Question for the Semester (Q4S)

An Adaptive Systems Design Method (ASDM)

Prepared for:
Farrokh Mistree
Jitesh Panchal

Written by:
Nathan Young

Engineering Design
ME6101A
Georgia Institute of Technology
Department of Mechanical Engineering
Atlanta, GA
Executive Summary:

The future will be dominated by paradigm shifts to agile enterprises and technological advancements. Behind these future shifts are forces that drive or encourage future change. I have termed these forces drivers. I view these shifts as a collective product of three future changes: a dynamic business sector, globalization, and technological advancements. With this World of 2020, I develop a design method based upon the Paul & Beitz (P&B) systematic design method. To adequately perform this task, a requirements list is constructed to guide the formation of an augmented and personalized design method.

After performing a gap analysis of P&B in the context of my World of 2020, I propose an augmented and personalized design method based on the Pahl and Beitz systematic design method. I integrate personalizations and augmentations into the P&B design method to achieve a systematic design method for the strategic design of adaptive systems.

I used my project, the comparison of systematic design to self-organizing systems, as means to validate my proposed Q4S method. At this point, I introduce the means by which I intend to validate my method. I evaluate the requirements list to identify which requirements were met by my method. Finally, I identify the learning experience that transpired while I developed my Q4S.
# Table of Contents:

Table of Contents:........................................................................................................... 3  
Table of Figures:................................................................................................................ 5  
Chapter 1: Framing the Q4S .................................................................................. 6  
  1.1 Context for the Q4S ..................................................................................... 6  
  1.2 Original Q4S ............................................................................................. 6  
  1.3 Interpreting the Q4S .................................................................................. 6  
  1.4 Vision of 2020 from Q4S Interpretation ...................................................... 7  
Chapter 2: World of 2020 .................................................................................... 8  
  2.1 Drivers of 2020 ........................................................................................ 8  
    2.1.1 Dynamic Business Sector: ................................................................. 9  
    2.1.2 Globalization: .................................................................................. 10  
    2.1.3 Technological Advancements: .......................................................... 11  
  2.2 Driver Metrics ............................................................................................ 12  
  2.3 Analysis of Paradigm Shifts for Drivers and Metrics .............................. 13  
    2.3.1 Paradigm Shifts: ............................................................................. 14  
    2.3.2 Extension of Paradigm Shifts Towards Shaping Tweaked Q4S: ...... 14  
Chapter 3: Tweaked Q4S .................................................................................... 15  
  3.1 Context for the Tweaked Q4S ................................................................ 15  
  3.2 Tweaked Q4S ......................................................................................... 15  
  3.3 Answering the Tweaked Q4S ................................................................ 15  
    3.3.1 Tweaked Q4S Clarification: ............................................................... 15  
    3.3.2 Tweaked Q4S and the Need for Systematic Design: ................... 16  
Chapter 4: P&B Design Method ......................................................................... 17  
  4.1 Overview of P&B Design Method ............................................................... 17  
  4.2 Explanation of P&B Phases and Steps ...................................................... 19  
    4.2.1 Product Planning and Clarification of the Task: .............................. 19  
    4.2.2 Conceptual Design: ...................................................................... 19  
    4.2.3 Embodiment Design: .................................................................... 19  
    4.2.4 Detail Design: ................................................................................ 19  
  4.3 Identification of Core Transformations ...................................................... 20  
  4.4 Developing the Requirements of P&B ...................................................... 20  
  4.5 Gap Analysis of P&B Requirements ....................................................... 22  
    4.5.1 Post Realization Product Improvement: ........................................ 23  
    4.5.2 Reconfigurable Enterprises: ............................................................... 23  
    4.5.3 Technological Capabilities: ............................................................... 24  
    4.5.4 Adaptive System Design: ................................................................. 24  
  4.5.5 Application of the Gap to my Augmented Method: ........................... 26  
Chapter 5: Augmented Method ........................................................................ 27  
  5.1 Requirements List for 2020 .................................................................... 27  
    5.1.1 Overview of Requirements: ............................................................ 27  
    5.1.2 Explanation of Requirements: ....................................................... 28  
    5.1.3 Application to Augmented P&B Design Method: ....................... 31
5.2 Augmented and Personalized Design Method ................................................................. 32
  5.2.1 Overview of Augmented and Personalized Method: ................................................. 32
  5.2.2 Explanation of Phases and Steps: .............................................................................. 34
Chapter 6: Verification and Validation .................................................................................. 43
  6.1 What is the Validation Square? ....................................................................................... 43
  6.2 Theoretical Structure Validation (Square 1) ................................................................ 43
  6.3 Empirical Structural Validation (Square 2) .................................................................. 43
  6.4 Empirical Performance Validation (Square 3) .............................................................. 43
  6.5 Theoretical Performance Validation (Square 4) ............................................................ 43
  6.6 What Aspects were Verified using the Project? ............................................................... 43
Chapter 7: Critical Evaluation of Augmented Method ............................................................ 43
  7.1 Limitations of Augmented Method ................................................................................. 43
  7.2 Future Research Questions ............................................................................................. 43
  7.3 Utility ................................................................................................................................ 43
    7.3.1 Value with Respect to Project: >1 ........................................................................... 43
    7.3.2 Value for A0 Goals: >1 .............................................................................................. 43
Chapter 8: Learning Experience ............................................................................................. 43
  8.1 Learning from Answering the Q4S ................................................................................. 43
    8.1.1 Principles of Adaptive Systems ................................................................................. 43
    8.1.2 Systematic Design ....................................................................................................... 43
    8.1.3 Future Engineering Requirements ............................................................................ 43
    8.1.4 Critically Evaluating my own Work and the Work of Others .................................. 43
    8.1.5 Utility of the Validation Square ................................................................................. 43
    8.1.6 Structuring a Document ............................................................................................ 43
  8.2 What Would I do Differently Next Time? ....................................................................... 43
Works Cited: ........................................................................................................................ 43
# Table of Figures:

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1</td>
<td>Affinity diagram for drivers of 2020</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Metrics for drivers of 2020</td>
<td>12</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>P&amp;B</td>
<td>18</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Core transformations of P&amp;B.</td>
<td>20</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Requirements list for P&amp;B</td>
<td>22</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>Augmented P&amp;B requirements list</td>
<td>28</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Generalized personalizations and augmentations to P&amp;B.</td>
<td>33</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>Product planning and task clarification phase of augmented method</td>
<td>34</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>Market segmentation grid</td>
<td>35</td>
</tr>
<tr>
<td>Figure 5.5</td>
<td>Basic TIES process</td>
<td>37</td>
</tr>
<tr>
<td>Figure 5.6</td>
<td>Conceptual design of augmented method</td>
<td>38</td>
</tr>
<tr>
<td>Figure 5.7</td>
<td>Global information flow map for adaptive system</td>
<td>39</td>
</tr>
<tr>
<td>Figure 5.8</td>
<td>Simplified voting mechanism for global emergent behavior</td>
<td>40</td>
</tr>
<tr>
<td>Figure 5.9</td>
<td>Relationship between reliability and agent specialization</td>
<td>42</td>
</tr>
<tr>
<td>Figure 5.10</td>
<td>Complexity relative to the number of agents</td>
<td>42</td>
</tr>
<tr>
<td>Figure 5.11</td>
<td>Summary of Steps of Utility-Based Selection Decision Support Problem</td>
<td>44</td>
</tr>
<tr>
<td>Figure 5.12</td>
<td>Embodiment design of augmented method</td>
<td>46</td>
</tr>
<tr>
<td>Figure 5.13</td>
<td>Iterative testing method for error and weak spot checks</td>
<td>47</td>
</tr>
<tr>
<td>Figure 5.14</td>
<td>Detail design of augmented method</td>
<td>48</td>
</tr>
<tr>
<td>Figure 5.15</td>
<td>Post realization product improvement of augmented method</td>
<td>49</td>
</tr>
<tr>
<td>Figure 5.16</td>
<td>Validation Square</td>
<td>51</td>
</tr>
<tr>
<td>Figure 6.1</td>
<td>Information flow in the Validation Square</td>
<td>52</td>
</tr>
<tr>
<td>Figure 7.1</td>
<td>Evaluation of requirements list</td>
<td>54</td>
</tr>
</tbody>
</table>
Chapter 1: Framing the Q4S

1.1 Context for the Q4S

- We imagine a future in which geographically distributed engineers collaboratively develop, build, and test solutions to design-manufacture problems encountered in the product realization process.
- We recognize that solutions evolve over time. Accordingly, we expect you to build on what has been done before.

1.2 Original Q4S

In this context, we want you to provide a method to support the realization of products for a global marketplace through distributed design and manufacture. Specifically, how should P&B systematic design method be personalized and augmented to support the realization of products for a global marketplace in a distributed environment?

1.3 Interpreting the Q4S

Before I can sufficiently answer the Q4S, I must adequately interpret the originally stated question. Within the original Q4S, there are several keywords that require an in depth interpretation to clarify the context with which they were proposed. These keywords are support, global marketplace, distributed, systematic, design method, personalized, augmented, and realization.

- **Support** – The prescription of guidelines that can be modified to conform to a desired task. This design process will cannot fully encompass every need of the world of 2020, but will act as a framework for design.
- **Global Marketplace** – This term refers to the initiation of new marketplaces due to the expansion of job markets in the world of 2020. New marketplaces will arise from the increased average wages in previously unexploited labor resources.
- **Distributed** – Distributed refers to a design environment that is operable despite geographic dispersion. Distribution will be the result of globalization and the necessity for organizations to expand and transform to maintain a competitive edge.
- **Systematic** – To me this term refers to a set of guidelines that provides sequential manner to accomplish a goal.
- **Design Method** – Provides the process to accomplish a design goal.
- **Personalized** – The “soft” side of engineering and design has its place here. Each one of us values one idea or concept above the others. In personalization of a design process, we develop a system in tune with what we consider critical in the world of 2020.(Raghu 2001)
- **Augmented** – Augmenting a process or article involves improving the current condition of a process/article by adding to it in a constructive and well thought out
manner. For the Q4S, the method needs to be augmented so it will be better suited for my world of 2020. (Raghu 2001)

- **Realization** – For me, this term encompasses the entire process from the inception of a product idea to the final distribution of the product.

### 1.4 Vision of 2020 from Q4S Interpretation

From the interpreted Q4S, I have abstracted a generalized vision for 2020. Within this vision are two prime factors that will influence the future of engineering design. These factors are a global marketplace and distributed design environment. Although I have defined the factors above, there are far greater connotations attached to the words. For my vision of 2020, these connotations include a future dominated by agile enterprises that react to a dynamic marketplace by utilizing cutting edge technological advancements. I elaborate in great detail on my vision of 2020 in Chapter 2: World of 2020 where I identify the primary drivers, metrics, and paradigm shifts that are catalysts of the future design environment.
Chapter 2: World of 2020

As stated previously, the future will be dominated by paradigm shifts to agile enterprises and technological advancements. Behind these future shifts are forces that drive or encourage future change. I have termed these forces drivers. In the following text, I elaborate on what my world of 2020 entails and how it affects the future of engineering design.

2.1 Drivers of 2020

As stated above, I have identified two paradigm shifts of the future. I view these shifts as a collective product of three future changes: a dynamic business sector, globalization, and technological advancements. I have displayed the aforementioned future changes and corresponding drivers in Figure 2.1.

As I have listed in Figure 1, the drivers in 2020 have many components which contribute to the overall driving force. From my three drivers, the dynamic business sector and its components form the foundation of my world of 2020.
2.1.1 Dynamic Business Sector:

A dynamic business sector is a current trend that has been particularly driven by the information revolution due to the internet. I believe that this trend will continue and even accelerate in the future. In the future, enterprises will be forced to adapt to a dynamic business sector to attain acceptable profit margins. In this context, I have defined a dynamic business sector as the combination changing markets and reconfigurable enterprises. With this in mind, a changing market would be the continually shift in the demand for commodities and a reconfigurable enterprise would be an adaptive company capable of altering its business structure to accommodate a dynamic marketplace.

Reduced Time to Market:

Ultimately, this dynamic business sector will be the result of concurrent engineering practices and reconfigurable enterprises. Concurrent engineering practices will greatly reduce the relatively large process times required for planning and conceptual design. By employing these design practices, enterprises will reduce the design cycle time thus increasing profit margins in the process.

Like concurrency in design, reconfigurable enterprises will contribute significantly to the manipulation of a business structure to employ supply chaining and outsourcing throughout the design process. This type of reconfiguration can best be explained through virtual corporations in which a core group of employees manages a network of outsourced solution providers. This type of corporation will empower smaller corporate entities in the future. Through this empowerment, competition will increase through the continual effort to reduce design cycle times and improve profit margins.

Customer Centric Market:

A customer centric market is yet another feature of a dynamic business sector that will require the involvement of the customer in the design process. A customer centric marketplace will be determined by the enterprise’s ability to employ mass customization as a means to increase the quality of each product with reference to each customer’s requirements and reduce cycle times as enterprises allow the customer to participate in product planning. I feel as though these practices are best articulated by examples of currently, successful enterprises.

Current companies that have employed mass customization to achieve success among competitors are Dell and Nike. As a manufacturing enterprise, Dell does not keep a stock of computers. Dell makes each computer upon the request of the customer. I believe that this is a root cause of their success. It makes customers feel as though they have control over their product's cost in a sense that they are not wasting money on (in their mind) superfluous features. Another example is Nike. They allow customers to customize shoes with their names, personalized colors, or designs. I believe that these features have distinguished these companies from their competitors and are the core reasons for their increased success in terms of profit.
2.1.2 Globalization:

In my context, I am referring to globalization in much the same way Friedman refers to “Globalization 3.0” in his book the *The World Is Flat*. The following excerpt from the popular book outlines this definition in detail (Friedman 2005):

“Globalization 3.0 is shrinking the world from a size small to a size tiny and flattening the playing field at the same time. And while the dynamic force in Globalization 1.0 was countries globalizing and the dynamic force in Globalization 2.0 was companies globalizing, the dynamic force in Globalization 3.0 – the force that gives it its unique character – is the newfound power for individual to collaborate and compete globally. And the phenomenon that is enabling, empowering, and enjoining individuals and small groups to go global so easily and so seamlessly is what I call the flat-world platform, which I describe in detail in this book.”

Through the empowerment of individuals and emergence of small, powerful companies across the world, international markets will emerge and demand mass customization to meet their specific expectations. Through this emergence of international markets, engineering expertise will be geographically dispersed to exploit thriving intellectual resources.

*International Market:*

As mentioned above, mass customization will play an important role in the accommodation of customer requirements. With respect to international markets, this still holds true. Through mass customization, companies will become more globalized due to the increase in competition for new international markets. This increase in competition will be the result of the development of thriving technological infrastructures in previously third world countries (i.e. India and China). This technical infrastructure will require significant technical expertise. All enterprises, not just corporate superpowers, will realize this intellectual resource and exploit it thus creating new international markets and geographically dispersed engineering expertise.

*Geographic Dispersion of Engineering Expertise:*

As mentioned above, engineering expertise will be geographically dispersed to employ the core competencies contained in a distributed engineering environment. By taking advantage of these core competencies, enterprises will outsource to achieve the most productive combination of resources while maximizing their profit. This will result in an overall growth in international markets satisfaction as it will result in a more quality product due to the exploitation of individual core competencies. Although international markets will further develop due to geographic dispersion of engineering expertise, there are still barriers that prevent the type of collaboration that will be present in the future. Some of these barriers reside in the requirement of technological advancements to progress international collaboration.
2.1.3 Technological Advancements:

By the year 2020, much technological advancement will occur. Below I have included three plausible, primary drivers of technological advancement that will significantly contribute to the progression of engineering design. These drivers include advancements in communication systems, data formats, and mechanical system design.

Communication Systems:

International collaboration among engineers will require significant advances in language neutral communication technology. By employing language neutral communication systems, collaboration will greatly increase as the interaction among distributed engineers will become more natural. Design teams will no longer be required to be centrally located. Ultimately, this type of technology will be the result of innovations in computer power pertaining to translation programs and video software. (Jeram 2002)

Standardization of Data Formats:

Advancement in computational technology will also contribute significantly to the standardization of data formats. By standardization of data formats, I am referring to the development of software interfaces that translate files into unified formats which increase the portability of files across all related software platforms. This would be comparable to the byte coder employed by the JAVA programming language which enables its portability across all platforms.

Adaptive Mechanical Systems Increase Reliability:

The next logical step in systems design is adaptivity. By adaptivity, I am referring to a system’s ability to adapt its control mechanism i.e. control system or software algorithm to accommodate environmental variations to produce a reconfiguration of its system architecture or performance. Before, these systems can be explained; the state of systems design must be articulated. Currently, we design systems based upon a phenotypical approach, whereby a function is determined based upon a requirement and a structure is developed to accommodate that function. By analyzing evolutionary biology, it has become apparent that this process is somewhat backward with respect to the emergence of natural phenotypes; thus, to enable adaptivity of a systems configuration there must be an evolution of sorts with respect to both the control mechanisms and the system configuration be it architecture or configuration.

I envision future systems employing “evolvability,” where the term evolvability, is best explained in the following definition. (Wagner 1996)

“For adaptation to occur, these systems must possess “evolvability,” i.e. the ability of random variations to sometimes produce improvement. It was found that evolvability critically depend on the way genetic variation maps onto phenotypic variation, as issue known as the representation problem.”
Since this definition is posed in terms of biological phenomena, I must extend the meaning beyond that of the life sciences to engineering. In my context, I adopt the term random variations to include the reconfiguration of the physical system. For example, in multi-agent robotics it is common for agents, individual robots, to manipulate their behavior based upon external cues and objectives. With this broad example, the manipulation of behavior can be extended to correlate to the variation of the genetic map mentioned above.

Like a genetic map, the algorithm or controller governs the behavior of a system. By creating an adaptive algorithm or controller, it would be plausible to induce emergent behavior in the system; hence, varying the phenotype of the system.

Finally, the adaptation of both the system’s control and architecture would result in an increase in the system’s reliability as it would be capable of adapting to variations in operating parameters.

### 2.2 Driver Metrics

Now that the drivers have been elaborated upon, it is necessary to propose a metric to determine how the driver will be measured. Also by developing metrics, the plausibility of the driver is confirmed with respect to the impacts it will have on engineering design. In Table 2.1, I have listed metrics corresponding to each driver I developed above. These metrics include design cycle time, customer satisfaction, geographic distribution, level of robustness, errors in communication, and the transfer of data. Clear explanations of how these terms apply to metrics will be introduced below.

<table>
<thead>
<tr>
<th>Context</th>
<th>Drivers:</th>
<th>Metrics:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Business Sector</td>
<td>Reduced Time to Market</td>
<td>Design Cycle Time</td>
</tr>
<tr>
<td></td>
<td>Customer Centric Marketplace</td>
<td>Customer Satisfaction</td>
</tr>
<tr>
<td>Globalization</td>
<td>International Markets</td>
<td>Customer Satisfaction</td>
</tr>
<tr>
<td></td>
<td>Distributed Engineering Expertise</td>
<td>Geographic Distribution</td>
</tr>
<tr>
<td>Technological Advancements</td>
<td>Adaptive Systems</td>
<td>Level of Reliability</td>
</tr>
<tr>
<td></td>
<td>Communication - Language Neutral</td>
<td>Errors in Communication</td>
</tr>
<tr>
<td></td>
<td>Standardization of Data Formats</td>
<td>Transfer of Data</td>
</tr>
</tbody>
</table>

**Design Cycle Time:**

Design cycle time is a measure of how long a product takes from product planning to full realization. This can be evaluated based upon a relative comparison of comparable products such as a Ford 2000 year car model relative to a 2006 year car model. This provides a relative evaluation for a reduction in time to market.
Customer Satisfaction:

As I mentioned in my drivers, mass customization will play an important role in meeting both the requirements of customer centric market, where the customer is integrated into the planning phase, and the opening of international markets. Customer satisfaction will be a measure of how well the needs of these individuals are met through post launch evaluations.

Geographic Distribution:

Companies are constantly searching for more cost efficient means to develop products. This is evident in the current utilization of vast intellectual resources in India and China. A measure of the geographic distribution of a design team will be necessary to determine current trends in the distribution of engineering expertise.

Level of Reliability:

Adaptive systems will be evaluated based upon their reliability. This reliability will be evaluated by testing the systems to determine their continuous operation despite hostile environmental variations or noise.

Errors in Communication:

As stated in my drivers, language neutral communication will be a significant advancement in communication technology. This will enable the geographically dispersed engineers mentioned in the previous metric to seamlessly interact. The quality of language neutral communication will be evaluated by the amount of communication errors (i.e. mistranslations).

Transfer of Data:

In the future, file formats will be seamlessly exchanged between operating systems. Current efforts by Apple Inc. are making this possible. In the future, this will apply to design software; thus, reducing the time engineers spends on frustrating file conversions. The transfer of data will be measured by the number of different file formats for general use software (i.e. Pro E, Catia, etc.)

2.3 Analysis of Paradigm Shifts for Drivers and Metrics

First of all, I will define a paradigm shift in my own context. A paradigm shift is a significant change in the way design practices are thought of and carried out. By analyzing both my drivers and metrics for my world of 2020, I have developed two primary paradigm shifts that will be significant in the future. These paradigm shifts include a shift to agile enterprises and adaptive systems design.
2.3.1 Paradigm Shifts:

*Static Enterprises to Agile Enterprises:*

Due to significant calls for a reduction in time to market and mass customization, business enterprises must adapt to the increased competition that will meet the growing demands of the customer. In this context, I denote most current corporations as static. I am loosely using the term static to refer to a corporation that is slow in turnover and adapting to the emergence of new markets. In the future, static companies will not meet competitive requirements of a dynamic marketplace and be surpassed by more agile enterprises. This agility will arise from the reduction in time to market and mass customization.

*Traditional Systems to Adaptive Systems:*

As mentioned above in my World of 2020, adaptive systems will be a significant force in increasing system reliability. For this increase to occur there must be a paradigm shift in the way that systems are designed to proactively account for the variability that is necessary to induce system reconfiguration. By developing a design method to account for this type of design, the efficiency and cycle time of these systems will be increased and reduced, respectively; thus pleasing the customer.

2.3.2 Extension of Paradigm Shifts Towards Shaping Tweaked Q4S:

As mentioned above, agile enterprises capable of developing adaptive systems will be successful in a dynamic business sector. Before this success can take place, certain steps must be taken to ensure that the theoretical principles and design procedures are developed for the design of adaptive systems in a dynamic market. These steps are elaborated below in the development of and answer to my tweaked Q4S.
Chapter 3: Tweaked Q4S

In the following text, I have augmented and personalized the original Q4S shown below. By augmenting and personalizing the Q4S, I have developed a clear, concise question that leads me towards the development of a method for the strategic design of adaptive mechanical systems.

Original Question for the Semester:

“In this context, we want you to provide a method to support the realization of products for a global marketplace through distributed design and manufacture. Specifically, how should P&B systematic design method be personalized and augmented to support the realization of products for a global marketplace in a distributed environment?”

3.1 Context for the Tweaked Q4S

- We imagine a future in which geographically distributed engineers collaboratively develop, build, and test solutions to design-manufacture problems encountered in the product realization process.
- We recognize that solutions evolve over time. Accordingly, we expect you to build on what has been done before.

3.2 Tweaked Q4S

In this context, we want you to provide a method to support the realization of products for a global marketplace through distributed design and manufacture. Specifically, how should P&B systematic design method be personalized and augmented to support the strategic design of adaptive systems for a global marketplace in a distributed environment?

3.3 Answering the Tweaked Q4S

Since the original Q4S has been analyzed in Chapter 1, I focus on clarifying the core augmentation and personalization that make the question applicable for my research. The core addition to the original Q4S is “the strategic design of adaptive systems.” To understand the context with which the core transformation was added, a definition of strategic design and adaptive systems must be proposed.

3.3.1 Tweaked Q4S Clarification:

By clarifying each definition individually, I answer the following question: “What is the strategic design of adaptive systems?” In answering this question, I show both my main augmentation and personalization categories and articulate the necessity for a combination of strategic design and adaptive systems.
Chapter 3: Tweaked Q4S

Strategic Design:

As stated in Chapter 2, I have identified a paradigm shift to agile enterprises pertaining to my world of 2020. A distinguishing feature of a successful enterprise will be agility through mass customization and reductions in design cycle time. The vehicle for mass customization and reducing design cycle time will be the strategic design of open engineering systems. Seepersad and coauthors have developed a definition for strategic design: (Seepersad 2002)

“Strategic design is a comprehensive approach for forecasting shifts or changes in markets, associated customer requirements, and technical capabilities and for devising artifacts that accommodate these shifts efficiently and effectively. It is a marriage of strategic product planning and market analysis, methods for leveraging and adapting existing products, procedures for assessing and infusing technological innovations, and systematic evaluation techniques for comparing and selecting among a portfolio of options.”

Strategic design is a broad definition that encompasses my overall intention for the augmentation of P&B. Through strategic design, enterprises can proactively adapt to changes in markets, changing customer requirements, and technical capabilities. The proactive technological forecasting nature of strategic design is an integral feature, which supplies the significant technical knowledge required for the effective design of adaptive mechanical systems.

Adaptive Systems:

As stated in Chapter 2, I have identified a paradigm shift from traditional systems to adaptive systems. I believe that the salient feature of future systems will be reliability. Reliability will be a key component in meeting the needs of customers as their systems would be capable of meeting many different operating conditions.

Since system adaptivity is my thesis topic, I have chosen to make it primary personalization towards my answer to the Q4S. By applying adaptivity to a system, a system will accommodate different operating conditions to provide the user with a more reliable end product. In a sense, the adaptive system is itself strategic in nature, but can also benefit from the use of strategic design ideas.

3.3.2 Tweaked Q4S and the Need for Systematic Design:

Currently, strategic design is an overarching vision for the future of systematic design; hence, a systematic, strategic design method has not been specifically proposed that is widely accepted. As my primary augmentation, I plan to integrate features of strategic design throughout the P&B process to introduce a systematic method capable of evaluating technological capabilities for the support of adaptive systems.
Chapter 4: P&B Design Method

The P&B systematic design process is a hierarchical set of guidelines that are to be utilized in a way that allows the design process to conform to the problem of interest. Although steps can be removed or reordered, the overall design process is sequential in nature. To realize the true efficacy of systematic design successive results must be maintained in order. For instance, the task must be clarified to arrive at a viable solution or preliminary layouts must be created before definitive layouts can be realized; hence, the design process should become more ordered and concrete at every working step or iteration in the design process. In the following text, I introduce the P&B design process by displaying the information flow diagram, explaining the phases, identifying core information transformations, developing a requirements list, and performing a gap analysis.

4.1 Overview of P&B Design Method

Within the P&B design process, there are four main phases of systematic design. These include Product Planning and Clarifying the Task, Conceptual Design, Embodiment Design, and Detail Design. These phases contain the working steps mentioned above that bring structure to an abstract, ill-structured problem. As I have shown in Figure 4.1, Product Planning and Clarifying the Task constructs a requirements list to acknowledge constraints and design expectations. Conceptual Design results in the formulation of a principal solution. Embodiment Design results in a definitive layout. Finally, the Detail Design phase yields the documentation of production, assembly, transport, and operation instructions.
Figure 4.1: Information flow diagram for P&B. (Beitz 2005)
4.2 Explanation of P&B Phases and Steps

As stated above, P&B is a systematic design process comprised of four primary phases. These phases are listed below and explained in detail.

4.2.1 Product Planning and Clarification of the Task:

The P&B process starts with a task which is generated by an identified need from the market or from within the company. The initial phase, Planning and Clarifying the Task, begins by clarifying the initial task into a product proposal. Based on this proposal, a requirements list is generated. These requirements form the basis for the rest of the design process are focused on constraints on the final design solution. The two main information transformations are the creation of the task proposal and the generation of the requirements list.

4.2.2 Conceptual Design:

The Conceptual Design phase converts the requirements list into a principal concept. The requirements list is abstracted to define the crux of the problem – a solution-neutral statement which summarizes the function of the product. This overall function is then defined in terms of input and output flows of energy, material, and signals. Sub-functions are created to accomplish the overall function and are combined into a function structure by linking compatible inputs and outputs. Multiple working principles are defined for each sub-function and combined to form working structures. These working structures are evaluated using technical and engineering criteria to select the most promising concept.

4.2.3 Embodiment Design:

The Embodiment Design phase converts the concept into a preliminary and then definitive layout. Layouts are defined as a concrete product design with dimensioned geometry and material specifications. Multiple preliminary layouts are created, refined, and reduced to the most promising layout through a selection process. The preliminary layout is converted to a definitive layout by defining the design geometry and materials. Cost and quality are used as criteria for evaluations and refinement at this point. The definitive layout includes enough information to thoroughly evaluate the design before moving into the detailed design phase.

4.2.4 Detail Design:

Design is the final phase of the P&B process. It is focused on finalizing the details of the design and creating documentation that can be used to manufacture the product. At the end of the detail design phase, all of the details of the design have explicitly specified, including dimensions, materials, production processes, and costs. The output of the detailed design phases is complete product documentation. Pahl & Beitz do not consider the manufacture or any tasks which follow as a part of the design process.
4.3 Identification of Core Transformations

In Figure 4.2, I display the core transformations of the P&B systematic design process. I leveraged this information from the A3 of Christina Hruska as I felt that her work captures the essence of P&B and expresses it much clearer than I had earlier in the semester.

Figure 4.2: Core transformations of P&B. (Hruska 2004)

4.4 Developing the Requirements of P&B

After analyzing the requirements list headings given in Figure 5.7 of the P&B text, I leveraged the analogous steps for creating a design method from Jordan Hall’s LE3. In LE3, Jordan caught the essence of the analogous design method steps.

- **“Geometry → Process Steps”:** This has to do with spatial layout. The design process is laid out as flow with a definite relationship between modules. Examples: number of phases, sequential order of phases, arrangement of phases.
- **Kinematics → Process Flow:** Kinematics concerns motion. What moves in a design process is information – large amounts of poorly organized information are transformed into well defined problem and solution. Examples: flow between phases, input and outputs of each phase, iteration requirements, parallel task definition, decision points.
- **Forces → External Processes:** Forces exert influence on a mechanical system from the outside. In this same way, external factors can "stress" the design process by adding
additional constraints. Examples: Design control, regulatory processes, technological limitations, market forces, customer needs.

- **Material → Information**: Information is the raw material of a design process. The information is converted into a design solution. Examples: design inputs, data types (CAD, FEM, text documents, databases, url/web-based), intuitive knowledge, personal experience, institutional knowledge (knowledge possessed collectively by a corporation).

- **Signals → Feedback/Analysis**: In physical systems, signals provide a method for feedback and control. A design process will also need feedback and control. The importance of analysis is emphasized here. Examples: simulation, prototyping, economic/cost analysis, usability testing, consumer research.

- **Safety → Failure Analysis/Prediction**: Since design is a human activity it is inherently prone to faults and weaknesses. Failure analysis and the search for weak spots in a design should be integrated into the design method instead of relying on the designer to perform it intuitively.

- **Ergonomics → Ease of Use**: To be useful, a design method must be usable for a variety of people. It is important to consider what skills and characteristics a person needs to learn and use the design process. Examples: training, education level, time to learn, simplicity/complexity.

- **Assembly → Team work**: Modern design work is typically handled by a team of designers and specialists. How this team interacts is critical to the design process. Team work can be related to the ideas of assembly – the pieces of the team must fit together or the project will suffer. Examples: communication techniques, required documentation, control of design decisions/authority structure, use of consultants, multi-disciplinary interaction.

- **Recycling → Knowledge Re-use**: Ideas can be re-used and recycle just like material. Since information has already been related to material above, it is natural to look at how information may be re-used in the design process. Examples: information storage/databasing, use of design catalogs, use of off the shelf designs, requirements for modular design, requirements for variable design.

- **Costs → Time**: Every design process takes time. Time is directly related to money, particularly when it is employees or billable consultants which are actually doing the design. Examples: estimation of time/effort for each phase, initial time investment required, monitoring time for design activities, minimizing time required for activities/streamlining.” (Hall 2006)

From these generalized categories, I developed a list of requirements for the P&B systematic design method. In Figure 4.4, I have listed these requirements under the headings process steps, process flow, feedback/analysis, and external processes.
Chapter 4: P&B Design Method

### Problem Statement:
Construct a requirements list for the Paul and Beitz design method.

<table>
<thead>
<tr>
<th>Changes</th>
<th>D/W</th>
<th>Requirements</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/27/2006</td>
<td>D</td>
<td>Product Planning and Clarification of Task Phase</td>
<td>Organization of Company</td>
</tr>
<tr>
<td>9/27/2006</td>
<td>D</td>
<td>Conceptual Design Phase</td>
<td></td>
</tr>
<tr>
<td>9/27/2006</td>
<td>D</td>
<td>Embodiment Design Phase</td>
<td></td>
</tr>
<tr>
<td>10/1/2006</td>
<td>D</td>
<td>Detail Design Phase</td>
<td></td>
</tr>
<tr>
<td>9/27/2006</td>
<td>D</td>
<td>Design process should be flexible to reflect the task.</td>
<td></td>
</tr>
</tbody>
</table>

#### 1. Process Steps:

9/27/2006 D Sequential information flow.
9/27/2006 D Information should move from abstract to concrete through design.
9/27/2006 W Minimize iterations between phases.
9/27/2006 W Minimize iteration in phases.
9/27/2006 W Design should produce maximum number of solution variants.

#### 2. Process Flow:

9/17/2006 W Design should meet ergonomic standards
9/17/2006 W Design should meet economic standards
9/27/2006 D Design should be safe
9/27/2006 D Design should be manufacturable
9/27/2006 W Design should be easy to assemble/disassemble.
9/27/2006 D Design must be a quality product.

#### 3. Feedback/Analysis:

9/17/2006 W Design should be easy to assemble/disassemble.

#### 4. External Processes:

9/17/2006 D Design must be based on a requirements list.

Figure 4.3: Requirements list for P&B.

With the P&B requirements in place, I have analyzed the missing information from P&B that will allow me to develop my own augmented and personalized method pertaining to my World of 2020. In this context, the missing information is represented by the gap analysis developed in the following section.

### 4.5 Gap Analysis of P&B Requirements

With respect to my World of 2020, I have identified several shortcomings of the P&B systematic design method. In this context, I intend to introduce these several shortcomings under topics that directly pertain to the paradigm shifts that I have identified in section 2.3.1. These topics are post realization product improvement, reconfigurable enterprises, technological capabilities, and adaptive system design.
4.5.1 Post Realization Product Improvement:

Within the P&B method, there are four primary phases: product planning and task clarification, conceptual design, embodiment design, and detail design. In this layout, the designer is primarily concerned with realizing the system and producing documentation to support technical instructions (i.e. manufacture, transport, operation) and finalized layout. After this, there is no mention of the product life cycle or continuous improvement of a product family.

For my World of 2020, I have identified a shift to agile enterprises. To accommodate agile enterprises, I suggest the use of strategic design as the primary augmentation to increase the agility of these enterprises. In this context, the support of a product includes ideas such as post realization surveys for continuous improvement and the development of product families to combat the growing demands of the customer and the corresponding quality that these demands entail. By using a post realization product improvement, ideas like continuous improvement and product families would increase the quality of realized systems and reduce the design cycle time due to the modularity of systems utilized in product families. Like post realization product improvement, the exclusion of reconfigurable enterprises is another limitation of P&B. By including reconfigurable enterprises, the design cycle time would be significantly decreased due to an enterprise’s capability to quickly enter and leave markets and shift their resources within a dynamic business sector.

4.5.2 Reconfigurable Enterprises:

As mentioned in my paradigm shift section, I predict that successful enterprises will be agile enterprises. As stated in my World of 2020, the primary drivers behind a reduction in design cycle time will be reconfigurable enterprises and concurrency in design practices. Currently, P&B is not configured in such a way that promotes the use of reconfiguration or concurrency within enterprises. As stated before, P&B is a highly structured design process by which there is a somewhat linear and hierarchical information flow where by many tasks are directly dependent upon others to proceed with the design process. At this point, I feel it is necessary to ask the question: “How can P&B be augmented to increase its concurrency and reduce its design cycle time?” To insert these capabilities into P&B, it is left to the designer to recognize its shortcomings and implement measures to adapt P&B into a more personalized and useful form.

For concurrency, there are many opportunities within the early design phases such conceptual design to concurrently determine technological capabilities while creating the working structure. By correctly identifying technological limitations, technology could be another tool used to identify the best plausible concept variants. Also, during early embodiment design the concurrency of supply chain manipulation and realization resource allocation (outsourcing) could be determined after the determination of preliminary layouts. This is plausible due to the more concrete information available to engineers about the final design; hence, many of the generalized assembly and production resources could be allocated to speed the realization of product design. As alluded to in my concurrency discussion, the knowledge of technological capabilities is imperative in the determination of a principal concept solution. Along with this
the knowledge of technology plays a key role in developing a firm foundation for my primary personalization: adaptive system design.

To enable the reconfiguration of enterprises, a design method should account for the term virtual corporation as mentioned in the World of 2020. From this term, the supply chain for production resources should be allocated as outlined by the concurrency discussion above. For an enterprise to be truly reconfigurable the method should support mass customization to a certain extent due to the flexibility and agility that is required to meet the customers continuously changing demands. In this context, mass customization in a design method should evaluate the potential for modularity within the product’s internal structure. By modularizing internal components, the internal variety can be minimized while allowing the external variety to be maximized to please the customer. Using this type of modularity, the speed and quality required for future reconfigurable enterprises can be met.

4.5.3 Technological Capabilities:

As stated in my World of 2020, there will be much technological advancement in communications, the standardization of data formats, and adaptive system design. For P&B, the design method continually suggests evaluate against technological criteria, but never mentions a method to aid in the evaluation of these criteria. By implementing a method to evaluate these types of criteria into P&B, a more applicable design method could be created that is rooted in the future as opposed to legacy ideas. It is imperative to identify design method core transformations that could increase the timelessness of the P&B method.

With respect to communication and the standardization of data formats, the identification and implementation of technological advancements would extremely increase the efficiency of enterprises due to seamless communication despite the geographic location of engineers and the portability of data despite the software application. By seamless communication, I am referring to the neutrality of communication systems with respect to language and culture. By portability of data, I am referring to the independence of operating system or software application.

By advancements in adaptive systems technology, I am referring to broader advancement of technology such as computational simulation capabilities, computational processing power, and system specific hardware advancements (i.e. power supplies, communication systems). If a design method could continually identify the cutting edge technology available to designers, a wider range of solution variants could be achieved; thus, developing a wider solution space for the design engineer.

4.5.4 Adaptive System Design:

With respect to my World of 2020, I declare that adaptive systems are the next logical step in systems design. To further elaborate on this concept, I must identify the specific differences between an adaptive system and the traditional mechanical systems that P&B is structured for. For a design method to accommodate adaptability within the system architecture there must be significant personalizations to the P&B systematic design method. These personalizations
include a manipulation of the function structure, a representation of the indirect design of these systems, and an evolution in the design of the system.

In terms of function structure, P&B has a relatively rigid function structure specific to the requirements for the overall system. The requirements and the abstraction of the design constraints without prejudicing the choice of a particular solution are developed to arrive at the function structure. To accommodate adaptive systems this function structure could be used for the bottom up design of individual agents within a system, but could not effectively represent the global emergent behavior of the system; hence, there needs to be a corollary to the function structure that represents the voting mechanisms by which the global behavior occurs. In this context, I am referring to the corollary as a practical consequence that follows the natural function structure of P&B. In a sense, this corollary is a voting hierarchy. This voting mechanism can be viewed as a positive/negative feedback mechanism, whereby the most beneficial global behavior can develop.

As I mentioned above, there must be bottom-up design of the individual agents of the system. I refer to this bottom-up design as indirect design; whereby, the global behavior is unpredictable due to the system’s ability to adapt to external influences. This would mean that a designer must cleverly design a de-centralized method of controlling the system where by emergent behavior is promoted; hence, the designer is still indirectly designing the continuous global behavior of the system. For P&B, the defined product is specified and the designer strives to achieve the global product through the direct design of systems. In this sense, there is a functional decomposition that takes place in the design process that converges towards a solution. Contrary to this, an adaptive system cannot be functionally decomposed due to its complexity. To understand this concept, a definition for a complex system must be proposed: (Bar-Yam 1997)

“A complex system is a system formed out of many components whose behavior is emergent, that is, the behavior of the system cannot be simply inferred from the behavior of its components. The amount of information necessary to describe the behavior of such a system is a measure of its complexity.”

Since, the global behavior of the system cannot be simply inferred from the behavior of its components; hence, it must be viewed as whole during the design process. Due to this type of behavior, computer simulation must be used as a means of validating the system behavior before actual embodiment of any system components can be realized.

Due to the global emergent behavior from indirect design, there must be an evolution of the system in the context that is capable of producing variability within its method of control and subsequently its configuration or architecture. With reference to variability, I am drawing inspiration from the way in which natural systems design through evolution. In this context, I defined variability from Wagner and authors: (Wagner 1996)

“Similarly, variability of a phenotypic trait describes the way it changes in response to environmental and genetic influences.”
With this definition posed, I will abstract the terms environmental, genetic influences, and phenotypic trait to design of artificial man-made systems. An example would best explain the abstraction of these terms; hence, I will use the example of ship. In terms of environmental variation, a ship would experience influences from ocean currents. For the ship, to autonomously, reconfigure its propulsion and physical navigation equipment (phenotypic traits) there would have to be an influence from the control system (genetic influence). In essence, there has to be the capability to co-evolve the configuration (phenotype) and control mechanism (genetic influence). Currently, P&B is ill equipped for the allocation of these design considerations. For this type of evolution to occur in design, P&B must account for a higher computational simulation of the creation of a corollary decision function structure.

4.5.5 Application of the Gap to my Augmented Method:

From my gap analysis, I have identified significant limitations of the P&B systematic design method in the context of my World of 2020. These limitations are rooted in the absence of post product realization improvement, support for reconfigurable enterprises, technology evaluation method, and adaptive systems design. In my augmented and personalized method, I have included measures to reduce the limitations identified in the section above.
Chapter 5: Augmented Method

After performing a gap analysis of P&B in the context of my World of 2020, it has become evident that significant personalizations and augmentations must be integrated into P&B to achieve a systematic design method for the strategic design of adaptive systems. To adequately perform this task a requirements list must be constructed to guide the formation of this augmented and personalized design method.

5.1 Requirements List for 2020

In developing a requirements list for my World of 2020, I have combined the core requirements of P&B systematic design method with the core requirements for my primary augmentations and personalizations.

5.1.1 Overview of Requirements:

In Figure 5.1, I list the requirements core to P&B along with my requirements of 2020, highlighted in blue. With respect to my augmentations, I have added support concurrent engineering practices, support mass customization, and support reconfigurable enterprises. As a bridge between my augmentations and personalizations, I have included a requirement for the support of technological evaluation. For my personalizations, I have added a section entitled “Adaptive Systems Design.” Within this section, I list the requirements for complex systems, reconfigurable function structures, and defining metrics for macro/microscopic behavior of a complex system.
## Problem Statement:
Construct an augmented and personalized requirements list for the Paul and Beitz design method.

<table>
<thead>
<tr>
<th>Changes:</th>
<th>D/W</th>
<th>Requirements:</th>
<th>Responsibility:</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/27/2006</td>
<td>D</td>
<td>Product Planning and Clarification of Task Phase</td>
<td>Organization of Company</td>
</tr>
<tr>
<td>9/27/2006</td>
<td>D</td>
<td>Conceptual Design Phase</td>
<td></td>
</tr>
<tr>
<td>9/27/2006</td>
<td>D</td>
<td>Embodiment Design Phase</td>
<td></td>
</tr>
<tr>
<td>10/1/2006</td>
<td>D</td>
<td>Detail Design Phase</td>
<td></td>
</tr>
<tr>
<td>9/27/2006</td>
<td>D</td>
<td>Design process should be flexible to reflect the task.</td>
<td></td>
</tr>
</tbody>
</table>

### 1. Process Steps:

- Product Planning and Clarification of Task Phase
- Conceptual Design Phase
- Embodiment Design Phase
- Detail Design Phase
- Design process should be flexible to reflect the task.

### 2. Process Flow:
- Sequential information flow.
- Information should move from abstract to concrete through design.
- Design must converge towards an "optimal" solution.
- Minimize iterations between phases.
- Minimize iteration in phases.
- Design should produce maximum number of solution variants.
- Support concurrent engineering practices.

### 3. Feedback/Analysis:
- Design should meet ergonomic standards
- Design should meet economic standards
- Design should be safe
- Design should be manufacturable
- Design should be easy to assemble/disassemble.
- Design must be a quality product.

### 4. External Processes:
- Design must be based on a requirements list.
- Support mass customization.
- Support reconfigurable enterprises.

### 5. Information:
- Support technological evaluation.

### 6. Adaptive Systems Design:
- Design method should be effective for complex systems.
- Support reconfigurable function structures.
- Define metrics for evaluating macroscopic/global behavior.
- Define metrics for evaluating microscopic/local behavior.
5.1.2 Explanation of Requirements:

In the following explanation of steps, I have denoted inherent steps to P&B with an (I), augmentations with an (A), and personalization with a (P).

Process Steps:

In an effort to retain the salient features of P&B, I have left all of the phases in my requirements list. I have also retained the requirement for the flexibility of the design method. Flexibility is an important characteristic of P&B. Since my method’s foundation is P&B, I felt it necessary to achieve the same flexibility in my design method. I have listed these requirements below.

- Product Planning and Clarification of Task Phase (I).
- Conceptual Design Phase (I).
- Embodiment Design Phase (I).
- Detail Design Phase (I).
- Design process should be flexible to reflect the task (I).

The above requirements are explained in greater detail in the Chapter 4.

Process Flow:

In the following list, I denote the individual requirements within this section as it contains one of my augmentations to the P&B method.

- Sequential information flow (I).
- Information should move from abstract to concrete through design (I).
- Design must converge towards an "optimal" solution (I).
- Minimize iterations between phases (I).
- Minimize iteration in phases (I).
- Design should produce maximum number of solution variants (I).
- Support concurrent engineering practices (A).

Sequential information flow is a feature of P&B which refers to the nature of the information flow through each phase. This nature refers to the necessity to maintain the appropriate order of the core transformations.

Abstract to concrete information flow refers to the qualitative decisions required early in the design process relative to the more concrete, quantitative decisions later in the design process.

Design convergence refers to necessity of the design process to accomplish the specified task determined during the product planning and task clarification phase.

Iteration minimization relates to the effort of the designer to make critical and correct early decisions to minimize the necessity of timely iterations within the design process.
Maximum number of solution variants is rooted in an effort to search the entire solution space to identify the best possible concept variant.

Support concurrent engineering practices is tied to my World of 2020, which will reduce the time to market by concurrently accomplishing design tasks.

Feedback/Analysis:

As in the Process Steps of my requirements list, I have left the design criteria from P&B the same. I feel as thought the requirements listed below are applicable to any design method.

- Design should meet ergonomic standards.
- Design should meet economic standards.
- Design should be safe.
- Design should be manufacturable.
- Design should be easy to assemble/disassemble.
- Design must be a quality product.

The above requirements represent criteria set forth by P&B to be a system of checks and balances to ensure the design meets acceptable standards with respect to the customer requirements.

External Processes:

- Design must be based on a requirements list (I).
- Support mass customization (A).
- Support reconfigurable enterprises (A).

Requirements list based design refers to the necessity to identify requirements in the product planning phase.

Support mass customization refers to an augmentation, which accounts for the post realization product improvement I have identified in my gap analysis. Also, this requirement will satisfy my World of 2020 with respect to an international, customer centric marketplace of the future.

Support reconfigurable enterprises is an augmentation I have included to account for the reduction in time to market identified in my World of 2020.

Information:

- Support technological evaluation (A/P).

Technological evaluation is a design method support tool for the identification of future technological advancements such as adaptive systems, communication, and data standardization.
**Adaptive Systems Design:**

- Design method should be effective for complex systems (P).
- Support reconfigurable function structures (P).
- Define metrics for evaluating macroscopic/global behavior (P).
- Define metrics for evaluating microscopic/local behavior (P).

In my World of 2020 and gap analysis, I identify salient features of an adaptive system as my primary personalizations. This list represents some of the core ideas which contribute to the advancement of a method for adaptive systems. These requirements will be discussed in great detail in my “Augmented and Personalized P&B Design Method.”

**5.1.3 Application to Augmented P&B Design Method:**

Since the requirements for an augmented method based upon my World of 2020 have been proposed, I display my augmented method in the following section. Within this section, I develop an explanation of the phases and steps along with the identification of my personalization and augmentations.
5.2 Augmented and Personalized Design Method

As stated in my World of 2020, I identified a paradigm shift towards reconfigurable enterprises and adaptive systems. In doing this, I constructed a framework for developing a gap analysis for the P&B design method. Within this gap analysis, I identified four primary areas my design method for 2020 should accommodate. These areas include post realization product improvement, reconfigurable enterprises, technological evaluation capabilities, and adaptive system design. In the following section, I display my augmented and personalized method and present changes to the method that pertain to my gap analysis of P&B.

5.2.1 Overview of Augmented and Personalized Method:

As I have displayed in Figure 5.2 on the following page, I have added generalized inputs into the P&B systematic design method. These inputs include technological evaluations, reconfigurable enterprises, design for adaptive systems, and a post product realization improvement phase. Following the generalized introduction of these inputs is an in depth explanation of specific details pertaining to each input.
In the context of P&B, I have added inputs to the product planning, conceptual design, and embodiment design phases. I did not change the detail design phase due to the variation in documentation standards from company to company.

**Figure 5.2:** Generalized personalizations and augmentations to P&B.
5.2.2 Explanation of Phases and Steps:

The following discussion outlines in detail the augmentations and personalizations I have made to the P&B design process. As stated before, all core transformations of the P&B design method have been retained in their entirety.

**Product Planning and Task Clarification:**

In Figure 5.3, I have displayed my augmentations to the product planning and task clarification phase.

![Diagram of product planning and task clarification phase](image)

**Figure 5.3:** Product planning and task clarification phase of augmented method.

**Augmentations:**

**Reconfigurable Enterprises:**

As stated in my World of 2020, markets will dynamically change; hence, enterprises must change with the market. The following augmentations: market segmentation grid, supply chain partner identification, and collaborative customers represent solutions to decrease the design cycle time and identify the customer’s constantly changing demands.

**Market Segmentation Grid:**

To truly implement a strategic design method, it is necessary to identify product expansion strategies. A method to aid in this identification is the market segmentation grid (Meyer 1997), shown in Figure 5.4. As stated by Seepersad and coauthors,
“The market segmentation grid (Meyer, 1997; Meyer and Lehnerd, 1997) facilitates the identification of product leveraging and expansion strategies for an enterprise.”

From this definition, it can be inferred that the market is segmented and evaluated to allow product architects to identify segments of the market that are accounted for by certain products and possible expansion opportunities for that product in other market segments. In this context, the market segmentation grid is strategic due to its extension of products beyond their first intended purpose. To use the market segmentation grid the format of the grid must first be identified, on the horizontal, major axis the market segments are located for a specific company’s products. On the major, vertical axis the price and performance of products within each market segment. If knowledge of the major axis properties is known, products can be leveraged to explore new markets by scaling one or more technologies or components. In this sense, the products can be extended horizontally to explore new market segments or vertically to explore different performance ranges. Also, a beachhead strategy can be employed to combine horizontal and vertical exploration of the market and performance segments. (Seepersad 2002)

Figure 5.4: Market segmentation grid.

Identify Possible Supply Chain Partners:

Once expansion strategies have been developed by employing the market segmentation grid, projected supply chain and shipping partners could be contacted to initiate an early development of strategic alliances. By beginning this process earlier, legal and logistically considerations could be accomplished concurrently with the design process. By developing a supply chain early, enterprises significantly reduce their design cycle time specifically during the embodiment design phase when the construction structure is created. Transport would no longer be a consideration at this point as it would be completed concurrently through product planning and
conceptual design. In conjunction with supply chain identification, collaborative customers could play a significant role in reducing product planning time.

**Collaborative Customizers:**

Collaborative customizers conduct a dialogue with the individual customers to assist the customer in making a customized product. This is appropriate for businesses whose customers cannot easily articulate what they want and grow frustrated when forced to select from a plethora of options. An example of this given by Gilmore is eyeglasses. When a consumer is deciding upon a pair of glasses first a computer takes a digital picture of the consumer’s face and, along with a set of statements about the consumer’s preferences, recommends a lens size and shape. Then the consumer and optician collaborate to adjust the shape, size, fashion, hinges, nose bridge and arms in order to complete the design. The customized pair of eyeglasses is then made to order. (Rockwell 2006)

In the context of a reconfigurable enterprise, this type of customer collaboration can be used to automate the identification of the customer requirements in such a way that reduces the product planning time. This automation could be induced by utilizing such resources as the internet and various graphical user interfaces specifically tailored to the intended product.

**Technology Evaluation:**

As stated in my World of 2020, communication and data standardization will play a key role in shaping the future. Although these predictions are specifically outlined there must be a systematic support process that can evaluate when these new technologies are available and how affective they can be at increasing the internal efficiency of an enterprise. By internal efficiency I am referring to the speed and accuracy with which the design work is being completed.

**TIES for Internal Upgrades:**

As stated above, I identify the Technology Identification, Evaluation, and Selection Method, shown in Figure 5.5, as a systematic approach to identify emerging technologies. To understand why TIES should be implemented in this context I present the following definition (Mavris 1999):

> “The nine step process provides the decision maker/designer with an ability to easily assess and trade-off the impact of various technologies in the absence of sophisticated, time-consuming mathematical formulations for project resource allocation.”

Before I can propose my method for implementing TIES, I must develop a general outline of the original intention of the method. “TIES was developed in response to an aerospace industry paradigm shift away from design incorporating only performance metrics and towards design processes that take into account both performance and affordability issues. To account for affordability, effectiveness –measured by performance, reliability, maintainability, and safety – is balanced against costs associated with acquisition, operation, support, financing, and disposal.
The TIES process is made up of eight major steps in an iterative cycle, as seen in Figure 5. The problem at hand is described, system metrics identified, and goals set forth in the first step. In the next three steps, design alternatives are identified, modeled, and their performance assessed. In the fifth step, the performance of the top design alternatives is compared to goals set at the beginning of the problem and a decision is made as to whether one of them would be sufficient or whether it will be necessary to invest in new technologies as a means of expanding product capabilities. The major strength of TIES lies in the final three steps of the process, in its usefulness for forecasting probabilistically the impact of emerging technologies on the metrics associated with design for affordability (Mavris and DeLaurentis, 2000).” (Seepersad 2002)

For the purpose of product planning, the TIES process can be reduced primarily to the sixth and seventh step, whereby new technology such as language neutral communication hardware or software for the standardization of data can be identified and evaluated. During this identification and evaluation, the new technology could be compared to existing technology within the enterprises infrastructure based upon comparable metrics such as communication speed or data transmissions errors.

![Figure 5.5: Basic TIES process. (Kirby 2001)](image)

**Technology Training:**

As with the introduction of any new technology into an enterprise, training is necessary to educate the designers on the appropriate use of the technology. Through this training, the speed and efficiency in which the designers use the new hardware or software would increase; thus, creating a more productive design environment. No specific training method is recommended due to the various training standards among enterprises.

**Conceptual Design:**

I have displayed my augmented and personalized conceptual design phase in Figure 5.6 below. In this phase, the core additions to P&B were the addition of steps to aid in the design of adaptive systems, evaluation of technology, and use of reconfigurable enterprises.
Personalizations:

Design for Adaptive Systems:

As mentioned in the gap analysis, an adaptive systems design method must contain many augmentations. Due to the extreme pre-embodiment requirements (i.e. modeling, simulation, metrics for performance, emergent behavior) there must be significant thought placed in the development of a best concept. The first of these guiding principles in adaptive systems is the global function structure.

Global Function Structures:

In the design of adaptive systems, there is a unique general feature which all these types of systems contain. This feature is complexity. As mentioned before, a definition for a complex system is a system formed out of many components whose behavior is emergent, that is, the behavior cannot be simply inferred from the behavior of its components. A definition of complexity is the amount of information necessary to describe behavior. (Bar-Yam 1997) With this in mind, it becomes obvious that each component or agent’s inputs (i.e. material, information, energy) are a function of the environmental variations, noise, and the output of other agents. From this the analysis of these systems becomes very difficult early in the design phase due to the necessity to analyze the system as a whole to discover emergence. To aid the designer in this analysis, I display a diagram in Figure 5.7 shown below.

Figure 5.7: Conceptual design of augmented method.
The diagram shown above is not a means to quantitatively predict any behavior. It is solely presented a concurrent development with the function structure to aid the designer in mapping the information, material, and energy or flow of exchange between the system. Before this diagram can be used, the individual components must explained to denote their importance in guiding the designers careful choice of system configuration or hierarchy which will be discussed later.

First of all, Figure 5.7 represents a generalized representation of an adaptive system; hence, the flow lines are shown as an entirely decentralized control. The green line denoted “E” represents environmental noise crossing the dotted environmental boundary of the system which cannot be controlled by the designer. With respect to this, there must be a determination of the system boundary. A designer must determine if the system is itself part of the environment or if there is a definitive boundary as pictorially shown above. As shown by the legend, the red arrows represent the agent/environmental exchange of flow within the system. At this point, it may seem as thought the central agent is not receiving environmental, but due to the diagrams 2D nature and the system’s current general configuration the exchange cannot be shown. Next, the blue lines represent agent/agent flow interaction whereby one agents input is another’s output; hence, the complexity issue.
At this point, it may seem necessary to define a separate structure to aid in the voting mechanism for an adaptive system’s decentralized control. A simplified voting hierarchy is shown in Figure 5.8.

![Figure 5.8: Simplified voting hierarchy.]

Initially, it may seem as though the voting mechanism is a form of centralized control. In essence, the structure is a decentralized method of determining the best global behavior analogous to an entirely idealized, democratic voting mechanism. The numbering system represents three possible choices for behavior amongst each agent. Individual agents make a determination of the current state based upon their neighbor agents and environmental inputs. The agent then proposes a behavior, which is best for its own selfish interest. Then, a localized vote amongst neighbors is developed to account for three possible choices of localized collective behavior. At this point, the localized behavior is represented by a simple average of the possible behaviors of each agent. The localized behavior would be a higher level representation of the behavior enabled by the individual agents; hence, the average would take into account the best behavior for the local group. At this point, a global average represented in the box would represent the best possible global behavior to eliminate nepotistic behavior among the localized factions. Nepotism is the service of selfish interests among factions; hence, a global vote would be a negative feedback, which contributes to the best global behavior.
By employing this type of global behavior mapping, the designer could be aided by the diagram to allocate the extent to which flow is decentralized in the system; hence, it may be determined that some specialization may be required among agents to accomplish a specific goal.

**Complexity Analysis:**

From the voting mechanism, it would be necessary at this point to determine a metric for complexity to develop a quantitative measurement of the state of the system during future testing. Bar Yam proposed the analysis method discussed in this paper. “If we have a system that could have many possible states, but we would like to specify which state it is actually in, then the number of binary digits (bits) we need to specify this particular state is related to the number of states that are possible. If we call the number of states $\Omega$ then the number of bits of information needed is

$$I = \log_2(\Omega)$$

(0.5.1)

To this we must realize that to specify which state the system is in, we must enumerate the states. Representing each state uniquely requires as many numbers as there are states. Thus the number of states of the representation must be the same as the number of states of the system. For a string of N bits there are $2^N$ possible states and thus we must have

$$\Omega = 2^N$$

(0.5.2)

Which implies that N is the same as I above.” (Bar-Yam 1997)

**Define Metrics for System Performance:**

During the conceptual design phase, it will be necessary to develop specific system metrics and trend lines to evaluate system performance relative to expected values in embodiment design. In Figure 5.9, a reliability versus the classification of agents trend line is developed as a qualitative example of the system metrics for the aiding the designer in determining the future metrics by which the system will be evaluated during the embodiment design phase.
As mentioned before, there may be a specialization of sorts within the architecture of a system; hence, there may be a slight deviation away from entirely decentralized control. By introducing specialization into agents, overall system reliability will decrease as the system is inherently dependent upon the specialized agent’s specific function. Upon failure of specialized agents, the integrity of the system could be compromised resulting in a reduction of global system function or catastrophic failure. Like reliability, another system trend that would be helpful in determining system performance during testing is the complexity relative to the number of agents.

As I display in Figure 5.10, the complexity relative to the number of agents will significantly increase relative to the number of agents. This is due to the increase of interactions between the
environment/agents and the agents/agents. Also, the measure of complexity could be extended to approximate the relative computational power required for each agent; hence, developing a more concrete estimation of system performance and capability.

**Modeling & Simulation:**

Due to the complexity as mentioned above, the necessity of the designer to employ modeling and simulation techniques to evaluate system performance early in the conceptual phase is integral to discriminate concept variants. This is plausible due to the necessity to evaluate control algorithms and various agent models to add another technical criteria evaluation. Since, this method is generalized based upon adaptive systems no modeling or simulation techniques are recommended to allow the designer to make an educated determination of software choices based upon the system type. In essence, this simulation would be qualitative/quantitative. It is qualitative/quantitative from the perspective that generalized models (lacking specified materials and hardware) would be used, but actual quantitative results could be produced to show the emergent behavior of the system.

**Utility-Based Selection Decision Support Problem:**

Based upon the uncertainty developed by the complexity of the system, there must be a method to aid the designer in making complex decisions with respect to system attributes. This method is the Utility-Based Selection Decision Support Problem (u-sDSP). I have displayed the summary of steps in Figure 5.11.

![Steps for a Utility-Based Selection Decision Support Problem](image)

**Figure 5.12:** Summary of Steps of Utility-Based Selection Decision Support Problem. (Fernandez 2001)

An explanation of the (u-sDSP) is proposed by Seepearsad and coauthors. “One such design tool is the Utility-Based Selection Decision Support Problem (u-sDSP), the word formulation of which is shown in Figure 6. As described by Fernández and coauthors(2001), the u-sDSP
Chapter 5: Augmented Method

combines the benefits of a selection method based on utility theory with those of Decision Support Problems to create a qualitative, axiomatic method for supporting human decision-making throughout the design process. The structure of the method is based on the selection Decision Support Problem (Mistree, et al., 1994), which facilitates the search for satisficing solutions for a variety of different types of decisions, including selection, compromise, and hierarchical or coupled decisions. A proven method, the selection DSP does have several drawbacks concerning its merit function, which tends to impose some restrictions on the decision-maker and does not handle uncertainty as rigorously as possible. These shortcomings can be overcome through the use of utility theory in the s-DSP. Utility theory provides a consistent means of numerically expressing the decision-maker’s preference when it is necessary to trade-off between multiple goals under uncertainty. Once a decision-maker’s preferences for attributes of a system are established, an expression for utility as a function of performance, cost, and other attributes can be generated and a numerical value of the utility of each alternative calculated. Alternatives can then be compared based on their utility values. The steps of the utility-based selection DSP are described briefly in Figure 6. We envision utility-based selection as just one of a suite of decision-support assets available to designers carrying out strategic design.” (Seepersad 2002)

Within this in mind, the u-sDSP should be utilized in the context of the strategic design of adaptive systems to aid engineers in determining system attributes relative to market and technology information.

**Technology Evaluation:**

Once again, I suggest the use of TIES as means to evaluate the technology available for the development adaptive systems. This is necessary due to the extreme technological requirements called for by the realization of an adaptive system. Examples of technological advancements would be machine vision, computational speed, MEMS, and a multitude of other technologies outside the realm of mechanical engineering.

**TIES for System Design:**

Since TIES was introduced with respect to internal enterprise improvement, this discussion will describe the reasoning behind the use of TIES as an evaluation tool for the software and hardware options for an adaptive system.

In this sense, the TIES method can be used to aid designers in allocating the necessary knowledge for the myriad of combinations of software/hardware implemented in adaptive systems. The implementation of TIES could be used as a stepping-stone to a further series of more quantitative simulation, which aid in the selection of concept variants.
**Modeling & Simulation:**

After technology combination selection, it would be necessary to perform a more quantitative series of simulations to evaluate the marriage of the technologies and their relative behavior. In completing this simulation, the designer would have a final more concrete technological evaluation method to discriminate between acceptable and unacceptable concept variants. As mentioned before, no simulation tools are recommended due to variation from system to system.

**Augmentations:**

**Reconfigurable Enterprises:**

**Concurrency between Supply Chain and Concept Variant Determination:**

As mentioned before during the project planning phase, I included a point at which preliminary alliances should be made after the necessary product planning steps are taken. In this context, during conceptual design further logistic planning should take place to account for shipping delivery and shipping specifications. Upon completion of the phase, the preemptive allocation of supply chain resources would be determined to increase the agility of an enterprise in reacting to unforeseen transportation problems within the supply chain.

**Embodiment Design:**

In Figure 5.12, I have displayed a personalized embodiment design phase of P&B. In the personalizations, I include steps to aid in the design of adaptive systems. These steps include the use u-sDSP and system testing.

![Figure 5.13: Embodiment design of augmented method.](image-url)
Personalization:

The following text outlines my personalization contained in my embodiment design phase.

Utility-Based Selection Decision Support Problem:

The u-sDSP is described in the conceptual design phase. Once again, the utility of this DSP can be exploited to aid in selection of system attributes pertaining to the system testing, which will be explained below.

In the context of adaptive systems, the development of a construction structure and layouts will involve yet another series of decisions to made relating to the manufacture and assembly or self assembly of the individual adaptive system components. Since this type of system design will leave some integral design decisions in the embodiment phase, designers must have a tool to aid in selection decisions. Using the u-sDSP will allow designers to have quantitative methods to express the utility of the design as a function of the performance, cost, and other attributes.

Extensive System Testing:

In using the u-sDSP, the designer must have some method to evaluate the overall utility of the design. This utility can be expressed in a tangible sense through extensive product testing. This product testing is also needed to evaluate the emergent behavior of the system to ensure the verification and validation of the proposed product. Through this testing, important parameters defined by the metrics developed in the conceptual design phase can be tested along with safety issues related to the emergent global behavior. A method for eliminating weak spots and checking for errors is proposed in Figure 5.13.

![Figure 5.14: Iterative testing method for error and weak spot checks.](image)

As I show in Figure 5.13, a construction structure is the input into the iterative testing loop. After the product is tested, the performance of the system should be evaluated based upon the
metrics defined in conceptual design phase. If results are unacceptable the product’s system control parameters should be adjusted in an effort to avoid the timely iteration to adjust hardware. The system should be reevaluated in this process until the test yields acceptable results. Once acceptable results are achieved, the preliminary parts list and production/assembly documents can be developed.

**Detail Design:**

As mentioned before, no augmentation or personalizations were made to the detail design phase. As stated in the following quote by Beitz and coauthor (Beitz 2005), there are many differences between documentation for separate enterprises.

> “Whether such checks are made by the design department itself or by a separate standards department will depend largely on the organizational structure of the company concerned, and plays a subordinate role in the actual execution of the task.”

This phase is often times dependent upon the enterprise in which it is implemented. Since there are different documentation standards from enterprise to enterprise, I have left the detail design phase the same as P&B. The information flow through detail design is shown in Figure 5.6.

![Diagram](image)

**Figure 5.15** Detail design of augmented method.
**Post Realization Product Improvement:**

This phase represents a post realization opportunity for designers to strategically develop a future plan for a product family through the use of customer feedback. The output from this phase would be the input to the next design cycle as it provides information helpful in the development of future products.

![Diagram](image)

**Figure 5.16:** Post realization product improvement of augmented method.

**Augmentations:**

**Post Release Survey:**

By post release survey, I am referring to the conclusion of the release process whereby customers provide feedback via internet surveys that are loaded into a design database. By compiling the information into a design database, the information could be filtered and sorted in such a way as to provide the product family designers statistical information about customer satisfaction. This type of feedback would ensure that product families continued to develop into more satisfying products through subsequent design cycles.

**Develop Product Family:**

Although this augmentation is developed underneath a post realization product improvement, the idea of a product family is rooted in mass customization. A product family is defined as a group of products that share common form, function, and technology base to address various related market requirements (Seepersad 2002). By developing a product family, enterprise
reconfiguration could be created due to its ability to quickly enter and leave markets due to modularity and standardization within product architectures.

In essence, I propose that a plan be developed after the product realization. I propose this because a product’s success can be developed in the post release survey mentioned above. After evaluating success, a roadmap for a product family, or strategic future plan of action, could be created based upon the ideas of standardization and modularity to input back into the market segmentation grid in the next design cycle.

With respect to modularity and standardization, I refer back to adaptive systems. Due to the generalized agents that constitute an adaptive system, the modularity and standardization needed to quickly manipulate the distributed governing system and subsequent emergent behavior would be present. From this, the subsequent design cycle times after the initial design of an adaptive system would be greatly decreased; hence, reconfiguration could be enabled along with enhanced product quality.
Chapter 6: Verification and Validation

Within my Q4S, I have proposed an augmented and personalized design method based on the Pahl and Beitz systematic design method. I used my project, the comparison of systematic design to self-organizing systems, as means to validate my proposed Q4S method. At this point, I will introduce the means by which I intend to validate my method.

6.1 What is the Validation Square?

The validation square (Pederson 2000), shown in Figure 6.1 is a systematic method for justifying the utility of a proposed design method. Following the conventions of the validation square, verification is concerned with the internal consistency of a method. Validation is more comprehensive and addresses the overall suitability and utility of a method. Validation of design methods have been limited by the reality that design methods are not based on fundamental physical principles and therefore cannot be validated using the traditional "logical empiricist" methods. Instead, the validation square seeks to build confidence in the proposed method with respect to a stated purpose. Utility is the focus, not an absolute judgment of truth or falsehood.

The process is described in detail by the information flow diagram in Figure 6.2 below. Square 1 primarily addresses the internal consistency of a method. This is established through literature references, information flow charts, logical arguments, and comparisons to existing methods. In Square 2, example problems are proposed which focus on characteristics of the proposed method and generating data to support validity claims. In Square 3, the result of the example problems are evaluated in terms of requirements generated at the beginning of the process. The focus is on using reliable and unambiguous data to demonstrate that the method contributed to the success of the example problem. In Square 4, all of the previous conclusions from Squares 1-3 are used to generalize the utility of the method beyond the example problems. The success of the example problems and the internal consistency of the method provide the foundation for the "leap of faith" required for potential user to accept the validity of the new method.
Chapter 6: Verification and Validation

6.2 Theoretical Structure Validation (Square 1)

Since I have not proposed a new method but have chosen the Pahl and Beitz method as a base for augmentation and personalization, building confidence in the internal consistency of our proposed method is simplified versus a new method. By retaining the core transforms of Pahl and Beitz, we maintain internal consistency. As shown in greater detail in Chapter 5, the process includes the five phases and the individual core transforms of P&B within those phases such as task clarification, a requirements list, creation of function structures, preliminary layout, definitive layout, and a detailed documentation phase. In addition, requirements for the proposed method were generated as a preliminary step to proposing the augmentation and personalizations. These requirements are shown in Figure 5.1.
6.3 Empirical Structural Validation (Square 2)

I propose a design method for adaptive systems. In developing this method, I used some requirements developed in my project which are based upon examples of artificial self-organizing systems. I chose these requirements due to the similarities between self-organization and adaptivity. In my project, I developed examples such as multi agent robotics that could be used to evaluate the validity of the method. Since, I do not have a working knowledge of multi-agent robotics at this time or a system to validate my method I cannot make a conjecture about any metrics that would be used in empirical performance validation.

6.4 Empirical Performance Validation (Square 3)

As stated above, I cannot produce useful results with the chosen examples due to the necessity of a working knowledge of the proposed system. From this, the empirical performance of my method cannot be validated.

6.5 Theoretical Performance Validation (Square 4)

Due to the absence of empirical performance validation, I cannot build confidence in my method to ease the ‘leap of faith’ required to produce useful results beyond my chosen examples.

6.6 What Aspects were Verified using the Project?

From the project, the internal consistency of method was verified due to the extensive use of references in the development of requirements for a self-organizing system. As mentioned above, adaptive systems are subset of self-organizing systems; hence, the requirements are somewhat generalized. By developing a method based off of these requirements and P&B, the internal consistency was verified.

Also, plausible examples were developed in the project, but further analysis of these systems would be required to identify metrics to evaluate the empirical performance validity. From this, I believe that approximately one fourth of the empirical structural validation was developed.
Chapter 7: Critical Evaluation of Augmented Method

7.1 Limitations of Augmented Method

Before limitations of my method can be evaluated, I will evaluate the requirements list to identify which requirements were met by my method. I show this evaluation in Figure 7.1.

![Table showing changes and requirements](image)

Figure 7.1: Evaluation of requirements list.
First of all, adaptive systems are a relatively new field. With this in mind, this paper represents a theoretical design method based upon observations of working systems similar to the idea behind adaptive systems. Due to this theoretical framework, the method itself could contain significant value, but also be lacking in some areas. I have evaluated the value of how the design method met each requirement. In instances where P&B is represented in the requirements, I denoted a value of >1. From this, I evaluated my design method relative to this evaluation scale.

**Augmentations:**

*Support concurrent engineering practices: Value <1*

For my method, the only augmentation that I added was concurrent supply chain manipulation throughout the product planning and conceptual design phase. To truly employ, concurrent engineering practices many more augmentations would have to be implemented to reap the benefits of a reduction in time to market.

*Support mass customization: Value = 1*

With respect to this requirement, I added a market segmentation grid, collaborative customizers, post release surveys, and product family development. Using these augmentations gives the method potential for mass customization with a focus on the reduction in time to market. From this I denoted a value of 1 due to its potential and not full accomplishment.

*Support reconfigurable enterprises: Value = 1*

With respect to the reconfiguration of enterprises, I added a market segmentation grid and concurrency in supply chain manipulation. From this, I believe that the reconfiguration of an enterprise could be manipulated early in the design process by manipulating supply chains.

**Personalizations:**

*Support technology evaluation: Value = 1*

For technology evaluation, I resorted to TIES a method for the identification, evaluation and selection of technological resources. Since this method is generally accepted, I view it as a worthy means to support technology evaluations.

*Design should be effective for complex systems. Value <1*

Within complex systems I added modeling and simulation, u-sDSP, complexity analysis, and system testing. From my extensive research, I do not believe that this fully encompasses the requirements that are needed to support the realization of a complex system. Although, I do believe that this is a good start. Further development of some of these ideas could result in significant design knowledge creation.
Support reconfigurable function structures: Value<1

Although I propose two diagrams to aid the designer, I still feel as though that the issue of a reconfigurable function structure would require further decision support tools to aid the designer in developing this type of function structure.

Define metrics: Value<1

Once again, I believe the value is low for meeting this requirement. In this part of the design phase, I recommend developing metrics, but never propose a method for selecting this metrics based upon design knowledge. From this, the designer is still left determining which metrics are in fact useful for evaluating system performance.

After analyzing each requirement, I feel it is necessary to identify the limitations of my method as a whole. There are three primary areas in which I feel the method is limited. These areas include additional time required in early design phases, application to generalized complex systems, and the clear understanding of the method.

Time Required in Early Design Phases:

Most of my augmentations to the P&B method were added during the product planning and conceptual design phases. For P&B, these design phases represent a significant part of the design cycle time. By adding most of my augmentations to these phases, I have increased the design cycle time despite my identification of the dynamic market place. In defense of this decision, I use the complexity of adaptive systems as a justification for the necessary time required to carefully design these systems.

Application to Generalized Complex Systems:

This design method was based upon multi-agent robotics and natural self-organizing systems. With this in mind, the method may not be applicable to systems that are not modular or decentralized in nature. From this, I can objectively say that this shortcoming could be identified through a more rigorous verification and validation process not represented in this paper.

Understanding the Method:

For a design method to be useful, I believe that it must be clearly understood by the individuals employing it. An assumption made during the creation of this design method is that the designer is somewhat familiar with the concepts of adaptive systems. With this in mind, the method would seem clearer to individuals knowing the context of the systems they intend to develop. In essence, the nature of adaptive systems causes the design method to reflect similar complexity; hence, its usefulness can seem compromised from an individual not familiar with the principles of adaptivity.
7.2 Future Research Questions

The following questions represent only some of the further research that needs to completed to fully realize an adaptive systems design method.

- From a design perspective, what is the best way to achieve decentralized autonomous decisions?
- What are the prospects for hybrid systems which retain limited aspects of self organization or use self organization on selected subsystem levels and not system wide?
- Is there a way to concurrently design the algorithm and agents for a system? In essence, is the algorithm somewhat generic to SO systems?
- How do few complex interactions compare to many simple interactions in terms of a global product?
- What tasks must occur between manufacturing of the SOS and release to customer to verify system performance?

7.3 Utility

7.3.1 Value with Respect to Project: >1

I used my project as a platform to construct my Q4S. In essence, this Q4S is extremely valuable to the project as it represents an extension of some of the ideas posed in the project report. By further developing these ideas, I have constructed a document which allows the project to extend beyond ME6101 into ideas that could possibly be implemented into my thesis work.

7.3.2 Value for A0 Goals: >1

1. To learn the fundamental principles of self-organizing systems. Once I have sufficiently internalized these concepts, I will continue to build upon the knowledge of my predecessors. Ultimately, I will apply this new knowledge to my research into the computational synthesis of adaptive systems.

Value > 1 By completing my Q4S, I have articulated some of the concepts behind adaptivity in systems design. In doing this, I gained insight into the care that must be taken when designing adaptive systems to guarantee that emergent behavior is controlled based upon the implementation of design parameters specific to decentralized control mechanisms.

2. To learn how to analyze a pre-existing engineering system. By completing this, I will acquire sufficient knowledge to understand a systematic way to “reverse engineer” a product. This will give a deeper insight into the nature of adaptive design.
By analyzing natural and artificial systems in my project, I was able to extend some of the knowledge gained from reverse engineering the requirements of these systems to arrive at a design method for adaptive systems.

3. To learn critical thinking skills pertaining to the development of new knowledge. I will use these skills to critically evaluate my work and the work of others to perform gap analyses.

By critically evaluating my own design method, I have gained insight into the importance of identifying shortcomings of my own work. In doing this type of critical evaluation, I can continuously determine future research efforts as they pertain to adaptive systems.

4. To learn the requirements of the future. I will use this knowledge to realize the ways in which I will have to continuously adapt myself to be proficient throughout my professional career.

By developing my World of 2020, I developed an outline of the adaptations I need to make to myself as an engineer to continually be successful in a changing design environment.

5. To internalize the concepts of the P&B design process. With this knowledge, I will be fully prepared to construct a new design method to fit my future needs.

By analyzing P&B to develop my augmented method, I discovered the core transformations of P&B and identified the usefulness of the design method. For me, its usefulness is contained specifically in the conceptual design phase. The usefulness I am referring to is the abstraction, creation of a function structure, identification of working principles, and development of a working structure. I find these concepts integral in guiding me towards creating a multitude of concept variants.
Chapter 8: Learning Experience

8.1 Learning from Answering the Q4S

In answering the Q4S, I learned a variety of new concepts that pertain to both my thesis and my development as a professional engineer. These concepts include the principles of adaptive systems, systematic design, future engineering requirements, critical evaluation of my own work, the utility of the Validation Square, and how to structure a document.

8.1.1 Principles of Adaptive Systems

By completing the Q4S, I developed a better understanding of the fundamental principles of adaptive systems. These principles include the concepts of evolvability, variability, reliability, decentralized control, generalized agents, and the concept of complexity. In my Q4S, I tied these concepts together in a coherent series of thoughts for future reference material. I learned that this type of continuous archiving is integral in creating new knowledge. I discovered this by writing learning essays during the semester to create my Q4S. In doing this, I have developed a platform for the future research I will perform in the field of complex, adaptive systems.

8.1.2 Systematic Design

Before I entered graduate school, I had never taken course on systematic design. After completing my Q4S and ME6101, I have discovered the value of a systematic design method in structuring design problems to a specific accomplishable task. I found that P&B is an extremely powerful design process due to its flexibility. This flexibility arises from its application to any engineering design problem. Also, the concepts of P&B can be augmented to deliver a new method specifically customized for the development of any realizable system.

8.1.3 Future Engineering Requirements

By extensively researching for my World of 2020, I developed a working knowledge of what the future requirements of engineers will be. Some of these requirements will be a distributed design environment, judgment with respect to strategic design, well developed computational skills, and the ability to reverse engineer products due to the prevalence of adaptive design. After realizing these requirements, I have discovered ways in which I can adapt myself for this future world to increase my utility with respect to engineering design.

8.1.4 Critically Evaluating my own Work and the Work of Others

During the creation of my Q4S, I learned how to critically evaluate my own work and the work of others. I realized this skill by writing learning essays, reading journal articles and conference papers, following Farrokh’s feedback, and writing the Q4S. By writing learning essays to construct my Q4S, I found that I had to continually evaluate my work relative to a specific goal to ensure that there was value with respect to both my Q4S and A0 goals. This type of
evaluation kept me focused on the appropriate task. By reading journal articles and conference papers, I learned how to continually question the work of others through the use of ORA. I discovered that ORA is an extremely useful tool that is generally applicable to any learning situation.

8.1.5 Utility of the Validation Square

By using the Validation Square in my Q4S, I realized the reasoning behind the Validation Square. Since design methods are not quantitative in nature, validity requires a ‘leap of faith’ to demonstrate a method’s utility beyond the extent of the proposed example problems. In realizing this, I discovered that it is a systematic method for demonstrating the usefulness of a method. By articulating this usefulness, the confidence in the method can be developed for its future application.

8.1.6 Structuring a Document

A major learning experience in developing my Q4S is structuring a large document. By listening to Farrokh, I realized the necessity of forming a story with a TOC. By developing a story, it not only aids in the logical flow of thought throughout the document, but gives the writer a systematic structure for creating ideas within the story’s framework. After realizing this lesson, I feel much more prepared for structuring my thesis and possible future dissertation.

8.2 What Would I do Differently Next Time?

I view this section as yet another opportunity to express a different type of learning. This learning is in the context of another large design project. I strongly believe that I would spend much more time scoping the problem to develop a deliverable schedule in the form of a PEI diagram. By investing this time, I would have a better developed idea of exactly which direction I wanted to go and when each deliverable should be accomplished. After developing this plan, the following work would seem less difficult and more productive towards an end product.
Works Cited:


