the spectrum, with adaptive design in between. In original design, the designers set out to design something new. In variant design, designers set out to use an existing concept in a new way, by scaling it to different uses.

I believe it is important to recognize that the first phase of engineering design as presented by P&B is not necessarily followed by the same company that will design the product. For example, one company might identify a market and make a requirements list, and then contract the development out to a company with greater knowledge in that area.

As I noted in Section 3.9.3, a very common example of this is when the Department of Defense or a scientific exploration organization such as NASA declares the need for a particular product or tool. This type of issue will also arise in supply chain management. I have augmented the product planning and clarification of task phase to recognize these differences, as I show in Figure 10.

### 6.5. Concurrent Engineering

Much of the content in this section comes from Bjoern Avak’s LE13. I would have liked to develop these ideas in more detail because I believe they are tied to my view of design and the role of game theory that I examine in Chapter 7.

Mr. Avak that his purpose in completing LE13 is the following:

- Lay down strategy for the division of work
- Determine steps in Pahl & Beitz where concurrent development is an option
- Minimize the loss of information through the clarification of interfaces

The first of these related to my process management step. Certainly determining where things can occur concurrently is a major part of process management, since that phase deals with the division of tasks and teams, as well as scheduling.

Mr. Avak and I share a common perspective that concurrent design is necessary in the year 2020. He relates his view to the automobile industry:

> It is an underlying assumption in “Engineering Design” that the entire design process is carried out by one single team. This is not valid for the automotive industry. The products developed there involve too many different fields to be handled by one team. Moreover, it would simply take too long for one team to develop a vehicle. That is why the sequential approach of Pahl & Beitz has to be replaced by a concurrent approach.

I believe that this is true is most applications of engineering design.
Mr. Avak proposes four principles for division of work:

- Minimize the need for information exchange
- Minimize the need for supervision
- Hand over responsibility to the lowest possible level
- Hand over responsibility to the most-qualified

The first of these is the most interesting to me. I have addressed this point in Sections 4.4.6, 7.6, and 11.3.6. I agree that the need for information exchange needs to be reduced, especially exchanges across time and distance. Information exchange across distributed locations and time is an imperfect process with significant overhead.

I disagree with the feasibility of Mr. Avak’s second principle. He writes:

Still, from a corporate perspective supervision is overhead, just like information exchange. Employing people to supervise other people basically commits resources to activities that will not lead to future profits. That is why I strived to improve my company of 2020 by reducing the necessary extent of supervision (see section 1.3.2). In order to achieve that objective, I introduced free enterprise in the company thus reducing the need for supervision by higher hierarchical levels. I plan to apply the same concept to concurrent product development. How does one reduce the need for supervision? In my opinion, the system itself has to be designed in a way such that the need for supervision is minimal. The need for supervision is smallest if the tendency to leave the target state is minimal. The target state in a company is defined as the state where all entities serve the higher objectives of the corporation. Ideally, the objectives of the individual entities should correspond to the corporate objectives. If that were the case, the need for supervision would be minimal. Consequently, the system has to be designed such that corporate objectives determined by the board naturally become objectives of all other entities down the hierarchy.

In my opinion, the individual teams cannot share the systems perspective without human supervision. A shared corporate philosophy will increase their desire to work towards the common good of the company, but on their own, they cannot understand the relationship between their actions and all of the other actions. I believe this is true at all stages of design.

Based on these principles, Mr. Avak introduces concurrent design into the P&B process. I agree completely with his assessment of the role of concurrent design in the clarification of task and conceptual design phases, so I have reproduced them here.

2.1 Clarification of Task – Low potential for concurrent design

During the Clarification of Task phase the task is pinned down based on technical, economic, and corporate considerations. At that stage, the problem has to be
considered from many different angles. There are numerous conflicting interests. The marketing department will want the product to have as many features as possible, the controlling department will focus on cutting down on costs and the development departments will stress technical feasibility. These conflicting interests will invariably clash. In that instance, the objectives of different corporate entities are differing, even conflicting. There are strong boundary conditions concerning supervision. Hence the Clarification of Task phase does not conform to the second principle for the division of work. As a result Clarification of Task has to remain centrally supervised. Having several teams working concurrently will result in conflicts.

As mentioned above, Clarification of Task is a process during which different aspects are considered from a high-level perspective. Hence, a large number of different departments contribute to the process. They compile information so that an all-embracing decision can be made. A continuous exchange of information is required. Thus, the second principle for the division of work is not fulfilled either. That is why I believe, that the introduction of concurrent design during the Clarification of Task will result in more difficulties and conflicts than potential benefits. One should stay with a conventional sequential approach.

2.2 Conceptual Design – High potential for concurrent design

During the Conceptual Design phase engineers set up the concept. The concept comprises the working structure and an underlying function structure. Like the Clarification of Task phase Conceptual Design – up to the point until function structures are established – is a highly interdependent and broad-level approach. However, once there is function structure, the situation changes. A function has well-defined boundaries, inputs and outputs. That is why each function represents a subtask. Because it is relatively independent of other functions, the need for information exchange is minimal. If a department focuses on one function, the need for the exchange of information with other departments dealing with other functions is relatively small. Since a function represents an independent entity, a large degree of responsibility for the individual function can be handed over to the respective department. That is why the search for working principles can be made a concurrent activity. The responsibility for working principles can be handed over to individual departments. At the end of the process, the results of individual teams and departments are compiled so that the final concept can be chosen. At that point the process becomes sequential again, because it involves highly interdependent decisions. One has to consider among
other things the interaction between different working principles.

When it comes to embodiment design, I only agree with Mr. Avak up to a point:

2.3 Embodiment Design – High potential for concurrent design

At the beginning of Embodiment Design, engineers have to separate main function carries from auxiliary function carriers. One of the underlying assumptions in Pahl & Beitz is that small problems are easier to solve if the big problems have been tackled systematically. That is why one should carry out the embodiment design of the main function carriers before the auxiliary function carriers. One should not work on those two tasks concurrently. Not only would that contradict the above-mentioned assumption, it would also conflict with the first principle for the division of work. However, several teams can work concurrently on several main function carriers. At that stage, the working structure has been laid down. Multiple functions and subfunctions can be integrated into modules based on the underlying working principles. Each of these modules can be presented as a separate small project on the internal market.

From here, he goes on to discuss having teams within the company bid for a project. I believe that this will take more overhead than human supervision and process planning. The amount of effort that goes into a bid will distract too many teams from their other work responsibilities. There will also be an increase in overhead within the team, since someone will have to look for opportunities to bid on tasks. I do not believe that this disagree in mechanism for distribution of the tasks to teams affects the feasibility of concurrent design in this phase.

Mr. Avak has stated the that potential for concurrent design is low in detail design. I believe that the individual teams can concurrently elaborate detail drawings and parts lists; complete production, assembly, transport and operating instructions; and check their documents. Each subtask will have its own documents, so they can be done concurrently. Mr. Avak is correct that there will be need to examine system level documents from a holistic perspective for accuracy and consistency, but this can only be done after each team completes their independent detail design.

Mr. Avak has summarized his view of the role of concurrent design in a figure, which I have reproduced in Figure 9. Unfortunately, it is not entirely legible, and I recognize that its value is therefore reduced, but I did not leave myself enough time to recreate it in a new figure. The focus should be on the left side of Figure 9 and how the sequential and concurrent activities align with the P&B process in the center.
Figure 9: Concurrent design in the P&B process
6.6. Augmented P&B Figures

Product Planning and Clarification of Task

Origin of Task

Customer/Client

In House

Analyze the market and company situation
Find and select product ideas
Formulate a product proposal

Preliminary Contract

Product Proposal

Clarify the task
Elaborate a requirements list

Requirements List
(Design Specifications)

Product Contract

Is Phase I finished?

No

Yes

Phase II: Conceptual Design

Figure 10: Augmented Product Planning and Clarification of Task
Figure 11: Augmented Conceptual Design
Figure 12: Augmented Embodiment Design
Figure 13: Augmented Detailed Design
Chapter 7. Decision-Based Design

I believe in the paradigm of decision-based design. Marston and coauthors define Decision-Based Design as the perspective that “the principal role of an engineer in the design of an artifact is to make decisions” (Marston, Allen et al. 2000). I also adopt the definition of a decision used by Marston and coauthors (Marston, Allen et al. 2000) that a decision is an irrevocable allocation of resources. Because the main role of an engineer is to make decisions, the best way to improve the design process is to enable engineers to make better decisions. Design tools—including models, simulations, knowledge management systems, and methods of risk assessment—have the primary role of help a human decision maker to make a decision. Therefore, these tools are discussed in this section.

7.1. Decision Support

Marston and his coauthors (Marston, Allen et al. 2000) have an unstated assumption that only human beings make decisions. In the end, it is individual preferences and judgments that lead to a decision being taken. Tools and methods such as those described in their paper and my answer to the question for the semester can only help the decision maker choose the most preferred option, given the assumptions, preferences, and information currently available.

Design tools—including models, simulations, knowledge management systems, and methods of risk assessment—have the primary role of helping a human decision maker to make a decision by increasing the amount and quality of relevant knowledge and information available at the time the decision needs to be made. In the end, a human takes the decision and must be responsible for its consequences.

Designers attempt to support their decisions in several ways. Marston and coauthors discuss a technique in which to frame the decision problem, the Decision Support Problem (DSP) Technique. The DSP Technique, when used without utility theory, is only meant to support designers in making decisions (Marston, Allen et al. 2000). Once utility is included in Decision Based Design (DBD), it “prescribes the methodology to ensure that a chosen design is the most preferred by the designer” (Marston, Allen et al. 2000). This perspective of supporting decisions is central to my answer to the question for the semester and my research.

Designers also support the decision process by making judgments [I have adapted all used of the word judgment to this spelling] and building models. Marston and coauthors (Marston, Allen et al. 2000) explain, “A judgment is a rendering of the state of nature. Judgment in engineering design is almost exclusively related to modeling. As designers, we make judgments so that we have the capability to make a better decision.” In the next section, I explore the role of modeling in design decisions.

7.2. Modeling and the human-computer cyborg

As noted above, judgments are related to modeling, which is part of my Q4S. A model can be used to generate information and knowledge that the engineer will use to make
judgments, and these judgments in turn affect the decisions taken. Therefore, *modeling is a critical activity for supporting human decision making* (Peplinski 1998), and this is the primary role of modeling in engineering design.

My view of modeling is consistent with human-computer cyborg (or a human-computer partnership) view that computers support, but don’t replace, human decision making. The notion of a human-computer cyborg is that computers are useful at performing certain functions, and if a computer can complete a particular task or serve a particular function, why should limited human rationality be expended on that task? According to the human-computer cyborg view, we should push onto the computer everything that we can, and the tasks that the computer can perform are a growing set. The important thing to remember is that human creativity, values, and judgment are indispensable (Peplinski 1998), and I believe they still will be indispensable in the year 2020.

I stated above that the *primary* role of models is to support decisions. Models can also be used by designers in other roles. For example, graphical or interactive simulations can be a terrific means of communication. Of particular value is in using models to communicate with stakeholders who are not necessarily trained in engineering design or related disciplines. Interactive models give “users the necessary touch-and-feel experience” such that “users can participate in the formulation of the specifications and in the immediate validation” (Fuchs 1992).

When an engineer decides to create a model, he faces several choices. Different criteria affect his choice of model, or even the decision to create an explicit model at all. For example, the type of information needed to make a decision and the information available to be used affects the choice of model, including its level of abstraction. These criteria are important because modeling should never be done just for the sake of modeling. Models should be used for a specific purpose—to generate or communicate specific knowledge. The objective is crucial as it affects the appropriate level of abstraction, assumptions, and other context of the model.

There are multiple types of models that must be integrated into a decision framework. These can be grouped into five main categories, which according to Peplinski (Peplinski 1998) are:

1. analytical relationship (equation) gathered from textbooks and such
2. analysis routines or simulations with specified inputs and outputs
3. relationships constructed from historical data
4. relationships constructed by running experiments and gathering data
5. relationship constructed using expert opinion

A decision structure must support the use of all types of models, because there is a cost involved in moving to more explicit models, if such a move is even possible given the current state of knowledge.
7.3. **Challenges making engineering decisions**

If human decision making and decision support are central to successful engineering design, then the challenges to decision making present significant challenges to the execution of a design process. These challenges can arise from several sources, including limitations of human cognition, limitations on the information available during the design process, limitations of computer capabilities.

### 7.3.1. Bounded Rationality

A human engineer faces several challenges when making decisions. First, an individual cannot process all relevant information at once. As adapted from Marston and coauthors (Marston, Allen et al. 2000), Herbert Simon states in his theory of bounded rationality (Simon 1947) that there are limits to human rationality. According to Simon, *objective rationality* requires viewing all alternatives in panoramic fashion, considering all consequences of every alternative, and selecting one from the whole set of alternatives based on a system of values.

Humans are not capable of doing this because their rationality is bounded; they cannot simultaneously consider all the consequences of all alternatives. A short summary of the limitations of rationality are that the knowledge of the consequences of a choice are fragmentary, imagination must supply the affective assessments of consequences that lie in the future, and not all alternatives come to mind. The role of tools in engineering design is to augment human rationality such that the bounds on rationality of the combined human-computer cyborg are broader than that of the human alone.

### 7.3.2. Unavailability of knowledge

In engineering design, the problems of bounded rationality are exacerbated by shortcomings in a design process. It is very difficult for the right person to have the right information available at the right time. This problem is even more likely with distributed design teams, since the person-to-person information flow is reduced.

#### 7.3.2.1. Knowledge flow: the role of knowledge management systems

Even if the team members are co-located, they may face “thought-world type problems” because they are drawn from multiple disciplines (Cooper 2003). In these cases, it is challenging to communicate knowledge from one discipline to the other. For example, “There are psychological factors that affect perception and interpretation of importance, such as only ‘hearing’ items that relate to your technical discipline, or that you are familiar with” [(Cooper 2003), referring to (Tversky and Kahneman 1974)].

The knowledge requirements of design continue to grow in depth and breadth, and this knowledge increasingly must be acquired from outside the core project team (Cooper 2003). Even after this knowledge is acquired, it is often “forgotten, mis-remembered, or otherwise ‘de-acquired’” (Cooper 2003). Sometimes too much knowledge is available—much of it irrelevant for the given decision—and the important grains of knowledge get lost in the flax.
I agree with Cooper that the difficulties described in the previous paragraphs, including bounded rationality “are not indicative of an incompetent workforce. Rather, they are indicative of a human workforce, subject to all of the limitations that people face” [Cooper 2003]. Following the notion of a human-computer cyborg, knowledge management systems need to be used to augment human abilities. Human judgments need to be formed from knowledge, but computers can support this process by providing complete, correct\(^5\), relevant, and timely knowledge.

7.3.2.2. Inherent uncertainty: lack of information

In addition to these limitations with current knowledge management systems, there is an inherent problem in design—decisions often need to be made before all relevant information is available. For example, decisions must be taken on one subsystem before all decisions are taken on the design of another subsystem with which the first interacts.

One way that a knowledge management system may mitigate this problem would be to capture the decision rationale, assumptions, and interactions between decisions in a way that a downstream constraint can be traced to an upstream decision automatically in the database. Such a system would allow for a more focused iteration in the design process, hopefully reducing the costs of revisiting a previous decision.

In these situations of decisions under a state of incomplete information, it is very difficult to define what the “best” decision is. If it is difficult to define what the “best” decision is, one must question if there is such a thing as “optimal design.”

7.4. Optimal Design

At a quick glance, it may appear that “optimal design” should be every engineer’s goal. In order to obtain optimal designs, engineering would need to make optimal decisions. How can this be done? I argue that it cannot be done, and designers must adopt a different paradigm.

7.4.1. What does optimal imply?

Merriam-Webster defines optimal as “most desirable or satisfactory” (M-W 2003). In this sense, there is absolutely no problem with the notion of optimal design. However, there is a human layer involved, and a philosophy of optimal design is dangerous. I believe that most mathematicians and engineers associate optimal with best. There is a connotation that an optimal solution is the best, leaving no room for improvement. In the context of engineering design, there invariably room for improvement. I will now discuss why.

\(^5\) I could get more complicated here, but I don’t really want to get into a discussion of who you would ever know if knowledge is correct. In this case, by correct I mean purely that the recall is perfect—the knowledge is retrievable exactly how it existed when it was initially acquired.
7.4.2. Optimal in design in not optimal in reality

Throughout ME 6101, Farrokh Mistree has hinted that optimization is not the correct approach to design. Mistree and his co-authors (Marston, Allen et al. 2000) have explained part of their perspective as:

For real-world, practical systems, all of the information for modeling systems comprehensively and accurately in the early stages of the project may not be available. Therefore, the solution to the problem, even if it is obtained using optimization techniques, cannot be optimal with respect to the real world because of the inherent approximations in the model. However, this solution can be used to support a designer’s quest for a superior solution.

Their main point is that the mathematical process of optimization—solving a mathematical program by minimizing and maximizing single objective function—will never give you a solution that in the end is the best that could have been designed with perfect information and knowledge about the world. This is especially true if the chosen design operates at a point that is extremely sensitive to noise in some un-modeled parameter. This is one of the motivations for a robust design approach, which I discuss in Section 7.5.

7.4.3. Multiple objectives in optimization

Most engineering design decisions have multiple drivers, or multiple objectives. These objectives can come from various requirements, cost constraints, and manufacturability, environmental, and safety concerns, to name a few. With multiple objectives, the problems with optimization are exacerbated because in addition to the errors introduced by lack of knowledge, it is very difficult to represent the tradeoffs between the multiple objectives. Two approaches are used in the DSP Technique (Marston, Allen et al. 2000) to handle this. The first is to create a weighted function of the deviations from the goals, and the second is a preemptive approach, in which the goals are considered in a particular order and “optimized” such that the best value of one is found, given the deviations from the preceding goals are fixed.

7.4.4. The role of constraints and the design space in optimization and engineering design

In addition to the limitations of optimization above, a mathematical optimization—I will use minimization as an example—seeks to set all available parameters such that the objective is minimized in the feasible space. The key notion here is “feasible” and how it relates to constraints in engineering design.

In order to explore this question, I introduce the notion of a design space. A design space represents all of the possible realization for a design. For a very simple example, assume that the entire design task consists of setting the value of two parameters, both of which are constrained to be positive numbers. In this case, the design space is the first quadrant of two dimensional space, as I have illustrated in Figure 14. Assume that there is exactly
one point in this design space that is the most preferred realization, marked by a ‘*’ in Figure 14. The design question now becomes, how do we get to this point?

![Figure 14: Design Space](image)

For the moment, assume that a solver is available that is guaranteed to find a globally optimal solution to the given problem. For example, assume that the problem is convex. In this case, the solution to the problem globally minimizes the objective function and is in that sense the best solution given the constraints. If this was the case and the problem could be solved all at once, the most preferred point would be obtained. However, this is not normally the case in engineering design.

Decisions in engineering design happen both sequentially and concurrently, and the concurrent decisions can happen with or without flow of information between them. In order to explore the consequences of this, we need to ask first ask, “what is the significance of the constraints in design optimization?”

Mathematically, if the shadow price on a constraint is high, it means that a slight relaxation of the constraint will yield a significant gain in the objective function. The key question in engineering design is, “Are the bounds on the constraints correct, or can a constraint be relaxed?”

An attempt to answer this question is complicated by the fact that decisions—irrevocable allocations of resources—taken early in the design process constrain the design space in later stages; early decisions have tightened the constraints on later optimizations. For example, I can present in Figure 15 a variation of my example from Figure 14. Instead of solving the problem by simultaneously setting the values of A and B, assume that A is already set. If A is set, then the realizable region has been reduced across all levels of B; the decision has constrained the realizable region of the final design, as in Figure 15.
Even if the level of A was only bounded within a tolerance, the realizable region has been reduced. There are two possible cases, which I have shown in Figure 16 and Figure 17. In Figure 16, the tolerances on A were set in such a way that the most preferred point is still in the feasible region. In Figure 17, the tolerances on A are such that the most preferred point not longer in the feasible region, meaning that it is unattainable irrespective of the value of B. Essentially, when the tolerances on A were set, the design freedom was reduced. In the case illustrated in Figure 16, the design freedom was reduced effectively, and in Figure 17, it was not.

This example can be extended in another way. Consider a design problem (perhaps satellite design), in which there is a hard constraint on some system parameter, such as total weight. If A and B in the preceding example represent the weight the two components of a satellite, then a constraint on A and B is “A+B=Weight_{max}.” If A and B are set simultaneously, both A and B can be traded across the entire range from zero to Weight_{max}. If a decision is taken to bound A between zero and one half of the maximum weight before the decision is made on B, then B can only be varied over between zero and one half of the maximum weight. Through the initial constraint “A+B=Weight_{max},” the decision made on A has introduced a new constraint on B, “B=0.5*Weight_{max}.”

The examples that I have just presented suggests that it is valuable to maintain as much design freedom as possible. Unfortunately, this approach is in tension with trying to take decisions and narrow the design efforts—monetary and time budgets are limited, and not all options can be pursued forever. If early decisions are expressed in tolerances on design parameters, there will be more space for trading parameters downstream, although
as I have illustrated in my example, even this does not ensure that the most preferred point is attainable.

My same example can be used to illustrate another problem with optimization. As Farrokh Mistree has explained in class on at least two occasions, a sequence of individual optimizations will almost never result in optimal system performance. He has related this to the notion of a greedy heuristic, in which each sequential optimization is made with no regard for later optimizations. These myopic optimizations are likely to constrain the design space for subsequent optimization to a region that does not contain the most preferred point from the system perspective.

This is exactly the case that I have illustrated in Figure 17. In this case, assume that the tolerances on A were set based on setting A near an optimal point of one objective function. Unfortunately, given the interaction with B, this range does not include the most preferred point overall, meaning that no matter what is done in setting B, the global optimum of the global, system-level objective function is not attainable.

In addition to occurring dispersed in time, design decisions are also dispersed in space, by which I mean that different people who are organized in different teams, working on different pieces of the design project, and possibly located at different geographic locations, are making decisions concurrently. If each team optimizes its design in isolation, the resulting systems will almost always have inferior performance, such as that illustrated in Figure 18. The constraints that one team’s design places on the designs of the other teams force it into a region of performance that is below where they thought their “optimal solution” would be. The solution is to embrace a systems perspective for design and to utilize ideas from game theory.

\[ \text{Figure 18: Attainable design space confined to non preferred region} \]

### 7.5. Robust Design

Taguchi has introduced and developed a paradigm of robust design (Byrne and Taguchi 1987). In this section, I discuss in what ways elements of this approach can be incorporated into my paradigm for design and the P&B process.

#### 7.5.1. The importance of robust design

A robust design is a design whose performance is not sensitive to noise. Since all designs will be affected by noise—including noise factors that designers had no knowledge of—there is no such thing as a completely robust design. In this sense it is better to speak of
the robust design approach—a design approach in which sensitivity to noise is explicitly considered.

When noise is neglected in the design process, the resulting system will be poorly designed. In some cases it might be over-designed, meaning that the noise in the real system interacts with the system such that a cheaper design will actually work better. In these cases, the designers can improve quality and reduce cost simultaneously. Alternatively, it may be that a different set of parameters would allow for much more robustness to noise than the ones chosen without considering noise. The savings in the loss factor might make up for the increased design cost, and in most cases the quality is gained less expensively during parameter design than by employing pure tolerance design.

**7.5.2. Taguchi’s assumptions**

Taguchi proceeds from the assumption of a single loss function. This limits his approach design decisions that are driven by only one factor. If anywhere, these types of decisions only happen very late in the design process.

Taguchi also assumes that the designers will have complete information. Designers must remember that they never have complete information. There are known-unknowns as well as unknown-unknowns, and consequently there is no such thing as a completely robust design. Nevertheless, there is a lot to be gained by adopting the approach of robust design.

**7.5.3. Robust design and risk reduction**

Taguchi’s approach to parameter design is important in my research because it emphasizes the necessity of considering parameter design and interactions with noise factors during the design, instead of over-engineering (spending too much money) in tolerance design to fix weak spots. One of the things considered during parameter design is sensitive to noise factors. These noise factors are by definition uncontrollable, and therefore their actual levels are uncertain. If the sensitivity to these noise factors is reduced, then this type of risk is also reduced by adjusting the levels of controllable factors such that the design is robust to noise.

**7.5.4. Robust design in Pahl and Beitz**

I would like to incorporate the approach of robust design—but not necessarily Taguchi’s implementation—into my augment Pahl and Beitz design methodology. In order to do this, I need to align Taguchi’s phases of design with the P&B process.

**7.5.4.1. Aligning phases**

I have summarized the definitions of the phases of design and aligned them in Table 4. The greatest tension is between parameter design and P&B. I believe that P&B should be modified to say, “Refine and improve layouts using a robust design approach that considers the behavior of the system under noise conditions” and also to “evaluate against technical and economic criteria including risk explicitly.”
Anything that could not be resolved or mitigated by trading these parameter levels will be a weak spot that must be “strengthened” in definitive design by spending money.
<table>
<thead>
<tr>
<th>Taguchi</th>
<th>P&amp;B (Based on figure 3.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Design</td>
<td>(Preliminary) Embodiment Design</td>
</tr>
<tr>
<td>• Selection of materials, parts and</td>
<td>• Preliminary form design, material</td>
</tr>
<tr>
<td>tentative product parameter values</td>
<td>selection</td>
</tr>
<tr>
<td>Parameter Design</td>
<td>(Preliminary) Embodiment Design</td>
</tr>
<tr>
<td>• Determines the product parameter</td>
<td>• Refine and improve layouts</td>
</tr>
<tr>
<td>values and operation levels of process</td>
<td>• Evaluate against technical and economic</td>
</tr>
<tr>
<td>factors which are least sensitive to</td>
<td>criteria</td>
</tr>
<tr>
<td>noise factors</td>
<td></td>
</tr>
<tr>
<td>Tolerance Design</td>
<td>(Definitive) Embodiment Design</td>
</tr>
<tr>
<td>• Tightening parameters or process factors</td>
<td>• Eliminate weak spots</td>
</tr>
<tr>
<td>whose variations impart large</td>
<td></td>
</tr>
<tr>
<td>influences on the output variation</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Taguchi Design versus P&B Design

7.5.4.2. **Is Taguchi’s approach relevant in other phases?**

I have tried to think of how such a “Taguchi” approach might be used in other design decisions, such as selection of a concept. However, I cannot yet relate it those types of decisions. The largest obstacle I face to forming a relationship is that I can’t imagine what the factors or levels are for a selection decision in conceptual design. Without recognizing these, I can’t vary them or evaluate noise factors, and therefore can’t run a series of experiments.

One example I’m trying to figure out in my head is a “person conveyance system” whose object is to carry one person across several hundred meters. I’m focusing on the concept for supporting the person/vehicle above the ground, and the two concepts are a car and a sled, or in other words a wheel or runners.

Each of these concepts has factors, for example a wheel has material, radius, composition (solid or pressurize hollow), track width, tread shape and depth, etc. A sled runner has length, width, material, stiffness, curvature, etc. The noise factors—especially those related to production—are also very different in each case. The only similar noise factor would be in the contour of the terrain the vehicle will need to traverse.

For each concept, experiments could be performed by setting levels of each of these factors and choosing the concept which has the most robust result overall. However, in doing this, a design will have really moved into and nearly completed embodiment design for two concepts, which might be a costly endeavor. I really don’t see how a parameter design could directly relate to this conceptual design decision.

However, when choosing a concept, one might want to consider how much flexibility in parameter design each concept will allow. In other words, which alternative offers the most design freedom via parameter design as opposed to tolerance design in the future design phases. Expert judgment might be able to provide insight into both this flexibility...
and the types of noise factors that it might face. This judgment might then be incorporated as a conceptual design decision criterion.

7.5.4.3. Augmentations to P&B for robust design

The Taguchi Approach to parameter design is most relevant in the two steps before articulation of the preliminary design, namely:

- Refine and improve layouts.
- Evaluate against technical and economic criteria.

After incorporating the Taguchi Approach, these two steps become:

- Refine and improve layouts using a robust design approach that considers the behavior of the system under noise conditions.
- Evaluate against technical and economic criteria including risk explicitly.

The incorporation of the Taguchi Approach here in embodiment design affects early phases. For example, a new conceptual design decision criterion might be which alternative offers the most design freedom via parameter design as opposed to tolerance design in the future design phases.

7.5.5. Parameter design and management culture

There is another lesson to be learned for 2020 from robust design. Dr. G. Taguchi’s work, as presented by these authors (Byrne and Taguchi 1987), identifies a failure of U.S. engineers and the contrasting success of Japanese engineers. This difference is revealed using a design philosophy of a loss factor that leads to a goal of reducing variation in product performance. I assume it is this “loss function” that gives this the name “Taguchi approach.” In order to reduce this variance at low cost, engineers must concentrate their efforts on parameter design before spending lots of money in tolerance design.

My hypothesis is that U.S. engineers tend to ignore parameter design and focus on improving quality by using more expensive materials and equipment because managers in the past used cost as a proxy for quality. Stated differently, engineers adopted practices that were the best given how they were being evaluated.

The lesson to be learned here is to develop and use measures of success that not only accurately predict and reflect success, but also that indirectly encourage engineers to make successful products as they directly try to meet the measures of success. This will probably necessitate more testing and analysis. Something will need to unambiguously demonstrate whether the million dollar widget or the thousand dollar widget comes closer to the target performance. This testing will cost money, but the motivation is that in at least some cases, the thousand dollar widget will perform better; the savings in these cases will pay for the increased testing.

7.6. The Systems Approach

According to Marston and coauthors (Marston, Allen et al. 2000), a principal component of the DSP Technique is a “design philosophy rooted in systems thinking.” My company in 2020 will embrace a systems view. A system is a regularly interacting or
interdependent group of items forming a unified whole (M-W 2003). All design projects are designing systems; at some level, it is the interactions between subcomponents or the product and its environment that are relevant to the requirements.

A systems approach may at first appear obvious; after all, the end goal is the performance of the final system. However, the systems view is often lost. Engineering design projects are usually quite large and have time constraints placed on them by budgets, contracts, and market conditions. In order to complete a design in reasonable time, the only approach is to partition the problem into sub-problems that are designed concurrently.

The notion of concurrent engineering is receiving attention in literature. Marston and coauthors (Marston, Allen et al. 2000) define, “Concurrent Design, in our view, is that part of Concurrent Engineering that is directly concerned with defining the product for manufacture and other downstream life-cycle processes….Clearly in concurrent design, the product developers need to focus on making decisions concerning the system and related processes simultaneously and in so doing, consider the interactions of these decisions.”

I choose to focus on the phrase “decisions concerning the system.” In engineering design, there are two systems in any project. First, there is the product system being designed. This product is a composition of many components and subsystems that must interact in a prescribed manner in order for the system level requirements to be met. Second, the designers form a human system of interacting groups of people who share a common high-level purpose.

The roles of these two systems are closely coupled, but ideally the two could be decoupled in the future. The interface between the two systems is the design method. Therefore, a design method must be designed to account for each system and their interactions. Also, both systems have to be designed. For example, in Chapter 4 I have outlined my corporate philosophy and policies. These policies are part of the design of the company’s human system. One of my suggestions from Section 4.4.6 can be repeated here in the context of these two systems.

I suggested that “the project must be carefully subdivided into tasks that are each assigned to teams, with the members of one team coming from as few locations as possible—preferably one. This will allow the project interfaces to match the geographic interfaces, something that I believe will smooth the design process.” Essentially, I was stating that interfaces in each individual system—for example between distributed groups in the human system, or subsystems in the product system—be aligned with interfaces in the other system.

My motivation for this is that at each interface, there is a limitation on the interactions that can be actively conducted. For example, communication tends to breakdown across geographic boundaries. Also, trades between subsystems are difficult to capture in interfaces. If a distributed team is working on one subsystem, then information problems
will be introduced within the subsystem, in addition to the problems with information flow between subsystems.

In this system view of design, nothing operates in isolation. First, the subsystems of a product system interact to affect the system level behavior and performance. In the human system, a designer must understand the impact of his or her decisions on others, as well as the impact of the decisions of others on himself or herself. One way to incorporate these issues into design is by borrowing from game theory.

### 7.7. Game Theory

According to Marston and coauthors (Marston, Allen et al. 2000), “Game theory is the mathematics and logic of strategic interaction: when the outcome of a decision under your control depends on decisions made by others.” This situation arises frequently in engineering design because subsystems designed by one team interact with and constrain subsystems designed by other people.

Game theory is broken into two main types, cooperative games and non-cooperative games. Both types are relevant in new product development.

In a non-cooperative game, the players do not formally communicate and the result is the Nash equilibrium. Non-cooperative game theory is applicable to various situations that arise naturally in engineering design (Marston, Allen et al. 2000). These situations can be grouped into two types based on the cause of non-cooperation:

1. There is no will to cooperate
2. There is no way to cooperate

I discuss the no will cause in the following section Intra-enterprise competition. The second cause (no way) arises when the teams are unable to communicate due to lack of knowledge, or lack of a means or opportunity to share knowledge. For example, in a distributed design environment, a team in the United States will not be able to get input from a team in Singapore during the same work day, so if a decision must be taken, it is taken in a non-cooperative setting due to the ~12 hour time difference.

In the cooperative or Pareto outcome, “the players communicate by sharing their respective models...[and]...all models are solved simultaneously” (Marston, Allen et al. 2000). From an optimization perspective, the parties are searching for a global optimum, as opposed to each optimizing their own sub-problem in isolation. Marston and coauthors (Marston, Allen et al. 2000) assume that engineering designers seek the cooperative outcome, but that communication barriers may prevent it. I believe that it is the role of a corporate management to encourage the cooperative outcome, because there are instances where teams might not strive for a cooperative outcome.

#### 7.7.1. Intra-enterprise competition

I claim that in some practical cases, the cooperative solution will not be sought by engineering designers. This could happen when there are pressures on the teams to meet certain objectives, for example cost. If a company has a policy that focuses on reducing costs, it must take a systems view of applying the policy. Unfortunately, my experience
is that management will look at the individual teams to see how they have each reduced costs. With each team feeling pressure to show that they reduced costs, they will compete with each other.

The competition between design teams will probably result in higher overall system design costs than if they had cooperated. It may be that large cost savings could be attained in two subsystems by design a third in a manner that increases its costs above original estimates. If the management structure does not assess the design from a systems perspective, the team designing the third subsystem will be reluctant to use the more expensive design, despite the benefit to the other two subsystems. Consequently, the cost of the whole project will increase.

My company in 2020 will assess design metrics from a systems perspective. This is not necessarily a simple task, and at this time I can only suggest one way to support such a policy.

One way to support managerial evaluations from a systems perspective is to capture the decision rationale. By formalizing such cooperative tradeoffs and other aspects of decisions—such as the models and judgments that supported the decisions—can be important not only for project evaluation, but also for future support of the design, future decisions and changes in the design of the same product, and also for future design projects.

### 7.8. Inter-enterprise competition

The design process is also subject to competition from external sources. For example, the supply chain is usually handled by other firms, and the final product is sold in a competitive marketplace.

#### 7.8.1. Subcontracting

A more likely and significant form of competition will result when subsystems are subcontracted to third parties. When the main designer enters into a contract with a subcontractor, the two parties state certain objectives and constraints in the contract. For example, in order for the contract to be firm, limits must be supplied on costs.

Unfortunately, these requirements split the objectives of the subcontractor from the systems perspective. It is unlikely that a contractor coming back and saying, “we have this great design that costs twice as much as what you wanted, but we think that it will save you money overall” will be greeted warmly, especially if there is any appearance of conflict of interest. I can imagine a sub-contractor suggesting a modification of the design that requires application of some of its other technologies.

#### 7.8.2. The marketplace

The most obvious application of game theory in engineering design is probably the market in which the company seeks to sell its products. When a target market is chosen during product planning, the ultimate success of the company’s product is not entirely controlled by the quality and completeness of the firms design process. From a business
perspective, “The number of other competitors in the market and the quality of their products, new or old, affects the amount of money that is expected from entrance into the market” (Marston, Allen et al. 2000).

I will not be addressing these market issues in my answer to the question for the semester. My goal is to bolster the rest of the design process such that my company has the best chance of getting a higher quality product to market before potential competitors. This will help to perpetuate the company’s image as an innovator and provider of superior products.

7.9. System level modeling

One way to appreciate the interdependencies between design teams is to analyze the interdependencies between partitions of the design. This analysis can be supported by the use of systems level models and simulations.

The system level design can be modeled using languages such as IDEF0 and UML. These languages have complementary strengths. Put simply, IDEF0 describes the what and UML describes the how. More specifically (Aughenbaugh and Rekuc 2003):

- IDEF is used for enterprise modeling of what should be done.
- UML is used for distributed object system modeling of how to do what should be done.

Different research efforts are underway to extend each language to the other domain, as well as to create a hybrid language. The primary advantage of using either language is that they both provide a standardized, graphical way of representing certain characteristics of the system.

In software engineering, the systems level is often captured in the form of executable specifications. Translated into an engineering design context, this executable specification is a simulation model of the function structure in conceptual design. As decisions are taken on subsystem designs, the system level executable specification can be decomposed to include the refined subsystem details. Their incorporation into the system level model allows for consistency checking.

The primary advantages of using executable specification in engineering design are (Aughenbaugh 2003):

- Refinement of system requirements and tolerances
- Identification of mistakes in assumptions and function structure at a high level
- Coupling of the simulation to the specifications; eliminates human translation
- Traceability to requirements and documents can be integrated in most tools
- Communication with stakeholders

In the future, I believe that physical models will be connected to the system level model. This will increase the value executable specifications in embodiment design. Currently, the primary advantages occur in the first two phases of engineering design. In these phases, executable specifications can help to guide the design process. Later, they
currently serve only as checks on consistency with the requirements and may assist in documentation and verification.

By the year 2020, the executable specification approach and tools will have matured to the point that they will be used to develop, capture, and analyze the function structure during conceptual design in my company. The same tools will be used during product planning and clarification of task to capture the requirements and the decision rationale at those stages. By fulfilling these functions, the executable specifications tools form a piece of the knowledge management systems for the project and company.

7.10. Decision-based design and risk

The application of decision-based decision and the systems perspective may reduce the risk in designs. The recognition of decisions as the core tasks of design that “bridge the gap between an idea and reality” (Marston, Allen et al. 2000) leads to the conclusion that the creation, capture, and accessibility of knowledge is central to creating quality designs, because knowledge is used to form judgments which in turn support the human decision process.

More generally, supporting human decision makers is a key activity in engineering. Humans have bounded rationality and other limitations in their ability to consider large amounts of knowledge at one time. The goal of a decision support problem technique, when used with utility, is to ensure that the designer chooses the most preferred alternative.

These alternatives must be considered from the systems view. By incorporating non-cooperating game theory into the decision, the designer is making his/her decisions more robust to the decisions outside of his/her control. This will help mitigate risk. Non-cooperative game theory may also reveal to design teams and management that the teams really need to cooperate, as the cooperative outcome is always better from the systems perspective, and often from the individual perspectives, too. The managers should not only encourage the will to cooperate, but also provide the means, such as knowledge management and sharing. If one of the system’s criteria is risk, then the use of game theory will provide a framework to reduce risk in the design.

7.11. Closure on decisions, tools, knowledge, and risk

Models are used to support the decision process by helping designers create knowledge and form judgments that they use to make decisions. The more relevant to the decision the models are, that is, the better the context of the model matches the context of the decision, the more the uncertainty in decision is reduced. Knowledge management systems can augment human abilities in decision making, including making knowledge accessible at the correct time and capturing decision rationale for future reuse.

As more knowledge is used by humans as they make decisions, the uncertainty is reduced, because more is known, assuming the knowledge is correct and relevant. This reduction in uncertainty translates to lower risks, which in turn should lead to better
designs. Unfortunately, neither modeling nor knowledge management systems can eliminate risk; they can only reduce it. Therefore, risk needs to be managed in the design process. If risk is to be considered as a decision criterion, it must be formalized. I develop and present my formalization of risk in Chapter 8.
Chapter 8. Risk in Engineering Design

In order to answer my question for the semester, I need to formalize the notion of risk. I must define risk and proposed methods for measuring it. This chapter of my A2Q4S is very important as it is my first step forward in articulating my research positions. It therefore ties directly to my primary A0 goal of forming the foundation for a research paper. However, the contributions here are not necessarily new to the field; they are to me and Chris Paredis a new way of thinking about risk and the first step in formalizing our position.

In this section I define risk, relate risk to reliability, place our interest in risk in the context of other activities including engineering design, explain the roles of different types of uncertainty in risk calculations, and present some examples of risk assessments.

At this time, the content of this section is almost entirely my own work. However, I have written it in the first person plural because as Chris Paredis, I, the rest of my research group, and Leyla Valladares (my ME 6101 team project partner) accept these ideas, they will become the basis for our work. In the interests of reuse, I have written this chapter as a stand alone document.

8.1. Definition of Risk

A prerequisite to answering my question for the semester is to define and explore the notion of risk. Standard dictionary definitions define risk as the possibility or probability of suffering harm, loss, or injury [adapted from dictionary.com and m-w.com]. We disagree with this definition and develop a definition that is more useful in engineering design.

In a qualitative sense, risk is a measure of how bad something might be. For example, most everyone would agree that the risk of sticking one’s finger in an electrical outlet is high. What makes the risk high? The notion of risk incorporates the consequence or cost of something bad happening and the likelihood of that event happening. In the electrical outlet example, the consequence is serious injury or death, and the likelihood—the probability of that even occurring—is near one (1).

Given these examples, it seems clear that risk is a function of probability of an event and the consequence of that event, as shown in Equation 1.

\[ \text{Risk} = f(\text{consequence, probability}) \]

8.1.1. Risk and outcomes

So far, we have defined risk in the context of a particular event. In order to eventually consider the overall risk of a design, it may be more useful to think of risk first in terms of the risk of a particular outcome, which in the context of reliability would be considered a particular failure. To illustrate the notion of outcomes, we return again to the electrical outlet example. There are really several outcomes that could result from sticking one’s
finger in the outlet. We have illustrated these possible outcomes, probabilities, and consequences in Figure 19.

We assume for now that a finite set of outcomes can be defined for the system performance. A more general formulation of risk would allow for continuous variations of outcomes, or levels of failure (degradation in performance), but in order to discuss the notion of risk more clearly, we begin the discussion with this notion of a finite set of outcomes.

### 8.1.2. Quantifying Consequences

The tree shown in Figure 19 illustrates one complication with our formulation of risk in Equation 1. In this example, it is difficult to quantify the consequences. Most people would see death as comparatively worse than severe burns, but by how much? Other people may prefer death to suffering with burns. How can consequences be quantified?

<table>
<thead>
<tr>
<th>Power</th>
<th>Fuse</th>
<th>Outcome</th>
<th>Likelihood</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off (1%)</td>
<td></td>
<td>1</td>
<td>1.0%</td>
<td>none</td>
</tr>
<tr>
<td>Malfunction (1%)</td>
<td></td>
<td>2</td>
<td>1.0%</td>
<td>death</td>
</tr>
<tr>
<td>On (99%)</td>
<td>Fuse blows (99%)</td>
<td>3</td>
<td>98.0%</td>
<td>Severe burns</td>
</tr>
</tbody>
</table>

Figure 19: Outcomes of Sticking Finger in Electrical Outlet

For some cases in engineering design, the quantification of consequences should not be as difficult as in this example. For example, if one outcome is complete failure of a system, then consequence of that outcome is the entire cost of the project plus the opportunity cost of lost future profits. However, there are clearly cases when the failure of an engineering system can result in the injury or death of humans. These situations become very tricky, as putting a value on a human life is a controversial topic.

Consequences cannot always be accurately expressed in dollars. Nevertheless, in order to proceed with establishing the framework for incorporating risks into design decisions, we assume that consequences can be estimated—albeit with uncertainty—quantitatively in units of dollars.
We admit that in some cases it will be difficult to estimate the consequences of future outcomes in a quantitative measure. This is especially true for human losses, as well as for degraded system behavior. For example, in the context of my ME 6101 project, what are the consequences of the FireSat (Wertz and Larson 1999) not being able to slew (change its orientation) at the rate specified in the system requirement? Certainly the entire mission is not lost, but there is some cost—some loss in productivity or usefulness.

### 8.1.3. Risk of a particular outcome

Proceeding from our discussion of risk, we define the risk of one outcome as the product of the probability of that outcome and the consequence of that outcome, as shown in Equation 2.

**Equation 2**

\[
\text{Risk}_\text{outcome} = \text{probability}_\text{outcome} \times \text{consequence}_\text{outcome}
\]

The next question is how to aggregate the risks of different outcomes into a measure of overall risk.

### 8.1.4. Aggregating risk across outcomes

If the outcomes are divided into a tree structure such as in Figure 19 where each outcome is mutually exclusive, then the total risk is merely the sum of the risks of the individual outcomes, illustrated here in Equation 3.

**Equation 3**

\[
\text{Risk}_{\text{total}} = \sum_i \text{Risk}_i = \sum_i \text{probability}_i \times \text{consequence}_i \quad \text{where } i \text{ indexes the outcomes}
\]

At this point we introduce the notation

\[
\begin{align*}
 p_i & \equiv \text{probability}_i \\
 c_i & \equiv \text{consequence}_i \\
 \rho_i & \equiv \text{Risk}_i \\
 i & \equiv \text{one outcome}
\end{align*}
\]

Using this notation

**Equation 4**

\[
\text{Risk}_{\text{total}} = \sum_i \text{Risk}_i = \sum_i \rho_i = \sum_i p_i \times c_i \quad \text{where } i \text{ indexes the outcomes}
\]

We will need to generalize this expression of risk in order to address

### 8.1.5. Limitations of development so far

Let’s revisit our definition of risk from Equation 2:

**Equation 2**

\[
\text{Risk}_\text{outcome} = \text{probability}_\text{outcome} \times \text{consequence}_\text{outcome}
\]

It is necessary but not sufficient to estimate the probability of an outcome; one must also estimate the consequence. We do not pretend that this is trivial. However, we would now like to focus on only one aspect of the consequences of a failure.
We present two cases of system failure:
1. The system fails one minute into its operational life
2. The system fails one minute before its design life ends (so for a 10 year design life, that means 9 years, 364 days, 23 hours, and 59 minutes into its operational life)

The respective consequences of these outcomes are approximately:
1. Project cost plus lost value (opportunity costs)
2. Zero. No one will really care at all that it fell one minute short because nearly all of the anticipated value will have been realized.

This example has illustrated an important characteristic of the consequences: they are time-dependent. Adapting our definition we form Equation 5, where $T$ is the time of the failure, or the time the outcome is realized, which is a random variable.

\[
Risk_{outcome} = \text{probability}_{outcome} \times \text{consequence}_{outcome}(T)
\]

Given this relationship, risk must be calculated and aggregated in a more complex way than we have developed so far. This will be done by incorporating and extending reliability theory, which deals with measuring and calculating the probabilities of outcomes, but not the consequences. After establishing the role of risk assessments in engineering design in Section 8.2, we provide an introduction to reliability in Section 8.3.

### 8.2. The role of risk assessments in engineering design

From the perspective of decision based design, the role of risk assessments in engineering design is to help designers make better decisions, where we consider a better decision to mean choosing the alternative (or alternative values) that are more preferred. We show in Figure 20 our view of where risk assessment fits into the design process.

There are three different viewpoints for risk. The first is a component view. Although risk cannot be calculated at the component level, the component view feeds directly into the system reliability, which is connected to risk by definition via the probability of an outcome being realized. The second view is the systems view. This perspective integrates the components, their interactions, and the system properties, including the consequences of failure. Finally, the decision perspective is the driving perspective; the other two exist solely for the purpose of supporting this view. We also recognize that other criteria enter the design process, so we have included an input of “other criteria” to the decision task.

The relationships that we have illustrated in Figure 20 allow us to place our research topics into a larger setting. Please note that FMEA stands for failure modes and effects analysis, FTA stands for fault tree analysis, ETA stands for event tree analysis, DOE stands for design of experiments, and DSP stands for decision support problem. Our focus is on the risk theory, risk assessment tasks, and the integration of risk into decision making. As our goal is this last element—inTEGRATING RISK INTO DECISION MAKING—so our
risk theory and risk assessment tasks must be formulated in this context of supporting design decisions.

Figure 20: Role of risk assessments in design

### 8.3. Introduction to reliability theory

Reliability and reliability-based design are fairly mature subjects. Our contribution in these areas will be to extend and modify the content of these subjects such that they are more valuable in engineering design. This section provides a brief introduction to reliability theory, and it assumes some familiarity with statistics.
8.3.1. Definition of reliability
The generally accepted definition of reliability is as follows (Rao 1992):
Reliability is the probability of a device performing its function over a specified period of time and under specified operating conditions.

8.3.2. Reliability notation used in this paper
We will use the following conventions in our discussion of reliability

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R(t) )</td>
<td>reliability at time ( t ), the probability that the system is still performing its function at time ( t )</td>
</tr>
<tr>
<td>( h(t) )</td>
<td>the hazard rate at time ( t ), also known as the (instantaneous) failure rate</td>
</tr>
<tr>
<td>( T )</td>
<td>time to failure, a random variable (also known as the lifetime)</td>
</tr>
<tr>
<td>( f(t) )</td>
<td>the probability density function (pdf) of the random variable ( T )</td>
</tr>
<tr>
<td>( F(t) )</td>
<td>the cumulative distribution function (cdf) of the random variable ( T )</td>
</tr>
</tbody>
</table>

8.3.3. Calculating Reliability
The notion of reliability is constructed starting from the distribution of the entity’s lifetime, or time to failure \( T \). The distribution of \( T \), or its probability density function is assumed to be given as \( f(t) \). The function \( f(t) \) can be thought of as the probability of the system failing during the time interval \((t, t+dt)\).

Using the preceding definitions, the following relations hold:

\[
F(t) = \int_0^t f(x)dx = P\{T \leq t\}
\]

\[
R(t) = P\{T > t\} = 1 - P\{T \leq t\} = 1 - F(t)
\]

Thus we see that reliability at time \( t \) is the complement of the cumulative probability of failure by time \( t \). Rao (Rao 1992) develops a definition of the reliability as follows:

Consider a fixed number of identical components tested simultaneously under similar operation conditions. Let \( N \) = number of identical components tested, \( N_s(t) \) = number of components surviving at time \( t \), and \( N_f(t) \) = number of components failed in time \( t \). As the test proceeds, the number of surviving components gets smaller and the number of failed components gets larger. Then the reliability of the component at time \( t \) can be defined as

\[
R(t) = \frac{N_s(t)}{N} = \frac{N - N_f(t)}{N} = 1 - \frac{N_f(t)}{N}
\]

Rao (Rao 1992) defines the hazard rate, or instantaneous failure rate as
Equation 7

\[ h(t) = \frac{1}{N_s(t)} \frac{dN_s(t)}{dt} \]

The hazard rate is the rate at which components are failing, scaled by the number of components that are still operation at time \( t \). By taking the derivative of reliability as in Equation 8, the hazard rate can be related to reliability as shown in Equation 9.

Equation 8

\[ \frac{dR(t)}{dt} = -\frac{1}{N} \frac{dN_s(t)}{dt} \]

Equation 9

\[ h(t) = -\frac{1}{R(t)} \frac{dR(t)}{dt} \]

According to this relationship, the hazard rate is in general not constant unless the reliability is constant\(^6\). In practice, the hazard rate is often found to follow what is referred to as the *bathtub curve*, which we discuss in the next section.

### 8.3.4. The bathtub curve

We have reproduced an example bathtub curve from Figure 1.1 in Rao (Rao 1992) in Figure 21. The bathtub curve illustrates that there are three major phases in a component’s operational lifetime:

1. Infant mortality (or burn-in period)
2. Useful lifetime (or normal operating period)
3. Wearout (or aging period)

---

\(^6\) There is a special case of exponentially distributed reliability. In this case the hazard rate is constant and failures are a memory-less process.
We have specified that these are the three phases of the *operational lifetime* to emphasize that there are other phases in a product’s *lifecycle*. For example, after the wearout phase (or whenever a product fails), there is a disposal phase. This phase (including reuse and recycling) is becoming more important in design due to environmental concerns and regulations. There may be risk elements in this phase as well, but for now we are only focusing on the differences between these three operational phases.

During infant mortality, defective components fail at a high rate. It is unlikely that such substandard components (which arise from manufacturing defects and poor quality control) will last long, so after a period of infant mortality, it is likely that mostly quality components would still be working. During the useful lifetime, the failure rate is approximately constant, with failures resulting from random events. After the useful life, a wearout phase occurs as components suffer from aging, a prime example being fatigue due to repetitive loading. As the components age, the failure rate increases.

The empirically derived bathtub curve indicates that hazard rates are not constant over product lifetimes. A calculation of risk—which depends on the probability of failure—must recognize this fact. We now have presented evidence that the probabilities and consequences of failures are time-dependent, and we must adapt our definition of risk to include this time-dependence.

### 8.4. Time-dependent Risk Calculations

Based on our conclusions in previous sections of this chapter that the probability of failure and the consequences of a failure are often time dependent, we must redefine risk to incorporate these conclusions. We would like to express risk of an outcome as the expected value of the consequences of an outcome. The probability of failure in a infinitesimal interval $dt$ at time $t$ is give by $f(t)$, the probability density function of the failure time, random variable $T$. Specifically, risk of outcome $i$ can now be defined generally in Equation 10.

**Equation 10**

$$\text{Risk}_i = \int_0^\infty f_i(t)c_i(t)dt$$

This can be redefined as in Equation 11 under the assumption that $c(t) = 0$ for $t > T_d$, where $T_d$ is the desired lifetime.

**Equation 11**

$$\text{Risk}_i = \int_0^{T_d} f_i(t)c_i(t)dt$$

### 8.5. Risk and reliability: systems view versus component view

The consequences of a failure can only be estimated at the system level. There is no meaning in the consequences of a component failing outside of the context of a system; the *cost* associated with the failure is a global, system-level characteristic that cannot be derived from sub-system characteristics.
For example, what is the consequence of a bolt failing? If the bolt is one of four holding an assembly together, it is likely that the failure of one bolt will not affect the system performance. One the other hand, if the bolt is one of two bolts holding a solar panel to a satellite bus, the failure of one will decrease the ability of the joint to exert moments, which could result in the inability to point the solar panel towards the sun. In both cases, it is the system level interactions and performance failures that lead to consequences.

Engineers often assign design budgets, with each subsystem getting a share. For example, in satellite design, there is a weight budget, with assignments made to each subsystem (plus some margin) such that the aggregate weight is within the bounds on system weight. The system-level specificity of consequences makes decomposition of a risk budget meaningless.

However, the likelihood of the system failure occurring can be aggregated from the reliabilities of the subcomponents. The way to determine which of these scenarios is likely for a given failure can only be determined by analyzing the system structure, failure modes, and component reliabilities. One possible outcome of our research might be a method for allocating reliability to subsystems with risk as the driving objective. The idea here is to design such that the probability component an outcome’s risk is reduced.

### 8.6. Designing for the three operational phases of system life

The bathtub curve has already been introduced in order to illustrate the time-dependent nature of hazard rates. As discussed earlier, the bathtub curve also illustrates the three operational phases of a system’s lifetime:

1. Infant mortality
2. Useful lifetime
3. Wearout

According Rao, “From a design point of view, the [useful lifetime] period will be of interest” (Rao 1992). We disagree with his perspective; we believe that design must be concerned with all periods (phases) of a product’s lifecycle. In this case, the three different phases of the bathtub curve each deserve attention in engineering design, although each will probably be treated differently. The three phases—including their durations and the magnitude of the failure rates in each phase—become multiple objectives for the design process.

The first phase, infant mortality, is dependent on manufacturing. If a product is built exactly to correct specifications, there would be no infant mortality period. Naturally, manufacturing is not a perfect process, nor are the specifications ever perfect. However, during the design process, special attention can be given to the manufacturing process to increase reliability during the infant mortality period.

For example, robust design (which I discuss more in Section 7.5) can be pursued such that design parameters are set to levels that are relatively robust to noise in the manufacturing process. According to Taguchi, this is often a cheaper solution to
improving quality—where here the aspect of quality we are considering is reliability—than to emphasis tolerance design, in which the tolerances on the material and manufacturing processes are tightened, usually at high cost (Byrne and Taguchi 1987).

During the second phase—useful lifetime—the emphasis is not on manufacturing but on the overall system design and requirements. We claim that the failure rate during this phase is result of poor execution of the more traditional design activities: component design and system structure. To have high reliability in this phase, the system and each of its components must be designed for the appropriate uses and environment. For example, if a component is designed to withstand a maximum load $L_d$ but the actual load experiences is $L_a > L_d$, then that component is not reliable; it will fail. It is this type of error in the design that we will focus on in ME 6101. The uncertainty involved in estimating $L_d$ and $L_a$ are discussed in the following section.

The third operational phase—wearout—is dependent on some of factors involved in the first two phases, as well as some additional factors. For example, if the system is not manufactured to specification, the system might suffer more fatigue that the design assumed; there may be one component that is manufacturing with a small crack that causes failure due to fatigue to result sooner or more rapidly under repeated loadings than the design assumed. Similarly, if the system is not designed for the correct loading cycle (frequency or magnitude) the system will age at a different rate than expected.

8.7. Consequences and deviations from targets

The framework we have developed so far works nicely for evaluating risk in systems whose performance and failures can be neatly decomposed into specific outcomes. However, engineering systems do not necessarily fit this mold. We proceed now by looking at one way of viewing the outcomes of an engineering system that does fit this framework. We then discuss the limitations of this perspective and suggest an alternative.

Many engineering systems, especially spacecrafts, are designed to meet certain requirements on operational lifetime. For the FireSat (Wertz and Larson 1999) mission extended in my ME 6101 project, the design life is ten years. We can use this design life as the perspective for evaluating the possible outcomes of the system. For example, at the end of 10 years, either the system is still in orbit or it isn’t (meaning it crashed). Another branch of the event tree is whether the fire detector is operational. The next branch could be whether the ADCS (attitude determination and control system) is still performing well enough to meet the pointing requirements.

Notice that there were assumptions made in the preceding paragraph when defining the branches. We essential phrased a question asking, “Is the satellite still in orbit?”, which does have a definite yes/no answer. However, a more appropriate question is “Is the satellite still in its designed orbit?” This question has a superficial binary yes/no answer.

The advantage of evaluating the outcomes at the end of the mission is that it provides a definite point in time at which to estimate the probability that a subsystem is working or
not working. Such estimates form the core of reliability theory and reliability estimates. *Reliability-based-design* strives to allocate reliability to subsystems in order to meet the overall reliability requirements of the system, for example with what probability the system must still be operating at the end of its design life.

While there are times that such an approach is valuable, often the more important question is, “How far out of its prescribed orbit is the satellite?” This question does not have a yes/no answer, but rather a continuous, quantitative answer. It may be a complicated geometric calculation, but we can measure how far away the satellite is from its prescribed orbital position.

The satellite’s deviation from its prescribed orbit will directly affect its performance. This can be illustrated using a method similar to how we illustrated the time dependence of consequences—using extremes. In one extreme, if the satellite has crashed into the earth or drifted outside the moon’s orbit, it is essentially useless for detecting forest fires. In the other extreme, if the satellite’s circular orbit has drifted into an ellipse of eccentricity 0.01 but in the same orbital plane, the effects on fire detection will be negligible.

8.7.1. **Discretizing continuum of outcomes**

In the preceding discussion, we have illustrated that there is really a continuum of outcomes, with each point of the continuum having different consequences. One way of dealing with this is to discretize the continuum by sampling different deviations from the target requirement or success criterion. For example, if a satellite has a slew rate requirement of 30 degrees in 10 minutes, a discretized series of outcomes can be created as we have shown in Figure 22.

For this example, we have chosen to measure slew rate in terms of how many minutes ($t_{slew}$) it takes to slew 30 degrees, since response time is really the driving criterion. We have used sampling points spaced 1 minute apart. The probability of the time falling within a range of ±0.5 minutes is calculated assuming that the time is normally distributed with mean 8 and standard deviation of 2. We have presented two possible consequence functions, one linear $c(t,d)=-?t*|d|$ (for $d<0$, zero otherwise) and one quadratic $c(t,d)=-?t*d^2$ (for $d<0$, zero otherwise), where $?t$ is a scalar multiple that captures the time dependency of the consequences and $d=10-t_{slew}$.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Time (min)</th>
<th>Probability Time~N(8,4)</th>
<th>Deviation from Requirement (min)</th>
<th>Consequences Linear</th>
<th>Consequences Quad.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;10</td>
<td>0.841</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>10.5</td>
<td>0.092</td>
<td>0.5</td>
<td>0.5</td>
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</tr>
<tr>
<td>3</td>
<td>11.5</td>
<td>0.044</td>
<td>1.5</td>
<td>1.5</td>
<td>2.25</td>
</tr>
<tr>
<td>4</td>
<td>12.5</td>
<td>0.017</td>
<td>2.5</td>
<td>2.5</td>
<td>6.25</td>
</tr>
<tr>
<td>5</td>
<td>13.5</td>
<td>0.005</td>
<td>3.5</td>
<td>3.5</td>
<td>12.25</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
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<td>...</td>
</tr>
</tbody>
</table>

*Figure 22: Discretized outcomes*
The difficulty that is hidden in Figure 22 is the calculation of the probabilities. The formulation that we used in calculating the probabilities of outcomes assumed that the distribution on the slew times is constant over the satellite’s lifetime. If the error in slew rate arose from design uncertainty (such as the torque of the control actuators was designed for a particular moment of inertia, which was exceeded in the final design), then this formulation is valid. If the deviations come from failures in operation (such as an actuator stops functioning), then this probability will change over time.

### 8.7.2. Continuum of outcomes

In a more general formulation of risk should calculate risk over the continuum of possible realizations, instead of considering discrete outcomes. In this formulation, the deviation $?_x$ from a target requirement or objective represents the continuum of outcomes. Given this, we can define the risk of not meeting a particular objective or requirement as shown in Equation 12.

$$
\text{Equation 12}
$$

\[\text{Risk} = \int_{\Delta}^{\infty} \int_{t_0}^{t_\infty} f(\Delta, t)c(\Delta, t)d\Delta dt\]

In Equation 12 we have defined $?_x$ as the deviation from the requirement using the convention that $?_x = (\text{target-actual})$ regardless of whether the target is an upper or lower bound, or an actual target (such that the deviation is two-sided). The importance of the sign (positive or negative) of the deviation will be captured in the consequences, $c(?, t)$.

### 8.7.3. Limitation: single objective only

It is obvious that this formulation of risk is getting quite complex. However, it is not yet complete. We have not yet accounted for multiple objectives and requirements. This will involve calculating the risk as above for each objective, and then aggregating them, which will not be a simple summation due to the likely dependence of both the probabilities and consequences across the multiple objectives. We do not try to formulate this aggregation, so we are limited to using specific outcomes or a single objective function at this time.

### 8.8. Uncertainty in risk assessments

Uncertainty has a role in nearly every design task and design decision. The word uncertainty is used here in the most general sense. There are really two main types of uncertainty, and different authors refer to them differently.

We prefer to refer to the first kind of uncertainty as variability. Variability is also referred to as stochastic uncertainty, aleatory uncertainty, inherent-uncertainty, and irreducible uncertainty (Oberkampf, DeLand et al. 2000). This variability arises from inherent variability in the physical system or its environment. Example sources of variability are wind effects on a building structure or variations in the exact dimensions of a manufactured part.

The second type of uncertainty is also called epistemic uncertainty or reducible uncertainty. We will adopt the current practice in risk assessment literature and will use...
the word \textit{uncertainty} to refer to this epistemic uncertainty. Oberkampf and coauthors (Oberkampf, DeLand et al. 2000) define uncertainty as \textit{potential deficiency in any phase or activity of the modeling process that is due to lack of knowledge}. The emphasis is on the source being a lack of knowledge, or incomplete information. Oberkampf and coauthors also emphasize that the deficiency is potential—it may or may not exist. For example, “there may be no deficiency, say in the prediction of some event, even thought there is a lack of knowledge if we happen to model the phenomena correctly” (Oberkampf, DeLand et al. 2000).

In the context of modeling and simulation, Oberkampf et al. (Oberkampf, DeLand et al. 2000) also define a third type of uncertainty, error, where they define \textit{error} as “a \textit{recognizable} deficiency in any phase or activity of modeling and simulation that is \textit{not} due to lack of knowledge.” They provide the examples of “finite precision arithmetic in a computer, approximations made to simply the modeling of a physical process, and conversion of [partial differential equations] into discrete equations.”

They proceed to define \textit{acknowledged error} as those deficiencies that are recognized by the analysts, and the analyst usually has some idea of the magnitude or impact of these errors. They define \textit{unacknowledged} errors as “those deficiencies that are not recognized by the analyst, but they are recognizable.” They provide examples as “blunders or errors” on the part of the human analyst. They make a very important point that, “There are no straightforward methods for estimating, bounding, or ordering the contribution of unacknowledged errors.”

This last statement is a limiting factor in determining model accuracy. In the Systems Realization Lab, Rich Malak is currently researching error (as defined in this paper) in modeling and simulation. Our concern during ME 6101 is with the implications of variability, uncertainty, and error for risk assessments.

All three can contribute to the probability of a failure of the designed system to meet its requirements. Therefore, all three need to be considered at design time.

\section*{8.9. Risk and design for the useful lifetime phase}

As discussed already, we are choosing to focus on the useful lifetime phase of a product’s lifecycle. We will begin to develop our notion of risk in design decisions by considering reducible uncertainty that results from lack of knowledge about certain design parameters.

The example that we will develop with be for the control system in a satellite. The parameter that we wish to design in the maximum torque required to rotate the satellite. For simplicity, we will consider only rotations about the z-axis, which we have illustrated in Figure 23. Our initial assumption is that Equation 13 captures the maximum required torque perfectly.

\textbf{Equation 13} \[\tau_{\text{max}, z} = I_z \cdot \alpha_{\text{max}, z}\]
Figure 23: Sample Satellite Design Problem

In this example, we have a perfect model, but we have not eliminated uncertainty. At the time that we need to design an actuator to supply the maximum torque, we do not know the actual moment of inertia $I_z$, because the system has not yet been defined. For added simplicity, we will assume that $a_{\max,z}$ (the maximum required angular acceleration about the z-axis) is known exactly. We also assume that there is no noise in the system such as structural vibrations or fuel sloshing. Thus, the only uncertainty is our lack of information about $I_z$.

This example is much simpler than the theory that we have developed so far, because there is no direct time dependence in our failure. At the end of the design, we either will have designed the actuator to provide sufficient torque given the realization of the designed moment of inertia or not. The example can still be used to explore the inclusion of risk as a decision criterion, because the risk can still be calculated as long as we have an estimated probability of failure and an estimate of the consequences.

8.9.1. Estimating the probability of failure

Although estimates of reducible uncertainty are often formulated in terms of intervals, we will take another possibility—that there is a probabilistic description of the value of the random variable $I_z$.

We will also assume that there is some uncertainty in our actuator, such that even if we design for a particular torque $t_{\max,z}$, the actual maximum torque $t_{a,z}$ is a random variable. This formulation is analogous to a typical reliability assessment of the probability of failure of a structure member under loading. In this type of reliability analysis, there are two random variables of interest

- The load, $L$
- The strength, $S$

The structure will fail if $L=S$, but since both $L$ and $S$ are random variables, a probabilistic formulation is used to determine the probability of failure. Specifically, the probability of failure is the probability that $L=S$, or $P\{L=S\}$, or $P\{L-S=0\}$. These types of strength based reliability estimates are well developed in reliability literature, such as in Chapter 6 of Rao (1992). There exist mathematical methods for combining the distributions on $L$ and $S$ to calculate the $P\{L-S=0\}$. We will not discuss these here, because our purpose is merely to relate our type of reliability assessment to this more traditional one.
Continuing with our example, our question is whether \( t_{a,z} = I_z a_{\text{max},z} \). Mathematically, this is no different than the strength-load formulation above, except for the introduction of a scalar, which introduces only trivial changes. The number that we require for our risk calculation is \( P\{ t_{a,z} - I_z a_{\text{max},z} = 0 \} \). Given distributions on the random variables \( t_{a,z} \) and \( I_z \) (in addition to the scalar constant \( a_{\text{max},z} \)), we can calculate the desired probability using the methods from strength based reliability.

### 8.9.2. Estimating consequences

In order to complete this example, we ask the reader to use some imagination to accept the following scenario. Our example has assumed that our torque actuator design and the final moment of inertia are completely uncoupled (meaning our actuator doesn’t affect the moment of inertia), and that the processes proceed simultaneously with no flow of information between the two teams. Hopefully in our companies in 2020 this would never happen, but we need to make this simplifying assumption to illustrate the process of assessing risk.

An additional part of the assumption is that these simultaneous design tasks proceed to completion, as does the rest of the design process. Therefore, the assembled satellite is ready for launch into orbit. Any prudent company will have performed checks to prevent this from happening, and most likely they will have uncovered the error and redesigned the system. We assume that this does not happen in this case, and the system is launched without corrective action on the torque actuators.

Given that the satellite is launched, there will be some consequences of the failure to have designed the torque actuator correctly. In one view, the mission is a complete loss because the system can’t meet the required slew rate \( a_{\text{max},z} \). The consequences are all of the design costs, plus the opportunity costs resulting from the inability to complete the mission objectives.

An alternative way to measure the consequences is to relate the costs to the degradation in performance, that is the deviation from the required rate \( a_{\text{max},z} \). The idea here is the same as we illustrated in the example in Figure 22 and the accompanying discussion in the section *Consequences and deviations from targets*.

In order to actually create the deviation consequence function, expert judgment and simulation models will need to be used. We do not propose a specific method for calculating these consequences, but we believe that at least subjective assessments are possible.

### 8.9.3. Combining estimates

Depending on the form and distributions of the estimates on consequences and probabilities, they will need to be combined in different ways. If the uncertainty in the estimates is given as probability distributions, they can be combined using Bayesian theory. If one is in the form of an interval, evidence theory will be needed. Depending on the formulation, the combination may not be trivial, although it is possible.
8.10. **Risk assessments in decisions**

For the answer to my question for the semester, I look at incorporating risk assessments into the decision process in only one formal way. I assume that the human decision makers are using the DSP technique to make their decisions.

At a high level, risk is incorporated into the DSP structure by setting a goal for risk. Since risk is expressed qualitatively, it is easily incorporated into a deviation function or a preemptive goal programming formulation.

At this point, I am stretching my understanding of risk and the DSP technique. My assumption is that in a compromise DSP, risk must be expressible as a function of the other decision variables. My assumption so far has been that there is not such closed form expression for risk, because it requires humans to form judgments on the likelihood of consequences and the magnitudes of the consequences. Perhaps the optimization routines would need to be connected to simulations that could estimate these quantities based on distributions provided by human.

An experimental approach to making decisions might be possible using a robust design approach, which I discuss in the Section 7.5. For example, if Taguchi’s notion of a loss function is replaced with an objective function that folds risk into it, then the different runs of the experiment can be executed including a calculation of the risk for each combination of levels that are a part of the experiment. As formulated by Taguchi (Byrne and Taguchi 1987), robust design is not a true compromise process, but rather a process in which a continuum of possible levels settings is discretized into a finite set. The decision then becomes a selection, and a selection DSP formulation would be needed.

I still cannot definitively state how to formally integrate risk into a decision. This is major area for future work. For example, my knowledge of the DSP technique is not sufficient to make a recommendation.
Chapter 9. Summary of my Augmented P&B Systematic Design Process

In Chapter 6, I introduced some specific augmentations to the Pahl and Beitz process. My focus in this section was on the Pahl and Beitz process and the changes necessary for the distributed design environment of the year 2020. In Chapter 7 and Chapter 8, I have examined my Q4S from a higher level.

9.1. New tasks

I made the following specific augmentations to the P&B process in Chapter 6:

- Process management
- Completion checkpoints
- Decision point for original design
- Allowance in product planning and clarification of task for subcontracting and supply chain tasks

I have shown these augmentations in their relevant positions along the right side of Figure 24. I have reproduced the original process (Pahl and Beitz 1996) in the center to show the context of my augmentations. Along the right side of the figure I have presented the augmentations that occur throughout all phases at a higher level, which I discuss in the next section (9.2).

9.2. New approaches

Before I can answer how to augment the P&B method to include risk assessments, simulations, and better reuse of knowledge, I must understand the design process and adopt a paradigm. The paradigm that I adopt is a decision-based design approach; the heart of this perspective is that “the principal role of an engineer in the design of an artifact is to make decisions” (Marston, Allen et al. 2000). After making this realization, I can begin to improve the design process by helping the human engineer to make decisions.

The role of the computer—including computer models and simulations—in the decision process is to support the human. I have accepted the notion of a human-computer cyborg. I will probably place my research in this context. I would incorporate risk assessments into the design process by including it as a decision criterion.

As far as answering my Q4S, I have identified the context in which modeling, risk assessments, and knowledge reuse can support the design process. I have not incorporated specific new steps to the P&B process, and I have not completely changed the approach that P&B have developed. I have created a relationship between my augmentations and the P&B process.

Pahl and Beitz recognize the importance of decision making in the process of finding solutions to tasks and problems (Pahl and Beitz 1996), and they note that, “This whole process, leading from confrontation through creation to decision, must be repeated in
each successive, increasingly concrete, phase of the design process” (Pahl and Beitz 1996). Therefore, my augmentations fit into the design process everywhere that a decision needs to be made. I have shown the general nature of these augmentations by displaying them along the left side of Figure 24.

**Figure 24: Summary of augmentations to P&B process**
Chapter 10. Verification and Validation

In this A2Q4S, I have presented augmentations to a design methodology. The open question is whether these augmentations are any good, which raises the question, “How does one verify and validate a design method?” In lecture 21, Farrokh presented the following motivation:

Due to the open nature of research in engineering design, where new knowledge is associated with heuristics and non-precise representations, we define scientific knowledge according to the relativist school of epistemology as socially justifiable belief. Thus, research validation becomes a process of building confidence in its usefulness with respect to a purpose.

One approach building this confidence is to use the validation square (Pedersen, Emblemstav et al. 2000).

10.1. The Validation Square

There are two parts to validating a design method. The first part is certifying the method, and the second part is determining if the method is worth using. These parts can be grouped more explicitly into four quadrants of a square, as shown in Figure 25. Each of these quadrants is described in the following subsections. In the validation square, the word validation is used generally, since the quadrants include activities that fall under the headings of both verification (internal consistency checking) and validation (justification of knowledge claims).

![Validation Square](image)

Figure 25: Validation Square for a Design Process
10.1.1. Theoretical structural validity
The activities in this quadrant seek to determine the internal consistency of the method, meaning the logical soundness of its constructs both individually and as an integrated whole. The first part of this, accepting the individual constructs validity, can be done by literature reviews, including the number of references, the maturity of the construct, and so on. The second part—examining the consistency of the whole—can be done using flow charts of the information flow.

10.1.2. Empirical Structure Validity
One the internal consistency of the model is validated, the next question is whether the method is useful. This must first be done in the context of example problems. The example problems must be similar to both the intended uses of the individual constructs and the problem for which the design method as a whole is intended. Also, the data associated with the example problems must be compatible with drawing a conclusion.

10.1.3. Empirical Performance Validity
The goal of this step is to build confidence in the usefulness of the model in the context of the representative example problems chosen in the empirical structure validation process. It answers, “Can the method produce useful results for the chosen example problems?” This process must show not only that the method yields useful results, but also that the method is the reason for the positive results. Just because the end result is good does not guarantee causality. One way to show that the results are caused by the method is to use another method. Another way is to evaluate the contributions to usefulness from each construct individually.

10.1.4. Theoretical Performance Validity
If the first three steps are completed, then we have built confidence in the model by showing that the individual constructs are accepted at some level of generality, that the method is internally consistent, that the constructs are applied in their intended uses, that the method achieves useful results for specific example problems, and that the usefulness is caused by the use of the method. The open question is whether the method is valid approach in situations other than the chosen example problems?

This is an important question because real world uses will always be a superset of the example problems; nothing can be tested for all circumstances. This step requires a leap of faith. Based on the results of other validation activities, a decision maker must evaluate the circumstantial evidence and decide if it is sufficient to produce belief that the method is in general useful for its intended purpose.

10.2. Verifying and validating my augmented method
In short, I have not consciously verified or validated my augmented method. I have carried out some of the theoretical structural validity, because some of the constructs that I have included (specifically P&B) are used in their intended and generally accepted uses. However, my additions—even the specific ones, such as process management and checkpoints—have not been validated in this manner.
These two steps have undergone some empirical structural and empirical performance validation. For example, in A3 I carefully picked my design project team, created a team contract, and created a project schedule. In A6 my team continued to use these constructs, and we also added a conscious checkpoint before moving on to the next phase of the design process.

As far as my more general augmentations—decisions based design paradigm and risk assessments—I have done even less. I have only begun to internalize the literature on these and to develop my formalization of risk. These have not yet undergone any validation. The original idea was to use the project as the example problem in which to assess the validity, by completing the empirical structural and empirical performance validation. As we did not complete the project, this validation is also incomplete. In the Q4S, I have shown that my risk formulation is compatible with some design examples, but I have not shown any usefulness.
Chapter 11. Closure

I began answering the question for the semester with a particular set of goals. In the opening paragraph of this paper, I stated the context of the course that Farrokh Mistree and Matt Chamberlain have offered me this semester. I acknowledged, “They have built scaffolding for me to learn how to keep learning and to help me define and reach my goals.” In this section of the paper, I assess how well I took advantage of this individual course in a group setting.

11.1. Critical Evaluation of my Answer to the Q4S

One way to keep learning is to identify areas for improvement. Only once I know what I don’t know can I start learning (SEE LEARNING SQUARE). I have benefited greatly from feedback from the course orchestrators while taking my journey through ME 6101. However, there will not always be someone helping to nudge me in the right direction by saying, “This is good. That can be improved. I disagree with this…” and so on. In order to learn to keep learning, I must be able to assess my own performance. In this section, I evaluate what I accomplished by answering my question for the semester.

11.1.1. Summary of accomplishments

As a started to answer the question for the semester, I realized that I needed to establish the context in which I was going to answer the Q4S. I stated my goals for the course and then established a mindset for answering the question for the semester. I also thought deeply about what was guiding my view of engineering design, and I articulated my view that knowledge flow in an engineering design firm is the key to its success.

In CHAPTER 2 I have developed my vision for the year 2020. I have applied three techniques for creating my vision and related aspects of my vision to historical events, analogies, and the work of others. By exploring my vision for 2020 from so many perspectives, I was able to extract some key principles for engineering design in the year 2020 that will guide my research and work both in this class and beyond.

In CHAPTER 3 I developed a requirements list for an augmented design process in the year 2020. This was a monumental undertaking, but I am not too confident in the results. I succeeded at reducing and prioritizing the requirements to a manageable list that was relevant to my goals and vision for the year 2020, but I am not sure they are good requirements because it is difficult to determine if they have been met. I also do not believe that my requirements are well communicated; it is unlikely that someone else could pick up the requirements list and understand what I meant. I have compensated for this some by including my own reflection on the requirements. This discussion is not tight and should be more concise.

I have accomplished a lot in CHAPTER 4. My vision, philosophy, and policies for my company in the 2020 are quite broad in scope and specific in detail. Naturally there are some things that I did not develop in detail, but I left very few things at a superficial level. I have tied my policies back to a central theme and to my vision for 2020. I have added value to other activities by incorporating lessons from my own work experience.
and including an intellectual property rights discussion based on a lecture I attended. There are places where the vision could be tightened. For example, the mode of operation needs to be developed more, but I do not really know enough about corporate structure to do that at this time.

In Chapter 5 I introduce and analyze the Pahl and Beitz method. I have leveraged a good amount of material from Steve Rekuc in this chapter, as well as some of my own work from the summer. Standing alone this would have left me with a very superficial view of Pahl and Beitz, and honestly at this time I don’t remember many of the details of Pahl and Beitz. Consequently, not all parts of my answer to the Q4S fit neatly into their Figure 3.3. However, I did more than summarize the steps of their process.

My real accomplishments in Chapter 5 are in Sections 5.2.1 and 5.2.2 where I abstract the main message and principal points of P&B. This exercise in deep reading, abstraction, analysis, and synthesis was a great personal achievement and tied into my A0 goals. Only after completing this deep reading and deep thinking could I begin to authoritatively identify the shortcomings of the Pahl and Beitz process and begin to augment it.

In Chapter 6 I provide some augmentations that are tightly tied to the P&B process. I have incorporated process management, which emphasizes that the design process in 2020 will not be executed linearly by one team, but rather by distributed teams that sometimes work concurrently. I have also included the use of checkpoints that act as gates between the phases. I have also addressed the different types of design, including subcontracting.

In Chapter 7 I introduce ideas from previous Systems Realization Laboratory work, and I tie them to my vision for 2020, my view of knowledge, and modeling and simulation. My major accomplishment in this chapter was the process of completing it.

I realized that I subscribe to a decision-based design perspective, and that my research interests can be set in this context. I have identified the importance of the systems view, the misguided use of the paradigm of *optimal design*, and related the two to my vision for 2020 in which distributed teams of engineers collaborate on design projects.

As far as answering the question for the semester, I have come up somewhat short in Chapter 7 because there is nothing substantial that can be used now, and I have not related decision-based design back to Pahl and Beitz, as the Q4S asks me to do. I have moved myself in the proper direction for answering the question for the semester and towards achieving my goals by building a foundation for my research, but with regard to just the Q4S, I have not answered it fully.

In Chapter 8 I have introduced and developed my notion of risk. As with Chapter 8, I have only loosely tied this chapter back to Pahl and Beitz. The strongest connection between both of these chapters and P&B comes from the one of the principal points that I identified in Section 5.2.2. There I wrote:

*The formulation of a systematic approach to design has allowed designers to recognize that the design process is...*
really a sequence of decisions. The question in 2020 will be how distributed teams of designers can coordinate their decisions. Each of these decisions is summarized by the following sequence:

- Abstract (identify crux of problem)
- Search for solutions
- Combine solution variants
- Evaluate solution variants
- Choose a solution

The emphases for decision-based design are on the last two steps—evaluate and choose. My inclusion of risk into the decision process affects the evaluation stage; I am formalizing another object to include in the evaluation.

### 11.1.2. Short-comings and limitation of answer

The primary limitation of my work is that it is incomplete. I have identified that process management needs to be included as a recurrent step in the process, and I have explained some of the tasks to be done in that step, but I have not fully answered how they could be executed.

This is even more true for my discussion of decision-based design and risk. The content of these two chapters is not tied neatly back to Pahl and Beitz, and it is not mature enough to be used in practice. There are several areas where my understanding of the subject is still weak—specifically in the DSP technique and game theory. Because I have not internalized these subjects, I cannot use or augment them to include my formalization of risk, since measures of risk only have value when used as part of a decision.

There is another limitation with my formalization of risk. There are several places in which I have noted it might be hard to estimate the probabilities or consequences. Many engineering applications will fall into these areas. Therefore, my formalization is not very practical at this time.

### 11.1.3. Identification of Additional Work

For me personally, I have additional work to do in the areas of internalizing the DSP technique, game theory, and some other earlier Systems Realization Laboratory work. I must also relate risk to these subjects as I begin to understand them better. I would also like to pursue the notion of concurrent design and its relationship to decision making, game theory, and knowledge flow.

In general, the notion of risk needs to be expressed formally and incorporated into the design process. Also, the tension between concurrent engineering and the systems view must be resolved. I have presented some ways of dealing with this, but I’m not sure that they will work in practice. There is a long way to go in these areas, and they are essential research topics. Until the process of coordinating the decisions of individuals within and across teams is formalized, there can be little progress in creating tools to support the process.
11.2. **Utility**

### 11.2.1. Has the Q4S been answered?

My personalized question for the semester is:

> How should the Pahl & Beitz systematic design method be augmented and personalized to include risk assessments, simulations, and better reuse of knowledge while supporting the realization of technical products and processes for a distributed design environment in the year 2020?

I have answered several parts of this question.
- I have presented specific augmentations to the Pahl and Beitz method that address the realization of technical products and processes for a distributed design environment in the year 2020.
- I have addressed the role of simulations, knowledge reuse, and risk assessments in the realization of technical products and processes for a distributed design environment in the year 2020.
- I have begun to formalize risk so that it can be incorporated into decision criteria in design.
- I have understood and accepted the role of a systematic design method for a distributed design environment.
- I have developed a corporate philosophy for a design company operating a distributed design environment in the year 2020.

There are other parts of the question that I have not answered
- What are the augmentations to the P&B method that address the inclusion of risk assessments, simulations, and knowledge reuse into design?
- How exactly can risk be estimated and incorporated into decisions?

I believe that my work this semester has been directed towards answering the question for the semester. I am surprised how I lost some focus and did not try to tie certain ideas directly into Pahl and Beitz. It appears that my goals and research direction guided my work more strongly than my personalized Q4S.

Despite this lack of focus in the end, I believe that I satisfied the motivation for the question for the semester. I have thought about the future and the changes that my vision of the future necessitates in the design process. I have internalized the Pahl and Beitz approach to design, although I can’t dictate every step of the process. I have also thought about design from a larger perspective, including adopting the perspective of decision-based design, and I have grounded my research interests in this context.

### 11.2.2. Analysis of Progress towards my A0 Goals

I articulated my A0 goals in the introduction to this paper as follows:
11.2.2.1. Primary Goal

I have not completed my primary goal. Chris Paredis and I agreed that I do not have enough material prepared to finish a paper by DETC 2004 submission deadline at the end of January 2004. However, my answer to the question for the semester has helped me to move towards this goal.

My view of knowledge in an engineering firm, my acceptable of a decision based design paradigm, and my formalization of risk will all help me eventually write a paper suitable for submission to DETC or another conference. By completing and including these topics in my A2Q4S I have forced myself to think deeply about several things. My understanding of these topics, combined with my efforts to relate them to my interests and other work, have helped to crystallize my ideas and to provide a context for my work. It has also helped me identify areas in which I need to do more.

By attempting to direct my A2Q4S towards my primary goal, I dug deeply into these issues. By setting my primary goal as I have, I have folded my research for this semester into the ME 6101 course. The end result of this effort was the discovery that I needed to expand my knowledge foundation much more than Chris and I believe at the beginning of the semester.

Despite falling short of my goal, I have received a lot of value from my progress towards my goal. My fear entering ME 6101 was that I would put in lots of work but have nothing to show for it after December 13, 2003. My primary goal has helped me to focus on generating value for my future work and longer term goals. As I anticipated when I set my primary goal, “The specificity required for a paper will help direct my attention towards actually formulating and synthesizing my thoughts in a consistent and presentable manner,” and this will help me to advance in my research.
11.2.2.2. Secondary goal
I have not achieved my secondary goal because I have not presented specific augmentations to the P&B process along the lines of these topics. However, the goal did direct my personalization of the question for the semester. By trying to meet his goal and to answer the related question for the semester, I confronted several issues.

For example,

My secondary goal primarily served to guide the way in which I pursued my primary goal. Although I did not augment P&B to include these tools, it was valuable to address each tool and to try to relate them to my vision for design in the future. The real value was in recognizing that I need an overarching philosophy or paradigm for approaching design; otherwise I can’t answer where there are opportunities to use or develop tools.

11.2.2.3. Deep reading goal
In the long run, I may have gotten the most value out of my efforts to meet this goal. This is one of the ways that I have learned to keep learning. In the future, I will be able to deep read and think deeply better than before. This will allow me to keep learning on my own, without a course orchestrators providing scaffolding.

Farrokh was very pleased with some of my efforts in this area, and I surprised myself by my ability to draw relationships and abstract the key lessons from my reading. I have recognized the value of deep reading. I can definitively say that my deep reading skills have improved significantly, but I have a lot more room for improvement. Among other things, I would like to improve the speed at which I deep read, and the efficiency of my reflections. Currently I get nice results, but with a high cost. Since value = benefit/time, I need to reduce the time while maintaining and increasing the benefit.

11.2.2.4. Group design goal
This goal is more related to the design project in ME 6101. However, since the project is tied directly to my Q4S, it is somewhat relevant here. Because my Q4S was related to my longer term goals and research interests, the project was, too, and it therefore had value beyond the task itself. It was also efficient to use the design project as an opportunity to pursue a systematic approach, because I could learn by doing.

11.2.2.5. 2020 vision goal
I have met this goal by creating a vision for design in 2020 and by articulating a corporate philosophy for 2020. I employed several methods for developing this vision, including exploration by analogy, leveraging the opinions of others, and drawing from my own experience. The ability to look to the future will help me to be a better strategic thinker, which will help me to position myself for the future. Hopefully I can be like Wayne Gretsky and “skate to where the puck is going to be.”
11.2.2.6. **Qualifier Goal**

I met this goal while completing my A1B. By abstracting and analyzing the main theme and principal points of Pahl and Beitz, I internalized the core of their approach. My understanding of these main ideas should help me on the design qualifying exam. My use of the P&B process to design the design project (which isn’t really part of my A2Q4S) has also helped me to meet this goal.

11.3. **Lessons Learned**

I learned a lot of lessons on my journey through ME 6101 and by formulating and answering my question for the semester.

**Writing helps learning**

The course orchestrators have introduced the ORA construct: observe, reflect, and articulate. The use of the ORA construct and deep reading approach really helped me learn a new way to learn. What I learned most from pursuing these approaches was the value of writing things down. First, writing helps to make sure you are really executing the ORA process, and not merely thinking you are doing each step. Second, I found the action of writing made me consciously aware of more things.

I discuss this more in my semester learning essay, but I summarize my ideas here. I have shown the learning square in Figure 26, and I have added arrows showing which writing activities can help me move to the know I know quadrant. I include two types of activities, the learning essays in which I complete the ORA process, and then a learning diary, in which I record my lessons learned. In summary, the Learning Diary helps to move knowledge from the unconscious to the conscious, and the learning essays help to create knowledge, and move me from incompetent to competent.

![Learning Square](image)

**Figure 26: The role of a learning diary and learning essays in learning**

11.3.1. **Learning to create and add value**

By writing my corporate philosophy: In addition to *creating* value by writing this essay, I *added* value to existing works. For example, I took the ASME talk on intellectual property rights that I attended and tied aspects of it in to my vision for 2020. I also
leveraged some of Bjoern Avak’s LE 10, in some cases using his ideas and in other cases building from them.

I also built off of my own life. Part of the process I followed in writing this paper was reflection on my own work experiences. As I recognized aspects that worked and aspects that didn’t, I tried to relate them to what I would do in a company in 2020. I believe that anyone can find fault with policies, but it takes a more extraordinary individual to be able to suggest specific changes.

Finally, the benefit of insight into the type of company where I would want to be an employee will linger the long. This course will only last a few more weeks, and my graduate studies a few years. However, my career should last 30 or more years. If I don’t recognize what I want, I won’t find it. To use the analogy one more time, when you start a journey, you’d better know where you are going, or you’ll never get there; instead, you’ll get to where someone else wants you to go (comment motivated by some of Farrokh Mistree’s various pontifications).

11.3.2. Learning to use a systematic approach

In my assignment 1B, I stated the main message of P&B as the following:

The main goal of an engineering design methodology should be to guide the designers down the correct path. Without a systematic approach, it is unlikely that designers will choose the correct path, and without the correct path, it is unlikely that the correct solution will be found.

Through my work and reflection during ME 6101, I have learned to accept this view. In addition to learning how a systematic process can be useful, I have also learned about myself and my reasons for shying away from systematic approaches. By identifying these reasons, I was able to challenge them, and hopefully I will eventually reject them completely.

11.3.3. Role of knowledge

A company’s employees are the key to a company’s success; it is the knowledge of employees and their willingness and ability to share their knowledge with their coworkers and to apply their knowledge to their work that creates value for the company. This is a prerequisite for the effective use of knowledge managements systems, because the knowledge has to come from somewhere.

11.3.4. Importance of altering perspectives

Engineering design is about solving problems by finding ideas and making decisions. In order to find good solutions and make good decisions, an individual must be able to employ multiple perspectives. When forming design teams, managers should seek to form a group that has diversity of mind.

Once teams are formed, there are attention directing tools such as the six thinking hats that can help individuals change their perspective. Individuals can also explore things via analogy; making the familiar strange and the strange familiar may help one develop new insights.
11.3.5. Human-computer cyborg
The role of the human in engineering design is still indispensable. The question that academic researchers such as myself should be trying to answer is how can tools be used to extend these abilities. The interaction of the human and the computer will improve the design process.

The use of the human-computer cyborg concept is a great way to capture this relationship. Unfortunately, it took me a while to understand what was meant by the cyborg, because the term cyborg has been used in less constructive ways. Therefore, the term cyborg might not be the best for communication this notion, but it is a terrific way to think about it. The notion allows for a view in which more and more tasks can be pushed on the computer; its role in the design process will increase, leaving more of the human designer’s bounded rationality available for tasks that the computer is not capable of doing.

11.3.6. Complexity of process
The process of engineering design is a lot more complex than the P&B approach realizes. The design process is broken into tasks that are assigned to different teams. Even if the teams are colocated, there are a lot of issues involved in coordinating them. The overall design will be better if teams focus on the systems view of the task instead of looking myopically at their own tasks. However, between the teams will act independently yet their designs interact with each other, this will be difficult. Future design tools and methods must recognize these independencies. Ideally the tasks would be broken down such that they are decoupled, but this will rarely be possible. The interfaces between teams—both the inter-team communications and the inter-task dependences—will determine the success of the design project.

11.3.7. Self evaluation
It was very difficult to evaluate my performance in my A2Q4S. I have put so much effort into this and attempted to address the things that I thought were most important. There were certain things that I set out to achieve and didn’t, but for the most part I completed was I set out to complete. Therefore, it is difficult to step back, especially as the purpose of this paper was to help myself. I was able to assess which parts of my goals I achieved and to identify certain areas where I need to do more work as I continue my research. However, on the whole, I am really pleased with my work and presentation in this paper. Therefore, it is hard to tell whether I am being too easy on myself, or whether I really did achieve what I think I did.
References


Klein, K. (2003). Answer to the Question for the Semester, Georgia Institute of Technology.


## Appendix A

### LEGEND

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### Facilitate creation of computer tools

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### Capable of being improved/optimized

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### Structure the tasks and responsibilities

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### Make the tasks more structured and aligned with tasks

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### Make iteration loops smaller and less frequent

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### Encourage creativity

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### Foster understanding

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<td>Allow for efficient elimination of weak ideas</td>
<td>TOOLS</td>
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<td></td>
<td>Reduce size of repeated step when reach failure</td>
<td>METHOD</td>
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<td>Knowledge Management</td>
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<td>Encourage the capture of knowledge, information, and decisions</td>
<td>METHOD</td>
<td>+  ?  + + + + + +</td>
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<td></td>
<td>Encourage the use of the computer to store knowledge</td>
<td>METHODS</td>
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<td></td>
<td>Easier distribution</td>
<td>TOOLS</td>
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<td></td>
<td>Faster search</td>
<td>TOOLS</td>
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<td></td>
<td>Visualization tools</td>
<td>TOOLS</td>
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<td></td>
<td>Incorporate searches of repository into solution finding</td>
<td>METHOD</td>
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<td></td>
<td>Use documentation as summary of repository or as procedural directions</td>
<td>METHOD</td>
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<td></td>
<td>Check for consistency of final design and knowledge repository</td>
<td>METHOD</td>
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<td>Check for consistency between repository and</td>
<td>METHOD</td>
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<td>Task</td>
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<td>Tools</td>
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<td>Encourage explicit discussion and agreement about process (reduce assumptions)</td>
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<td>Help cross linguistic boundaries</td>
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<td>Provide a framework for each of the following tasks</td>
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<td>Clarify</td>
<td>TOOLS</td>
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<td>Abstract</td>
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<td>Ideate</td>
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<td>Qualitative Evaluation</td>
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<td>Decide</td>
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<td>Coordinate People</td>
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<td>Coordinate Resources</td>
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<td>Coordinate Information and knowledge</td>
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<td>Prioritize</td>
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<td>Support the search of knowledge repositories</td>
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<tr>
<td>Encourage and support tinkering</td>
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<td>Incorporate the use of prototypes early in design</td>
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<td>Integrate the use of modeling and simulation at multiple levels of abstraction, from the system view down to component analysis</td>
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<td>Direct consideration of what is possible to do using a computer</td>
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<td>Support evaluation of what is valuable to do using a computer</td>
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<td>Support selection of how to use the computer</td>
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<td>Frontier Requirements</td>
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<td>Help you bring the correct tools to the table</td>
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<td>Help you anticipate, react, and adapt quickly</td>
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<td>Encourage support structures to develop</td>
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<td>Help you get in the game first (reduce time to market)</td>
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<td>Help you stay strong (adaptive and variant design)</td>
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<td>Stretch the bounds of creativity and innovation</td>
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<td>Protect the environment and resources—including corporate resources—that you have</td>
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