Semester Project

Intelligent Division and Coordination of Distributed Corporate Workforces

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Executive Summary

Design complexity leads to the failure of many engineering systems because modifications to one component of the design cause successive feedbacks through interrelated design components. This feedback chain reaction ripples through the project and does not allow the design solution to converge. To compensate for these difficulties and answer our tweaked Question for the Semester, we are proposing a new design method for the future design world of 2030. This design method is based on the Pahl and Beitz systematic design method but accounts for the design of complex systems using globally distributed designers.

In order to create the design method for complex engineered systems in 2030, we have created our vision of the world of 2030 which accounts for other changes in the design environment and global dynamics. Using these drivers, we see required changes in the design process relating to the organization and coordination of design teams. By using the P&B design method as a basis, we augmented and personalized the P&B steps to modify the flow of information to complete design of complex engineered systems in 2030.

In this context, we put forward our augmented and personalized method to effectively organize the workforce and coordinate the activities of design teams. The personalization and augmentation of P&B include three novel steps: 1) determine the interrelated tasks in the design, 2) intelligently divide the design workforce into teams to complete the tasks, and 3) determine when and how to coordinate the teams to minimize the design feedbacks. These three stages will be applied at the beginning of the Conceptual, Embodiment and Detailed Design phases of the design process.

To complete these steps, we use three computational tools to model the design and the designers. First, we use the Design Structure Matrix (DSM) to identify the interdependence among design tasks. Second, we use a genetic algorithm (GA) to divide workforce into teams for the tasks. Finally, we use agent-based modeling (ABM) to find out the best coordination strategy. The modeling approaches involving the DSM, GA and ABM are introduced and verified with test cases.

Finally, we begin the validation of our augmented method by going through the Validation Square process. We argue the theoretical structural validity of the method by demonstrating the information flow within the augmented and personalized method is consistent. Then to show the empirical validation by selecting a complex design project. We look at the design of a hybrid vehicle to illustrate that the method gives good results and to begin the empirical performance validity of some of the components of the new design method. With additional examples and meaningful results, the theoretical performance validity of this method can also be expected.

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1. Context of the Project

1.1 Original Q4S

The original Question for the Semester presented in this class was:

> We imagine a future in which geographically distributed engineers collaboratively develop, build, and test solutions to design-manufacture problems encountered in the product realization process.
>
> In this context, we want you to provide a method to support the realization of products for a global marketplace through distributed design and manufacture. Specifically, how should the P&B systematic design method be personalized and augmented to support the realization of products for a global marketplace in a distributed environment?

Within this question there are a number of key phrases which have been underlined. By understanding them, it is easier to come to grasp with the goals of this assignment.

- ***Distributed*** – Refers to a design environment with the geographic dispersion of designers. Distribution will be the result of globalization and the necessity for organizations to expand and transform to maintain a competitive edge.
- ***Collaborative*** – Engineers will work together in this distributed environment by using new communication and design integration technologies. In the distributed world, engineering collaboration will be essential for completing design projects.
- ***Global Marketplace*** – This term refers to the initiation of new marketplaces due to expanding job markets in the world of 2030. New marketplaces will arise from the increased average wages in previously unexploited labor sources.
- ***Personalized*** – Making a design process usable for what we consider critical to the world of 2030. With this in mind, the process can be used to accomplish design tasks tailored to our needs.
- ***Augmented*** – Refers to increasing the utility of the P&B design process to accommodate the requirements of a global marketplace and distributed environment.
- ***Realization*** – This term encompasses the entire process from the inception of a product idea to the final distribution of the product.[1]

1.2 Context for the Tweaked Q4S

The Tweaked Q4S focuses the new design method on a major problem facing designers today. This problem is the complexity in design and the complexity in organizing a network of designers who are working concurrently but collaborating discontinuously. Major reasons for this direction are:

- Engineered systems have failed due to project complexity (Bar-Yam 1997).
- Design companies must harness the globally distributed engineering workforce to remain competitive.
- Designers and design teams are only effective if they are coordinated properly.

[1] Adopted from the Systematic Design for Self-Organizing Systems project report (Hall, J., Wagar M. & Young N. 2006)

- Coordination becomes more difficult and essential when:
    - teams are distributed.
    - company workforce is large.
    - the design is complex.

1.3 Tweaked Q4S

We chose to modify the Q4S in such a way that it would guide our augmented Pahl and Beitz method to utilize the increasing computer power available in order to design complex systems via effectively utilizing a dispersed engineering workforce.

The Tweaked Question for the Semester is:

> **How should the P&B method be personalized and augmented to support the design of complex systems in a high-paced global marketplace through the unification and coordination of globally distributed designers?**

This leads to the underlying questions that make up the Q4S:

1. How should Pahl and Beitz be augmented to be effective in the design of complex systems?
2. What is complexity? And how does it apply to systematic design?
3. How should Pahl and Beitz be augmented to employ geographically dispersed designers efficiently and effectively?
    a. How should teams be formed?
    b. Once teams are formed how should they coordinate with one another?
    c. What coordination methods should be used for a given project or task?
4. Can computational models assist the managers to form teams, develop team structures, and distribute work? If so, how?

1.3.1 Complex Designed Systems

Complex systems are hard to define because there are many scales and perspectives to view them. A definition provided by Amaral and Ottino (2002) states:

> A complex system is a system with a large number of elements, building blocks or agents, capable of interacting with each other and with their environment. The interaction between elements may occur only with immediate neighbors or with distant ones; the agents can be all identical or different; they may move in space or occupy fixed positions, and can be in one of two states or of multiple states. The common characteristic of all complex systems is that they display organization without any *external* organizing principle being applied. The whole is much more that the sum of its parts.

This definition shows the powerful nature and difficulties in working with CAS (Complex Adaptive Systems). Since the organization or control is decentralized the system can be very adaptive, but at the same time designing these systems or working with them is highly challenging. A designer who wants to design a complex system must define simple rules for the agents in the model, and hope that the global control propagates as the designer was intending.

1.3.2 Team Creation

One of the challenges that employers will face in 2030 will be how to create teams from their workforce. There will no longer be obvious divisions of the company geographically, so any member of the company could be potentially pair with any other member of the company to complete design tasks.

1.3.3 Designer and Team Coordination

Once the teams have been created, how can individuals coordinate their efforts with teammates and other teams? Coordination becomes far more difficult when the designers are geographically distributed and also when the number of team members increases. Both of these situations will occur in the future due to the flattening of the world (Friedman 2005) and as complex systems require more designers to complete them.

1.3.4 Personal Goals

The tweaked Q4S was crafted to direct our work toward our learning objective and competencies. The common competencies of the team were found at the beginning of the project and we created the tweaked Q4S based on our goals. In a nutshell, we wanted to learn and develop skills that related to systematic complex systems design in a globalized world, computational methods, and working with multidisciplinary teams. Our learning objectives and competencies are listed below.

Learning Objectives:

1. Learn and predict challenges and advantages involved in having a global engineering workforce. Investigate how management strategies and coordination mechanisms can compensate for the new difficulties.
2. Learn to use technology to accelerate and assist with the design process and find methods for creating autonomy in the design process.
3. Learn strategies to work better with multidisciplinary and large teams that may consist of non-engineers.

Competencies:

1. Ability to apply systematic design methods *in a future with a global engineering workforce.*
2. Ability to apply computational methods *in order to accelerate & assist with the design process.*
3. Ability to analyze multidisciplinary systems *and better work with multidisciplinary teams.*

1.4 Vision and Divers of 2030

Our vision of 2030 has engineering teams and individuals distributed around the world. Companies will no longer be interested in maintaining a large engineering division because it will be far cheaper and equally effective to find out-of-house people to complete their work. Communication and collaboration will prove challenging, but technological advances will ease the difficulties of group interaction, as well as assist with the design-manufacture process. Technology will also provide some autonomy in the design process and accelerate engineering designs.

Our view of the world of 2030 is driven by three major and currently ongoing changes: globalization, new technologies, and the evolution of corporate structure. These areas are broken down into components of the drivers in Figure 1. Design engineers must adapt to these changes in a timely manner to continue to excel as designers of the future. Our Q4S and augmented Pahl and Beitz method are based directly on the new drivers generated by the differences of 2030.

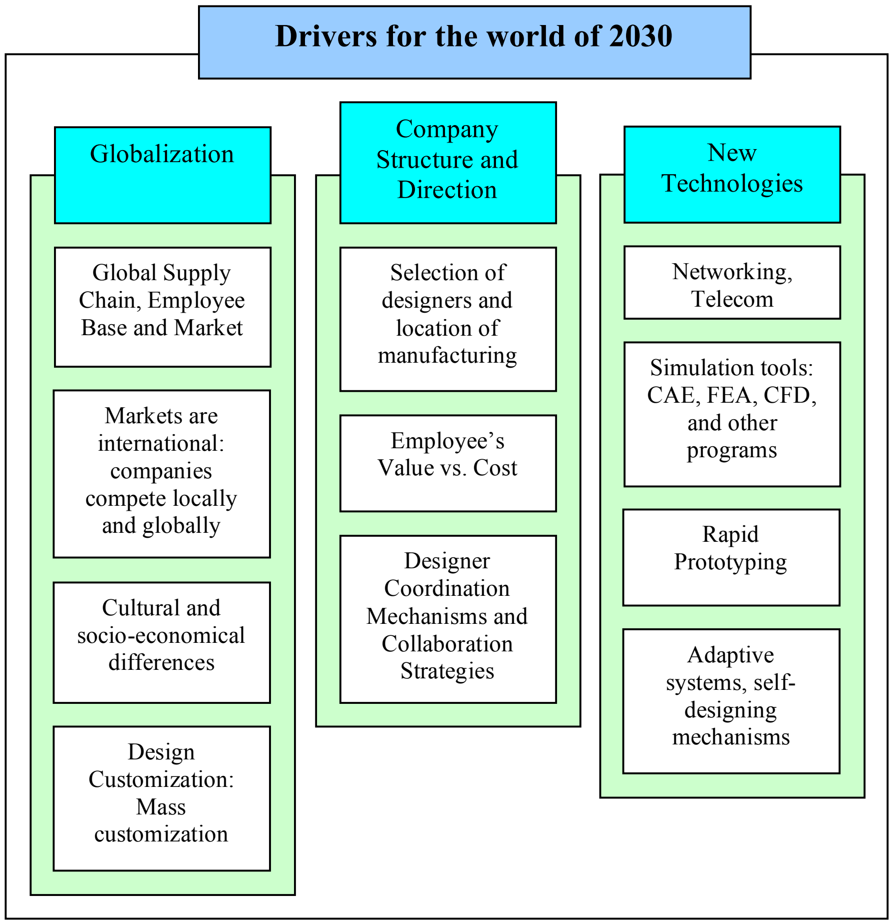


Figure 1: Drivers for the year 2030.

In order to better understand how these drivers are changing the design world, it is important to create a means to measure them. This is done by creating metrics for each of the components of the drivers. The metrics, shown in Table 1, are a tool to measure the affects of different aspects of globalization, new technologies and company and enterprise restructuring.

Table 1: Driver Metrics for 2030.

Driver	Components of Driver	Metric
Globalization	Global employees	Labor costs
	Global consumers	Profitability
	Cultural and socio-economical differences	International growth and foreign market penetration
	Design Customization	Consumer options for products
New Technologies	Telecommunications	Bandwidth
	Simulation tools: CAE, FEA, CFD, etc	Speed, errors
	Design-centric Computational Models	Man-hours on projects
Company Structure	Dispersed work force	Labor costs
	Supply chain	Profitability
	Team networking structures	Ease of communication

1.4.1 Globalization

Globalization has and will continue to distribute engineers more uniformly across the planet. This will require companies in the future to work with designers located across the globe. Further, globalization will force companies to sell their product everywhere in the world, in numerous countries and cultures. Globalization will lead to the evolution of team, company and enterprise structures, coordination methods, and new forms of communication.

1.4.2 New Technologies

Technological advances are giving designers new tools everyday. Since the publication of Pahl and Beitz, technological developments such as CAD, FEA and CFD have changed the way the design process is structured in many ways. In the future, collaboration will drive engineering design, and will be the foremost topic of discussion in this paper. Companies will improve production rates from fewer engineers by distributing tasks more efficiently. This added production will also come from companies' ability to use models to develop better coordination methods between designers and design teams. Lastly, communication technology will be far more efficient than it is today and allow geographically distant teams to collaborate more easily.

1.4.3 Company Structure

Company structure has also been evolving since the Pahl and Beitz publication; companies are leaving behind the "chief engineer" model and moving to more of a team structure. We feel this will continue to occur in the future at an accelerated rate, thus it becomes increasingly important to be able to form and coordinate teams. This is where our modeling is applied, which will help managers effectively do this work.

2. Augmented and Personalized P&B Design Method

2.1 Overview of P&B Design Method of 2030

The Paul and Beitz methodological foundation has remained intact for the new design method for the year 2030. The structures are also built from abstract to concrete seen in Figure 2 and there are still four phases of design concretization, including:

1. Planning and Clarifying the Task
2. Conceptual Design
3. Embodiment Design
4. Detail Design

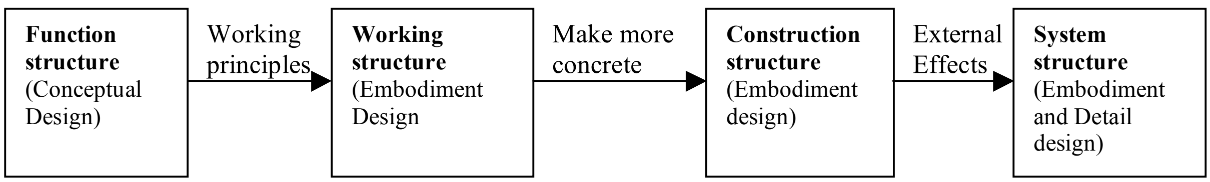


Figure 2: Method to move from a function structure to a system structure.

2.2 Information Flow in the Method

The flow of information through the P&B design process can be illustrated as a transformation of information into knowledge. As shown in Table 2, inputs of information about the design are transformed into outputs of known information at the end of each phase of design process.

Table 2: The core transformations in the P&B systematic design phases.

Transformation	Input(s)	Output(s)
Clarification of the Task	Problem	Requirements list, design proposal
Conceptual Design	Requirements list, design proposal	Function structures, morph matrix, solution selection
Embodiment Design	Function structures, morph matrix, solution selection	Preliminary layout and design, solution evaluation
Detail Design	Preliminary layout and design, solution evaluation	Technical layout and design

This can be expanded to include the deliverables that must come out of each of these phases of the design process. As shown in Table 3, the deliverables and their value to the design process are listed.

Table 3: The deliverables and their value in the P&B design phases (Mistree 2007).

Phase	Deliverable	Value
Planning and Clarification of Task	Requirements list	Identifies customers want for the product
Conceptual Design	Abstract requirements list	Identifies the function specific requirements to form solution-neutral problem statements
	Function structure	Identifies the functions and organized the flow of energy, matter and signal
	Morphological matrix	Catalogs the working principles and organizes them to meet the functions
	Solution evaluation	Systematic method to evaluate concepts in order to proceed with the design
Embodiment Design	General layout requirements	The requirements that only deal with the layout of the design are identified
	Preliminary layouts	Form the general layout of the produce in a solution neutral format
	Solution evaluation	Again, systematic method to evaluate, in more detail, design as they proceed
	Preliminary Diagram	Help to envision the layout of the design in with minimal knowledge about the details of the product.
Detail Design	Final Layout, forms, dimensions	Enables the part to be made, operated, assembled, etc.

2.3 Gap Analysis of P&B Requirements

From our vision of 2030, it was clear that there are number of unidentified needs in the P&B method. To determine what was precisely missing from the P&B approach and how it could be improved, a gap analysis was preformed on their methodology.

The gaps in the current Pahl and Beitz method include:

1. difficulty organizing and collaborating with a distributed team of engineers and using concurrent design options
2. no means to communicate with a multidisciplinary, globally distributed team
3. no software based design tools

P&B saw the designers working under one roof on one project but in the future engineers are going to be distributed around the globe. This will redefine the way the problems need to be posed as well as solved. Organizing who is going to take responsibility for which aspects of the designs and working out how everyone can stay on the same page will be difficult. There is also is a lot of emphasis on concurrent engineering to accelerate design times and produce products quicker. There must be a means to work some of these tasks in parallel to reduce the time to production.

P&B also did not consider multidisciplinary design or the use of software in the design process. Their method is for mechanical design and solely addresses the processes to create mechanical products. In the future designs will incorporate many disciplines to create complex systems, so P&B cannot handle this situation. Additionally their method was created before the use of computational tools in the design process. Therefore their design method does not use them to evaluate design solutions or organize the design process. In the future computational tools will be utilized for organization of the design process as well as the in the design process itself.

2.4 Requirements List for 2030

After completing a gap analysis between the P&B requirements list and the method for 2030, a number of major additions had to be made to the requirements list. From the Tweaked Q4S there were two fundamental goals for the augmented and personalized Pahl and Beitz method:

1. provide a systematic means for the design of complex systems
2. present a method(s) to divided and coordinate engineers into efficient groups.

Other changes to the requirements list were formulated from the influences of the drivers of 2030. Looking back at the drivers for the world of 2030, there were a number of gaps in the current P&B method, and thus the modifications in Table 4 were made.

Table 4: Modifications to the design process requirements list based on drivers of the world of 2030.

Modification	Basis from Drivers of the 2030 world
Compatible with data processing *and online/transmittable media*	New Technology, Networking
Provide a method to continuously share information	New Technology, Networking and Telecommunication
Capable of being used with different collaboration techniques (e.g. evolutionary design, general teams, concurrent engineering)	Management Effects, Coordination
Capable of producing advanced systems like complex adaptive systems and self-designing mechanisms	New Technologies, CAS and self-designing mechanisms

Combining all these concepts, the original P&B method gaps are bridged using the requirements list shown in Table 5.

Table 5: Requirements List for the World of 2030.

ME6101	**Augmented Requirements List for P&B design method**		Issued: 10/10/07 Page 1 of 1
	**Problem Statement:** Reconstruct the requirements list for the Pahl and Beitz design method		
Changes	**D/W**	**Requirements**	**Resp.**
09/05/2007		**1. General requirements**	
	D	Encourage problem-directed approach	
	D	Applicable to all life cycle design activities – encompass original, adaptive and variant designs	
	D	Open to expansion, customization, adaptation	
	D	Compatible with data processing *and online/transmittable media (augmentation)*	
	D	Means of standardization	
	D	Compatible with concepts, methods, and findings of multiple disciplines	
	W	Flexible and adaptable for the specific application	
	W	Easily allows iteration	
	W	Incorporate constraints (economic and technical)	

	W	Include goals, sub-goals and their importance	
09/05/2007	 D **D** W W W	**2. Human Effects** Easily taught, learned, understood and followed Basis of communication for all people involved Reduce design workload Prevent human error *by demonstrating variant principles with hardware and software tools (augmentation)* Give designers a means to compare solutions	
09/05/2007	 D D D D W W W W W W	**3. Solution finding** Facilitate the application of known solutions Foster inventiveness and guide designers Abstract the problem to open up solution possibilities No reliance on chance Incorporate designs for cost, quality and mass customization Allow designers the freedom to specify the design towards its intended purpose e.g. assembly, recycling Create variants Remove prejudices *Allow concurrent design methods (personalization)* *Allow the design of complex systems (personalization)*	
09/05/2007	 W W W	**4. Economics** Look at the market and consider risk prior to initiating the design process Require economic feasibility checks *Looks at the sustainability of the design and environment – energy and material costs (a)*	
09/05/2007	 W **D**	**5. Group structure** *Provide a method to divide designers into efficient groups (p)* *Suggest group structures and the coordination mechanisms to communicate between the groups (p)*	

To briefly touching on the changes:

- 'Compatible with data processing' has been expanded to include online and transmittable media, because the method will no longer be useful if the designers work is not sharable. It must be sent back to the company, to other engineers and to the manufacturers.
- Preventing human error has been elaborated to indicate which ways the method should do this: by software and hardware checks. This can be quick or time consuming, but are generally very cheap and if these methods catch human errors, who knows how much money would be saved.
- Having the team centrally located was needed in the original P&B method, but has been removed for the world of 2030. Teleconferencing or storable, sharable media will replace this requirement.
- Teams need a way to share their information continuously so that everyone associated with the project is up to speed when they need to add input. This way everyone can be working on the same project at the same time from anywhere in the world.

2.4.1 Design Teams in the Design Method of 2030

The major change to the design method is to handle the distributed designers. By the year 2030 the engineering workforce will be distributed throughout the entire world, making it impossible for corporations to remain competitive without a new way to organize teams. Organizing teams consists of three parts: first creating the teams, second distributing tasks, and thirdly creating coordination methods between teams. The facets of this are summarized by:

- **Creation of Teams:** P&B assumed that the design process would occur with a small team in a central location. With designers scattered across the world, there is more emphasis on grouping and managing them.
- **Collaboration of Teams:** Once the teams are formed they must collaborate to ensure their respective components of the design are compatible.
- **Communication between Teams:** The design processes should also allow a means to continuously update and upload the design information and requirements list. This way everyone involved with the project is aware of the changes being made and can access that information. This online community will also assist with the collaboration issues and provide information continuity between everyone on the design team in order to orchestrate the design process with a distributed workforce.

3. The Augmented and Personalized Design Method

3.1 Overview of Components of Augmentation

Once we completed our gap analysis between the present form of Pahl and Beitz and the year 2030 we found there were three major areas that needed to be addressed. These areas are design complexity, team formation, and team coordination. In our Augmented Pahl and Bietz our augmentations to Pahl and Beitz do not affect the overall information flow of the Pahl and Beitz design methodology; instead, we have added steps to assist the process. We have made distinct changes to each phase of the design. Within each of these areas we have focused on three main areas: design complexity, workforce division, and coordination.

3.2 Changes to the P&B Design Method

The augmented P&B method takes into account the needs formulated from the Requirements List, as shown in Table 6.

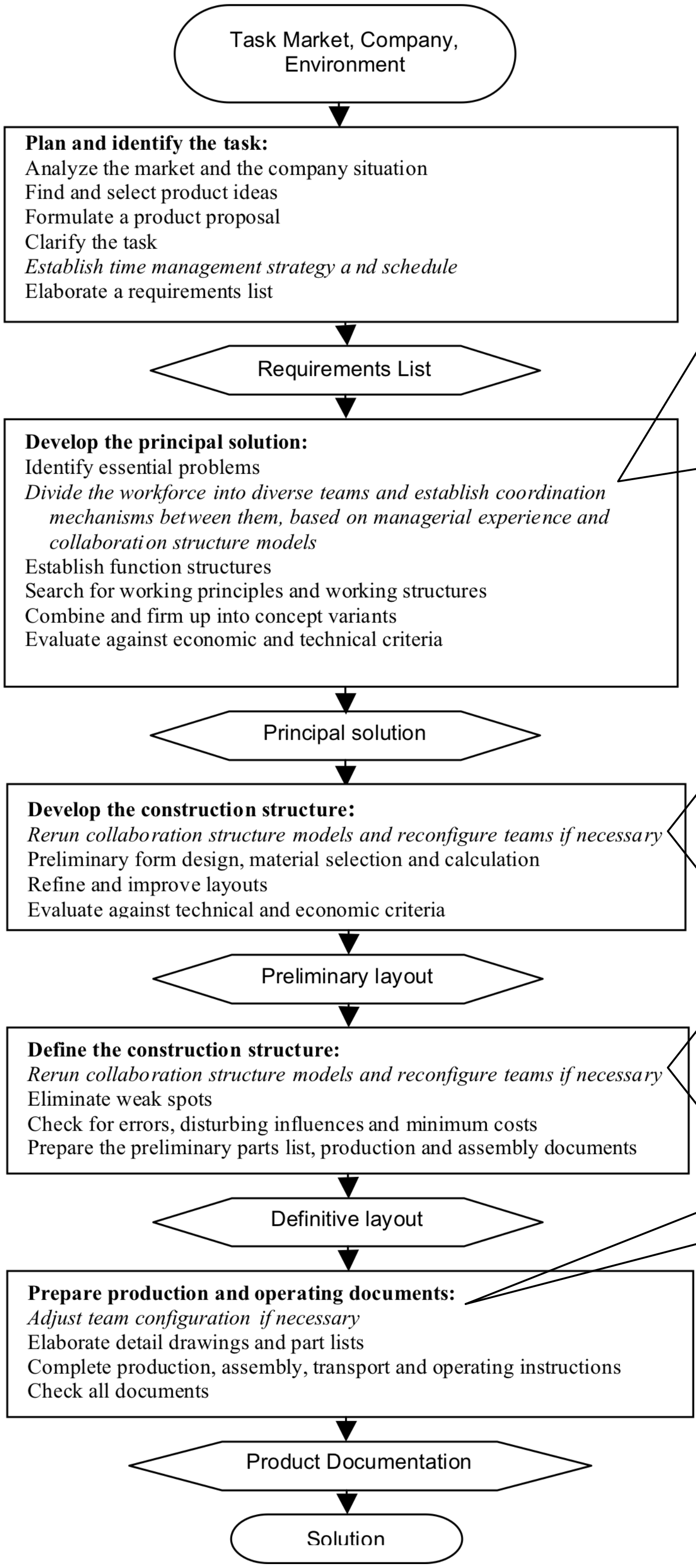
Table 6: Modifications to the P&B design method.

New Design Process Ability	Where it appears in the Process
Complexity of the design is modeled	conceptual, embodiment and detail design phases
The workforce is divided	conceptual, embodiment and detail design phases
The design teams are coordinated	conceptual, embodiment and detail design phases
Design process is divisible and available for concurrent engineering	conceptual, embodiment and detail design phases
The process utilizes electronically distributable and adjustable concepts, solutions, structure, ideas, documentation, layouts, forms, and other design resources	along the entire process, but not shown

3.3 The Augmented and Personalized Pahl and Beitz Method

After considering each of these components of the design process we were able to apply these ideas to the Pahl and Beitz method to derive our augmented method. Our augmented Pahl and Beitz method can be found below in Figure 3. From this figure it is clear that we added a similar three-step processes to each of the four main phases of Pahl and Beitz. This three-step process is going to help each phase of the design process run more quickly and more efficiently in the distributed environment of 2030 and will be necessary for the design of complex systems.

From the diagram it is clear that each step we have added to the Pahl and Beitz method is associated to a certain core transformation. These core transformations that we have added to the system are going to continue to become more important in the future. These transformations can be seen on the right side of Figure 3.



New steps for the conceptual design phase

Transformation	Requirements	Goals
Step 1: Determine which designers are working on the project and their skills		Find designers for the project and understand their strengths
Step 2: Divide workforce into teams for conceptualization	Know the available designers and their skills	Create teams to generate concepts
Step 3: Find the best coordination strategy	Know the teams and the estimated amount of time for conceptualization	Determine which teams should coordinate and when they should coordinate.

New steps for the embodiment and detailed design phases

Transformation	Requirements	Goals
Step 1: Use DSM to identify the interdependence among design tasks	Know the tasks/ components required in the design	Find concurrent and sequential tasks
Step 2: Divide workforce into teams for the tasks	Know the available designers and their skills	Create teams to complete each of the tasks in the least amount of time
Step 3: Find the best coordination strategy	Know the number of teams and the estimated amount of time for the project	Determine which teams should coordinate and when they should coordinate.

Figure 3: Augmented Pahl and Bietz Method

3.4 Understanding Design Project Complexity

We have defined complexity as the interrelationships among tasks within a design, i.e. is task 1 related to the other tasks. If we can fully understand what tasks are related to one another then we can accurately determine what order the tasks should be completed. There are many methods used for evaluating design complexity, we have decided to adopt the Design Structure Matrix (DSM) tool. We feel DSM offers the clearest way to illustrate task interdependencies and offers designers a way to break blocks of tasks into independent chunks that can be addressed sequentially.

3.5 Team Division

A large change we have made is the computational division of the workforce into teams at the beginning of each of the phases of conceptualization, embodiment and detail design. In the conceptualization phase the design teams will be constructed by maximizing the diversity in the group of individuals by emphasizing different specialties so that the full range of design issues and concepts can be investigated in conceptualization. In the embodiment and detail design phases the teams will be created on the basis of their expertise. The mechanical engineers will work on ME things and the electrical engineers will work on the electrical engineering components of the design. They will need to be coordinated to ensure that their component designs will be compatible with each other when the design comes together. In order to do this effectively a new concept has been developed: the idea of "skilled man-hours." This allows us to quantify both our designer's skill in each task and the difficulty and duration of the tasks. This idea relies on two major assumptions: 1) it is possible to accurately rate our designers task specific skills, and 2) designer talent can be combined with no loss, i.e. if it takes one designer 2 days to complete a task it should take 2 equal designers one day to complete the task

3.6 Team Coordination

We define team coordination as the sharing of information between two teams working on two interrelated tasks. It is important to note that the more frequently teams coordinate does not mean the more effective and efficient they will work. We suggest that the coordination between the teams, which drives the reduction of design oscillations, need to find a balance between too frequent and not frequent enough. To model this, we have once again we have had to introduce a new concept: the idea of "coordination cost," which is in essence is the time lost to meetings. Our goal was to develop a computational method to find the best balance between coordination and coordination costs. In the simplest terms, there are three areas we can the coordination frequency can lie: too much coordination, too little coordination, or in the middle ground, as shown in Figure 4.

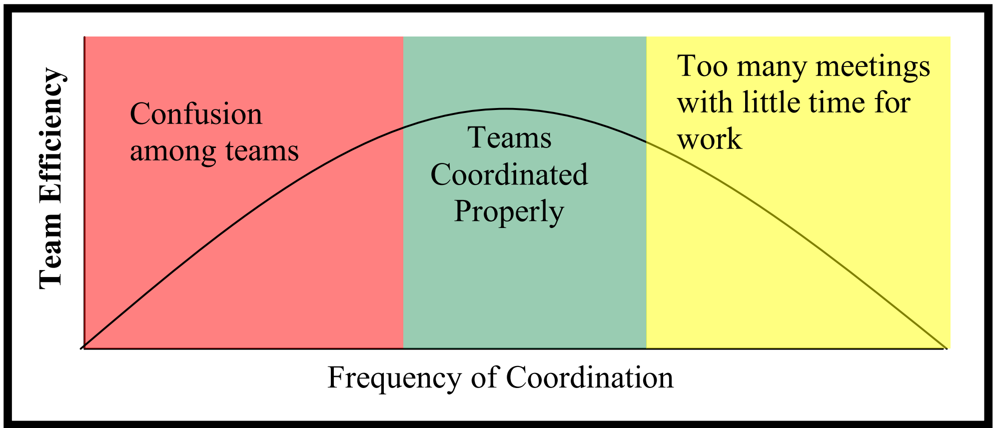


Figure 4: Efficiency vs. Coordination Frequency

An important distinction to make regarding coordination mechanisms is that continually sharing information is not the same as having one large team. Each of the groups is working on their own solution to the problem but sharing their work with the rest of the community to try and keep the other groups from making the same mistakes.

Within coordination there are three main types we have chosen to look at seen in Figure 5.

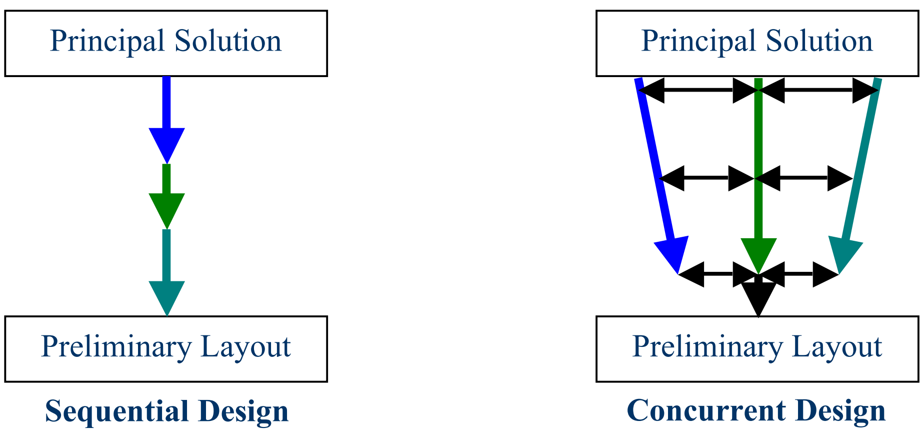


Figure 5: Team coordination mechanisms

These three coordination fit into two main categories:

- Sequential Engineering (Sequential Design)
  - If the design teams work in series then there may be a reduced chance for iteration because the previous work will be finalized. This is most applicable when the teams' design parameters are not tightly interrelated.
- Concurrent Engineering (concurrent design)
  - When designers have decoupled design parameters it is simple to have each of the teams separately complete their designs independently.
  - When the parameters of the design are interdependent this can also be helpful because the designs move from the abstract to the concrete at the same time. So it is easier to find design conflicts before extra embodiment work has occurred.

4. Modeling and the Computational Tools in the Method

4.1 The Big Picture: Where the models fit into the Method

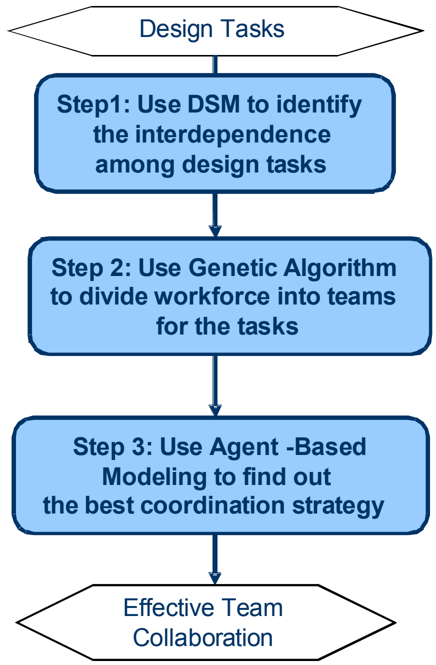


Figure 6 : Overall map of modeling process in our method

The three step modeling method we propose should be used in the conceptual, embodiment and detail design. As shown in Figure 6, when there is a design project, we first use Design Structure Matrix (DSM) to identify the interdependence of the design tasks and propose a design team for each design task from the available skilled designers. Then we make use of the Genetic Algorithm to assign them into design teams in order to minimize the design time. Afterward, we use Agent-Based Modeling method to identify the most appropriate coordination strategy for the design teams. Through this modeling process, we achieve the effective team structure and collaboration.

4.2 Modeling Design Complexity

Why do we need a model of complexity? The design complexity is what provides feedback on the design process. Without complexity the design process can proceed completely smoothly. However, when two components are not designed compatibly, design iterations will emerge. To this extent, the complexity is the major contributor to the design iteration. To handle complexity, first we need to find a description of it. There are many kinds of definitions to complexity, but we consider complexity to be "the interdependencies and interactions of design tasks."

There are several kinds of relationship between design tasks, as show in Figure 7. The first type is series, in which design task B simply needs information from task A. In the second kind, called parallel relationship, the progress of both the tasks does not need information from the other. These two types of task relationships are relatively easy to deal with. However, if the design process of task A needs the information from task B, at the same time task B needs information from task A, this kind of coupled relationship will make it difficult to make the design decisions since the interdependence will lead to design iterations.

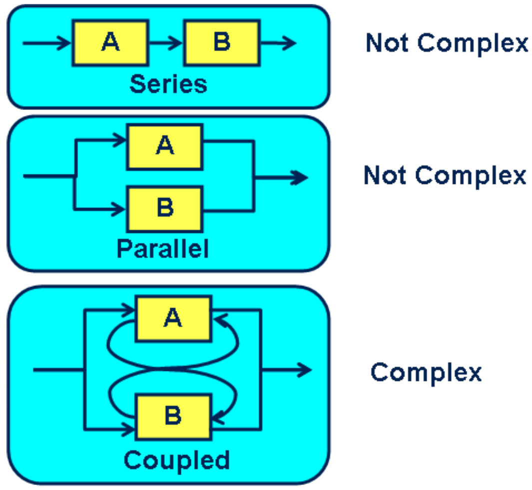


Figure 7: Complexity of design task

4.2.1 Introduction to DSM

To model the interdependencies among tasks, we will use the Design Structure Matrix (DSM). It is an important support tool to group the activities in order to minimize the interdependencies among groups.

Based on the product architecture and the resulting component interfaces, the DSM captures the interdependencies among the design tasks in the sense that tasks need input from other tasks in order to be completed. The philosophy of the DSM method is that the design project is divided into individual tasks, and the relationships among these tasks can be analyzed to identify the underlying structure of the project (Eppinger 1994).

	A	B	C	D
A		X		
B			X	
C		X		
D	X		X	

	B	C	A	D
B		X		
C	X			
A	X			
D		X	X	

Figure 8: Original and Partitioned DSM

For example, in Figure 8 the left DSM shows four design tasks, A, B, C, and D. The marked elements within each row identify which other tasks must contribute information for proper completion of the design. For example, the marks in row D are in column A, C, indicating that execution of task D requires information to be transferred from A and C. These tasks can be reordered as shown in Figure 8 on the right DSM, so that the tasks do not case as significant design feedbacks (indicated with tick marks above the diagonal).

4.2.2 Methods to model interdependencies

The first step of design structure analysis is to find a sequence of these design tasks which allows this matrix to become lower triangular. If the tasks can be sequenced so that each one can be executed only after it receives all the information it requires from its predecessors, then no coupling remains in the design problem. However, because of interdependencies of tasks, this kind of situation rarely happens. Instead, analysis usually yields a matrix in a block-lower-triangular form. The blocks on the diagonal depict coupling due to feedback, and the remaining below-diagonal marks represent the feed forward of information to later tasks. The right part of Figure 8 shows the matrix from the left part of figure 9 after the tasks have been rearranged by interchanging rows and also swapping the corresponding columns to achieve a more organized design sequence. After this rearrangement, we find that the sequence of the design tasks should have B and C proceeding concurrently, then A, and finally D. To sum up, DSM can provide the structure of interdependencies of the design tasks.

4.3 Modeling Designers

This part of the modeling process helps to identify the skills of the designers, in order to assign them to the design task teams.

4.3.1 Modeling assumptions

As with all modeling processes, there are a number of underlying assumptions in the model. In our models, all of the designers are ranked on a 1 to 5 scale for each of the tasks. Some of the assumptions that went into modeling the designers were:

- The designers' abilities can be ranked accurately.
- All designers and their managers will use the same scale to rank all employees.
- Everyone can be broken down into skill, but whether this incorporates ambition, tenacity, dedication, intelligence, or other personal attributes is unknown.

4.3.2 Modeling process

For any complex design project, there are many available designers who need to be assigned to work on a number of interdependent design tasks. It is necessary to assign these designers to the design tasks according to their skills and the requirements of that task. Generally each task will be spearheaded by a design team, but the first step of this process is to model the skills of designers.

For a given design project, each task/team may require quite different types of skills than other tasks. We first summarize the design tasks/teams need, and then rank the designers' ability of these skills. The rank is based on a 5–point scale. The designer's rating can be determined by managerial, coworkers or self-evaluation. Table 7 is an example of designer rating: Called a Designer-Task Matrix.

Table 7: Modeling Designers' Skills

	Team1: ME	Team2: EE	Team3: CS	Team4: CE
Designer 1	2	4	4	1
Designer 2	3	1	1	2
Designer 3	2	1	3	2
Designer 4	2	1	2	1
Designer 5	1	2	1	2
Designer 6	4	5	3	5
Designer 7	5	3	4	4
Designer 8	5	1	1	3
Designer 9	2	4	1	4

In this table, designer 1 has more skill in Electrical Engineering (EE) and Computer Science (CS), while she/he is not an expert with ME or CE topics since the abilities in these categories are only 2 and 1, respectively.

4.4 Modeling Division of Workforce and Teams

Once the available designers and their skills are known, the design manager must select who is going to work on each of the tasks. The flow of information through this section of the design is show in Table 8. The requirements for this step of the design process are determined in the previous step using DSM and designer modeling and from an estimation of the time to complete each of the tasks. The goal is to have teams selected to complete each of the design tasks.

Table 8: Requirements and goals from the Division of the Workforce.

Design Step	Requirements	Goals	Computational Tool
Division of the workforce into teams	The designers and their skills, the tasks and their approx time to complete	Teams to complete the tasks in the least amount of time	Genetic Algorithm

To verify this step of the design, the computational tool must also be verified. The tool was calibrated to find a set of parameters which would produce optimal results the majority of the time. Since the process is stochastic, there is always a chance that the results do not represent the global optimal, but a local optimization of team formulation.

4.4.1 Modeling Assumptions

To run this optimization routine there are a number of assumptions that must be made. Some of the largest assumptions are:

- Everyone is capable of working with everyone else. Language, culture, geographical location, religion and other life experiences do not conflict with the creation of any type of team.
- Productivity is additive: “Two heads are twice as good as one.” If 2 designers can each complete a task in 1 day, then they can complete the same task in ½ a day. This could be

an overestimate or an underestimate. They may be able to help one another finish the project quicker by pushing each other, encouraging work, and double checking each other's accuracy; or they may tend to encourage negligent and lazy behavior. However both of these effects are expected to be insignificant because in the distributed world of the future, the designers will not be interacting directly with each other (at least not face-to-face all of the time), so they will be able to work uninterrupted and without distractions from the other team members. Therefore, their skills will be assumed to have the superposition property.

- There are no hard and fast "rules" on how many people should be on a team. The code has no preference in evenly dividing the workforce between the tasks. That means that one person could be working on one task, and 10 people are completing another task.

4.4.2 The Algorithm

A genetic algorithm (GA) was written to input the designers and task times and explore the team possibilities to find the best team selection. The logic of the algorithm is shown in Figure 11. Basically, the population of designer divisions (chromosomes) are initialized randomly, but in a way that the total time will not be infinity. From there, two of the divisions are selected at random and a random point in the string of designers is selected as the crossover point. Two children are created from the resulting genetic exchange as shown in Figure 9.

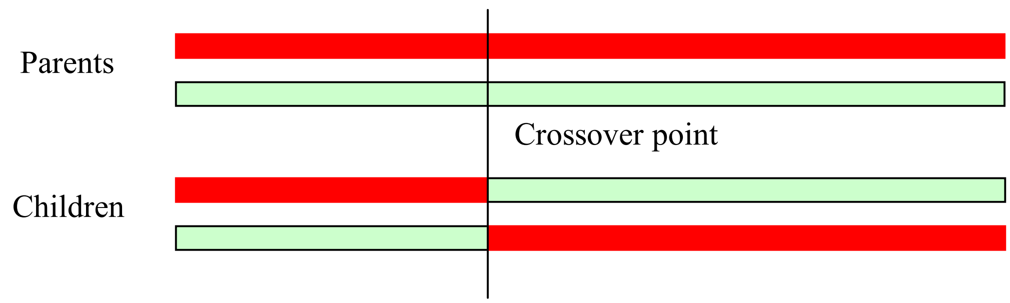


Figure 9: Principle of Crossover.

These children or new designer divisions then have a percentage chance of having a mutation of some of their designers to new tasks (their genetic structure is randomly mutated). After the mutation step, the total population is sorted based on a fitness function. This fitness function is the total time to complete the project, or the maximum time of all the tasks. Once that is done, the weakest members of the population (the designer divisions with the longest time) are removed from the population and the gene pool. To determine the termination of the GA, the change in the total population fitness is inspected. If the current fitness and the fitness from the Y^{th} previous generation show a changed less than a certain percentage (about 0.5% in the code), then the code is terminated and the best team division is output. For a small Y value the code termination can be seen in Figure 10.

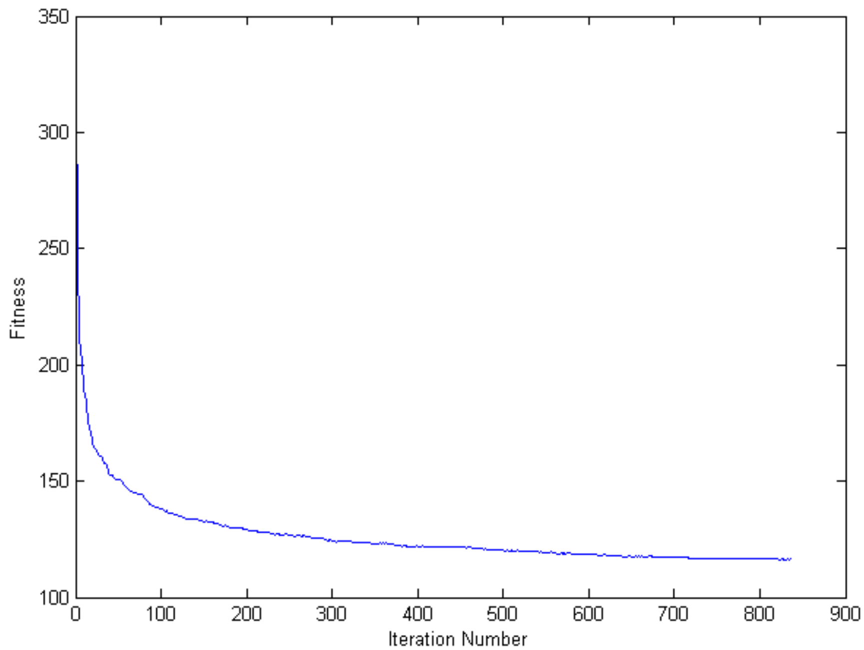


Figure 10: The change in population fitness with time.

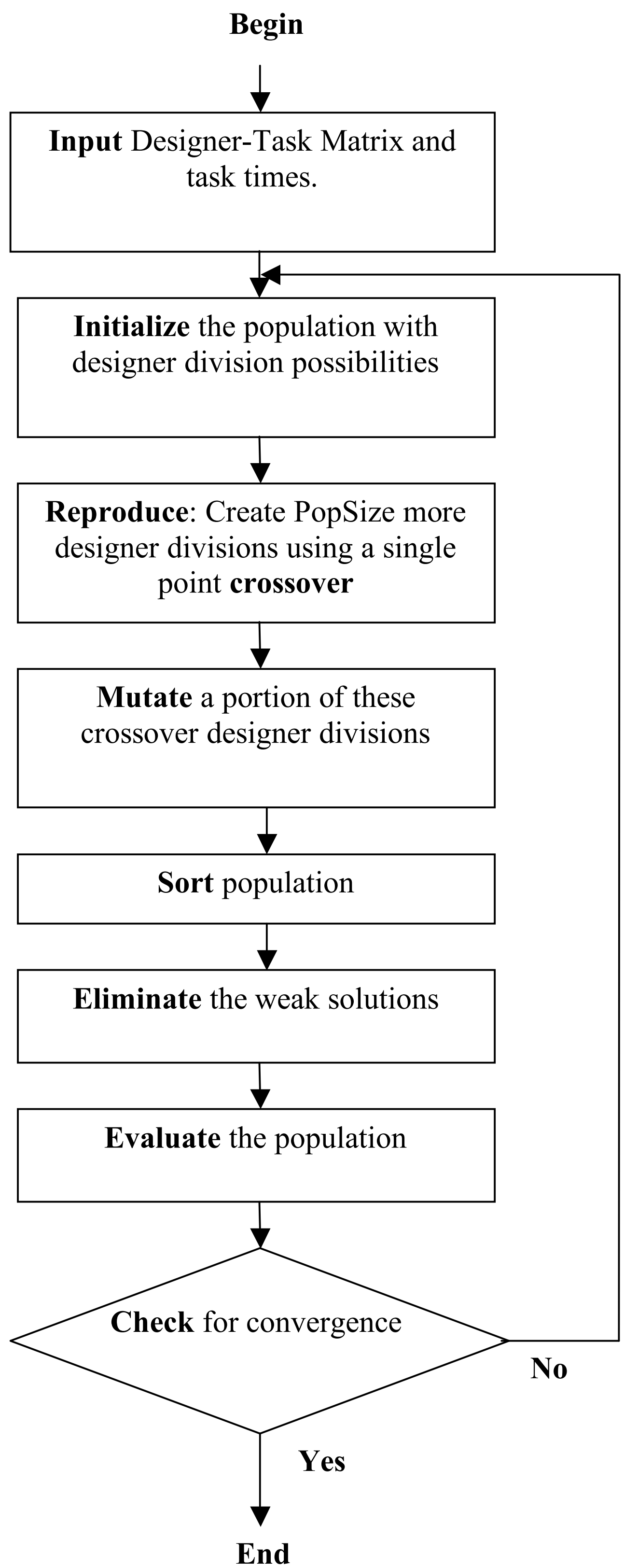


Figure 11: Genetic Algorithm Logic

4.4.3 Test Case

In order to find the parameters to use in the model, a test case was created. The size of the design space was kept to a minimum so that the true solution could be determined. In this case the Designer-Task Matrix is shown in Table 9.

Table 9: Designer-Task matrix with skills for each task on a 1-5 scale.

	Task 1 Skill	Task 2 Skill	Task 3 Skill
Designer 1	2	1	2
Designer 2	3	4	1
Designer 3	5	3	2
Designer 4	4	3	2
Designer 5	4	3	4
Designer 6	5	1	2
Designer 7	2	3	1
Designer 8	1	3	1
Designer 9	4	5	2
Designer 10	1	3	4

Given the task times were 70 for Task 1, 30 for Task 2, and 20 for Task 3, the brute force code determined the best team division at a total time of 3.5 time units. Using this as the standard for basis between different parameters, a table was created to find the best parameters in the GA, shown in Table 10. To create the table, 1000 trials with each of the different cases were run, a histogram was created and the average value of the solution and the number at the optimal were used to compare the methods. In Figure 12, the changes in the solutions for different population sizes can be seen.

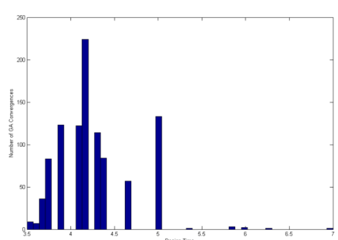
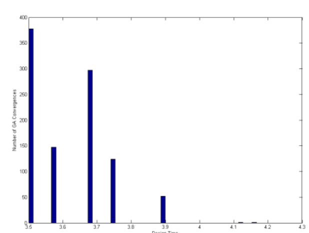
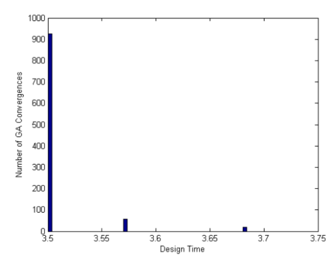
Population Size = 5.	Population Size = 200.	Population Size = 200.
		

Figure 12: Histograms for different population sizes in the GA.

Using the inputs of population size, mutation probability and rate, and convergence parameter (number of iterations/generations without a significant change in the population fitness before termination), the parameter values for larger scale designer division problems were selected. Because of time constraints some of the "well performing" simulation parameters were not used, but instead poorer performing parameter combinations were run multiple times to find the optimal convergence. To automate this process, a hybrid GA was created that reinitialized the entire population except the best from the previous solution. This is not as good as rerunning the GA because the solutions are biased toward the previous solution, but it often found new minimum times, as shown in Figure 13.

Table 10: Parametric Variations for the GA, with average value and convergences at the optimal solution tabulated.

PopSize	MuProb	CoRate	MuRate	Number of Trials	Convg Param	Best	Avg	# @ optimal
5	10%	PopSize/2	30%	1000	50	3.5	4.2496	9
10	10%	PopSize/2	**30%**	1000	50	3.5	3.9595	45
20	10%	PopSize/2	**30%**	1000	50	3.5	3.7893	120
30	10%	PopSize/2	30%	1000	50	3.5	3.7037	198
50	10%	PopSize/2	30%	1000	50	3.5	3.6177	378
100	10%	PopSize/2	30%	1000	50	3.5	3.5448	687
200	10%	PopSize/2	30%	1000	50	3.5	3.5075	**924**
10	10%	PopSize/2	**60%**	1000	50	3.5	4.0080	22
20	10%	PopSize/2	**60%**	1000	50	3.5	3.8317	83
10	10%	PopSize/2	**100%**	1000	50	3.5	4.0541	21
20	10%	PopSize/2	**100%**	1000	50	3.5	3.8726	81
10	10%	PopSize/2	**20%**	1000	50	3.5	3.9494	**56**
20	**10%**	PopSize/2	**20%**	1000	50	3.5	3.7761	**136**
10	10%	PopSize/2	**10%**	1000	50	3.5	4.0605	34
20	10%	PopSize/2	**10%**	1000	50	3.5	3.8623	87
20	**25%**	PopSize/2	20%	1000	50	3.5	3.6665	307
20	**50%**	PopSize/2	20%	1000	50	3.5	3.5921	457
20	**75%**	PopSize/2	20%	1000	50	3.5	3.5525	570
20	**100%**	PopSize/2	20%	1000	50	3.5	3.5229	**737**
20	**90%**	PopSize/2	20%	1000	50	3.5	3.5285	672
20	100%	PopSize/2	**30%**	1000	50	3.5	3.5383	636
20	100%	PopSize/2	20%	1000	**25**	3.5	3.5371	654
20	100%	PopSize/2	20%	1000	**50**	3.5	3.5194	778
20	100%	PopSize/2	20%	1000	**200**	3.5	3.5153	787
100	100%	PopSize/2	20%	1000	**500**	3.5	3.5004	994
100	100%	PopSize/2	20%	1000	**200**	3.5	3.5003	996
100	100%	PopSize/2	20%	1000	**100**	3.5	3.5003	996
100	100%	PopSize/2	20%	1000	**50**	3.5	3.5004	994

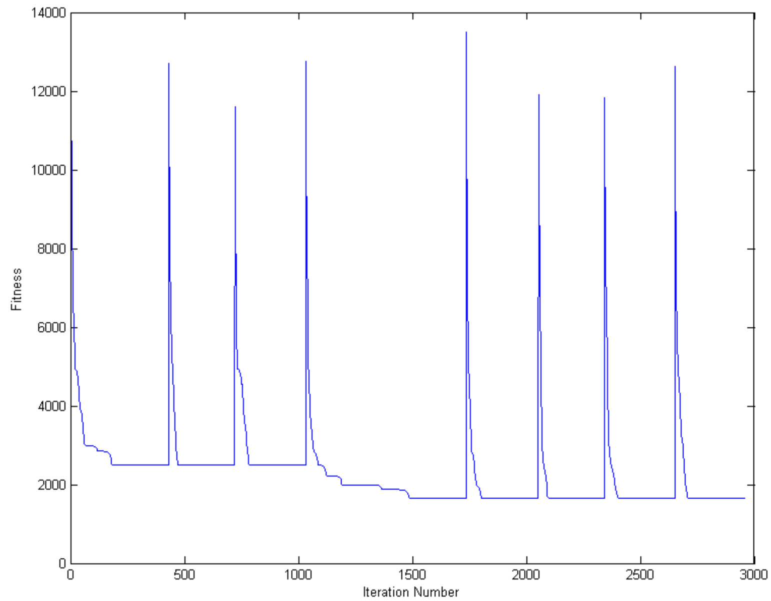


Figure 13: Multiple GA runs where the best solution from the previous test is saved. Notice a new minimum was found on the 4th trial.

4.5 Modeling Coordination

Now that we have identified the organization of the design team and the relationship among design teams, the next step is to find the coordination mechanism for these design teams. In this project, we make use of the Agent-Based Modeling method to model the design coordination and help find the appropriate coordination strategies among design teams.

4.5.1 Introduction to Agent-Based Modeling

An Agent-Based Model (ABM) is a computational model for simulating the actions and interactions of autonomous individuals in a network, with a view to assessing their effects on the system as a whole. In ABM, the focus is on global behavior arising from local rules and interactions of individual agents. Bonabeau (2000) gives some key characteristics of Agent Based Models as:

- Complex, real-world systems are modeled as collections of autonomous decision-making entities, called agents
- There is no centralized control or planning required.
- The agents follow a few simple rules and have bounded rationality.
- Agents only require local knowledge and visibility.
- Interactions between these agents result in complex emergent global behavior.
- Behavior exhibits dynamic-equilibrium and adaptation.
- Agents can communicate with each other directly or through the environment.

ABM is a method for studying systems exhibiting the following two properties: (1) the system is composed of interacting agents; and (2) the system exhibits emergent properties, that is, properties arising from the interactions of the agents that cannot be deduced simply by aggregating the properties of the agents. By simulating an approximation of real-world behavior, the ABM approach focuses on how processes evolve over time and how policies might be changed to affect the outcomes of an evolving system. (Bonabeau 2000)

4.5.2 Using ABM to Model Coordination

As stated by DSM in a previous section of the project, many design tasks are dependent on each other. While each design team can make design decisions according to its own experience, knowledge or rules, its behavior will influence others and the overall design process will present emergent behavior. In the ABM context, we consider each design team (and task) as an agent. Each agent coordinates with others according to its own coordination rules. With all the agents interacting with each other based on these rules, we get performance results. For example, we can see how many iterations these agents need to make the design converge. By changing the coordinating rules of these agents, we expect to get different results for the design process and overall design performance.

4.6 Rules of agents

The rules of agents are the key issues of the ABM practice. Our research aim is to find the best rules of coordination for a particular design problem. The coordination rules of agents will be mainly about three aspects: 1) whom to coordinate with 2) how to coordinate with them, and 3) how often to coordinate with them.

For different coordination rules, the time (or iterations) they require to converge the design parameters will vary. The best coordination mechanisms are those which need the fewest iterations to make the design converge. Basically there is a mapping: the design situation is mapped into a simulation and the best coordination mechanism is found, which is then mapped back into the real world.

4.6.1 An example of ABM for design coordination

For this project we develop coordination mechanism in Matlab with the concepts of ABM. This model is elementary, but it captures many of the facets what an ABM will be capable of performing with the design process in the future. Our model contains two interdependent design agents, each of which determine their own design parameters. The coordination aim is to make their design parameters the same as soon as possible after 1000 iterations, which is the expected time to complete the design process (and considered the minimal solution convergence time in the model).

In each iteration, the design parameters are determined based on a random walk. That is to say, in the uncoordinated case, the possibilities that the parameter of the next iteration is larger or smaller than current one are both 50%. Every so many iterations the teams have a meeting and check on each other. During meetings, the agents compare their design parameters. If there is conflict among the parameters, the agents will adjust their future movement to decrease the difference. In this example we define a conflict as occurring when the difference of parameters exceeds certain value and the teams will adjust their movement by changing the probabilities which govern their motion. The goal of which is to drive the teams toward a common solution, or the same value for a design parameter or parameters. The difference in coordinated and uncoordinated teams can be seen by comparing Figure 14 and Figure 15, which use the same random numbers to generate their walks.

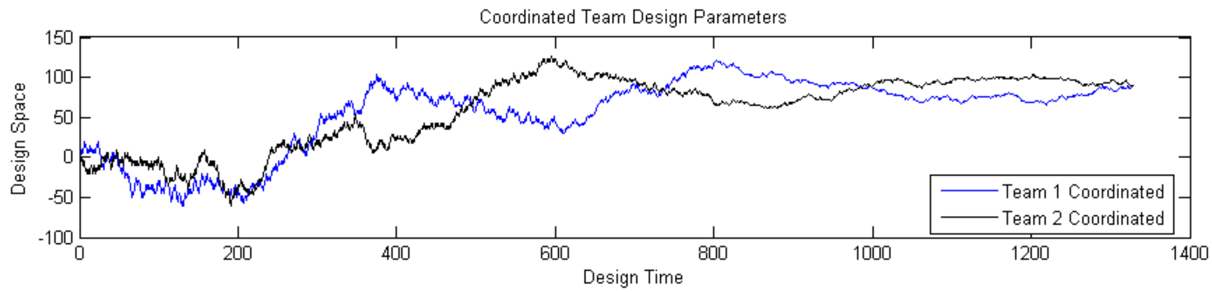


Figure 14: Converge process with a coordination meeting every 200 iterations.

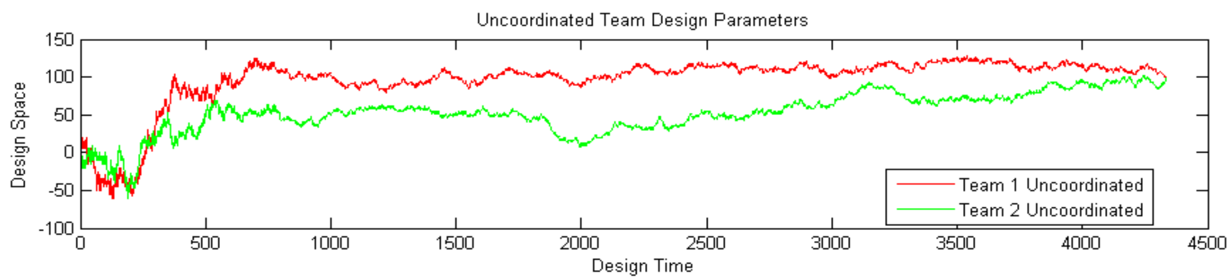


Figure 15: Converge process without coordination.

It is not that the more meetings the agents have, the better coordination effect they get, since there is an associated coordination cost for each meeting. In this example, we simply add the coordination cost to convergence time to get the total time. The more meetings agents have, the more coordination cost they will have, so the problem becomes a balancing act between meeting too often and not enough.

The rules of the agents include how frequently they should meet. With different meeting frequencies, the time until convergence will vary greatly. In this example, we show how different coordination rules of agents lead to different coordination results. Additionally, through the comparison of these rules, we try to identify the best coordination strategy for the design problem by using the least number of iteration as a comparison.

For the simplest case, the agents have a meeting on a regular basis throughout the design process. For example, one rule could be that the agents meet once every 200 iterations (coordination 1) and in another they meet every 100 iterations (coordination 2). For 1000 trials we run the program and record the converge time of each coordination. In the histogram in Figure 16, the distributions for these different coordination strategies can be seen. It is clear from the histogram that the average converge time of coordination 1 is smaller than coordination 2. That is to say, the rules of coordination 1 are more efficient than coordination 2. To find the most efficient coordination frequency, we try a large number of coordination frequencies, the plot of which is shown in Figure 17.

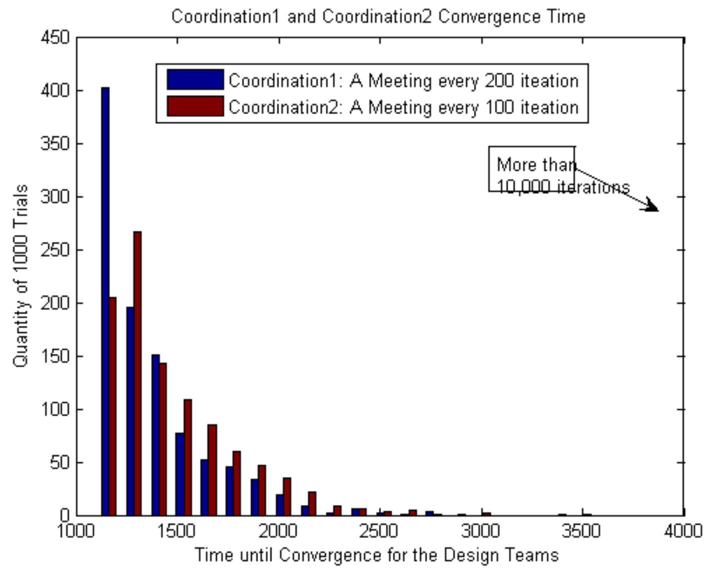


Figure 16: Comparison of converge time of different coordination rules

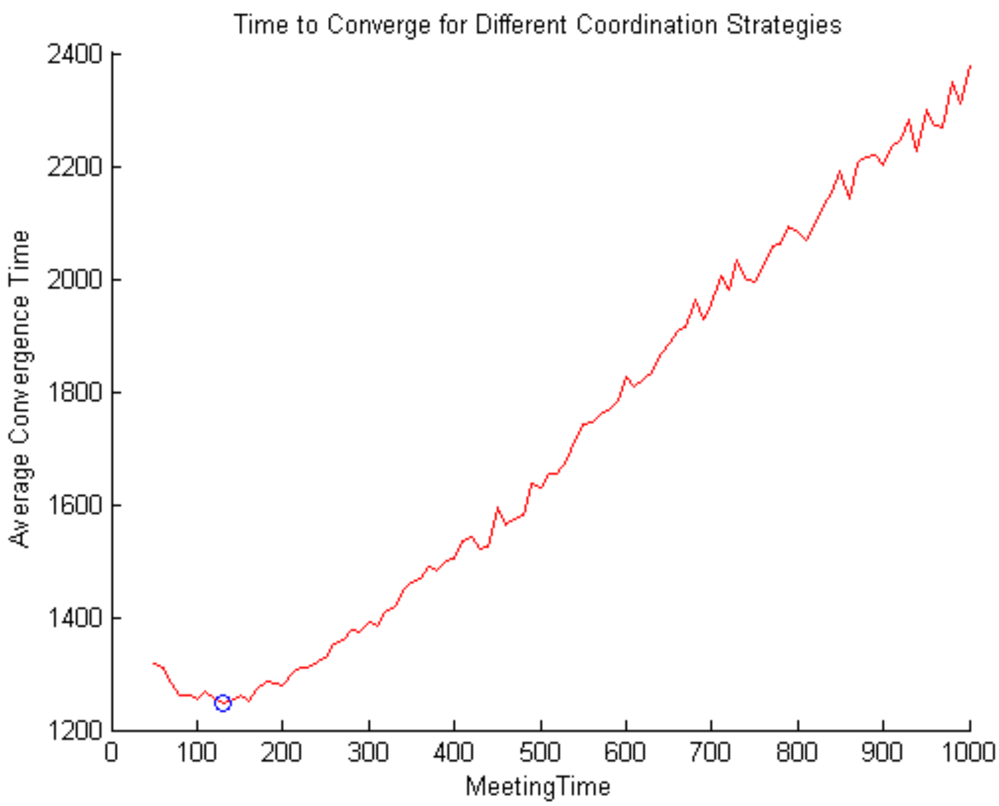


Figure 17: Converge time of different coordination frequency

From Figure 17, we find that the best coordination strategy is to have a meeting every 130 iterations, and the corresponding converge time is 1247. Depending on what kinds of meetings the teams have, the meeting costs will be adjusted, which will change the shape of this plot and mean a different coordination mechanism should be used, as shown in Figure 18. To determine the meeting frequency for different meeting costs, we can select the coordination frequency according to Table 11.

Table 11: Best meeting frequency based on meeting cost

MeetingCost	2	4	6	8	10	12	14	16	18	20
Best meeting frequency	1247	1368	1452	1536	1672	1702	1755	1780	1802	1822

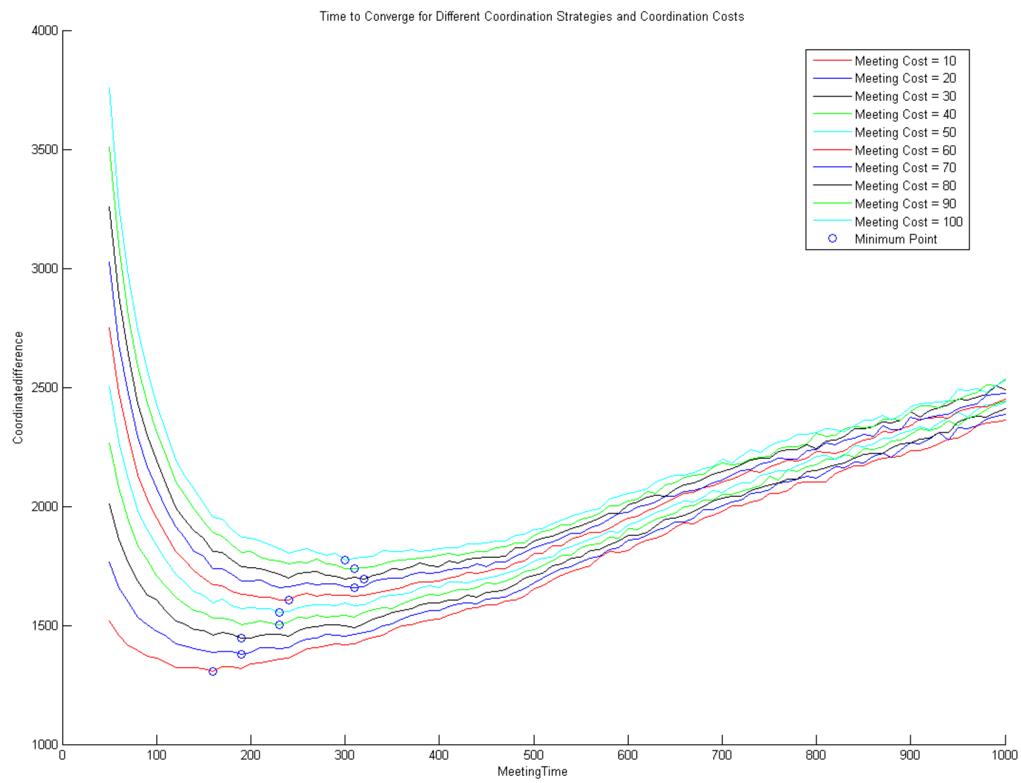


Figure 18: Converge time of different MeetingCost

Through this example, we find that by changing the coordination rules of agents, the Agent-Based Modeling environment can help work out appropriate coordination mechanism for interdependent design teams. That is the utility of Agent-Based Modeling. At the same time, we admit that our current model is based on many assumptions and is not perfect. In the future, we hope to improve this model and get more applicable results.

5. Verification and Validation

5.1 What is the Validation Square?

The validation square (Pederson 2000), shown in Figure 19, 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.[2]

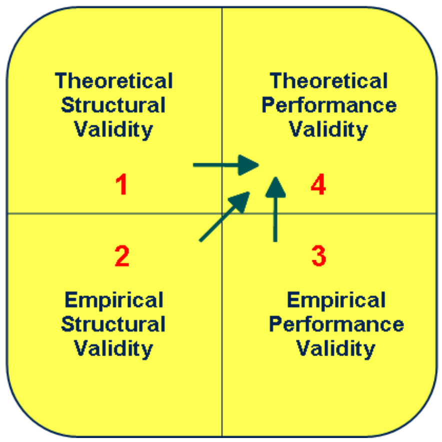


Figure 19: Validation square.

In order to validate the augmented design method, the team will use the Validation Square explained above. Figure 20, shows the information flow through the validation process and the plan of action to move toward validating this model. In summary, 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.[2]

[2] Partially extracted from Nathan Young's Q4S. See (Young 2006b).

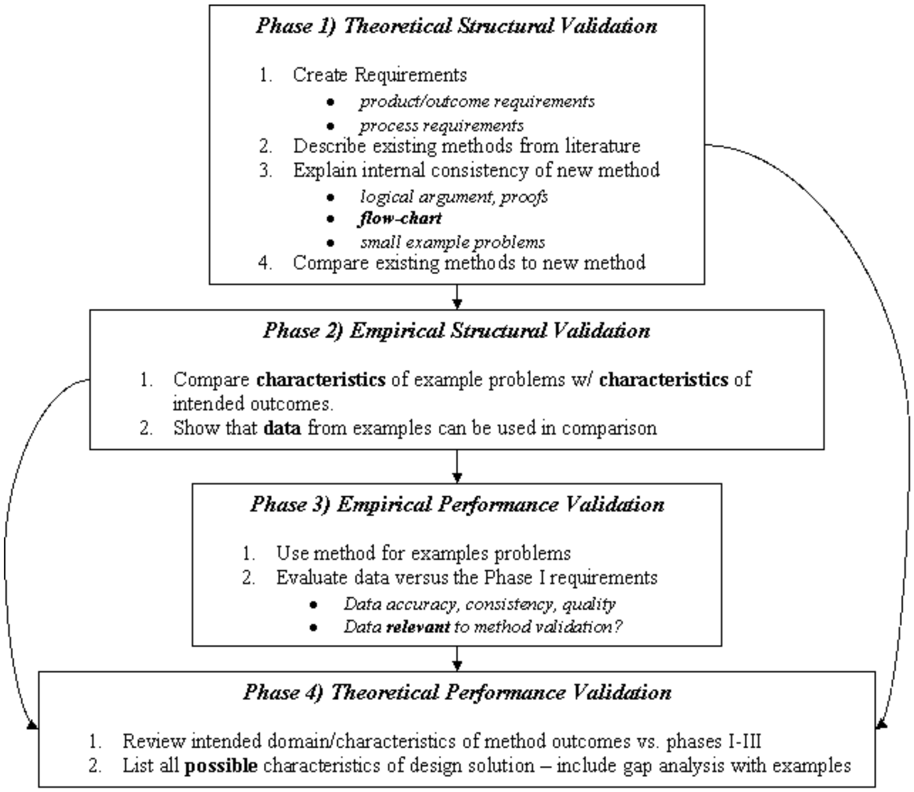


Figure 20: Information flow in the Validation Square.

Table 12: The plan of action to show validity of the new design method.

Square	Component of the Validation[3]	How this is shown for our Method
Theoretical Structural Validity	Internal consistency of design method, i.e., the logical soundness of its constructs both individually and integrated	The **information flow** within the augmented and personalized method is **consistent**, using the foundation of P&B with the addition of personalized managerial steps
Empirical Structural Validity	The appropriateness of the chosen example problem(s) intended to test design method	The design of a **hybrid vehicle** is highly **complex** and will require distributed designers in the world of 2030
Empirical Performance Validity	The ability to produce useful results for the chosen example problem(s)	The **hybrid car** example gives **excellent results** using our method for the year 2030.
Theoretical Performance Validity	The ability to produce useful results beyond the chosen example problem(s). This requires a 'leap of faith.'	With **additional examples and meaningful results**, this method may become validated for design processes.

[3] Taken from an in class lecture on Validation. (Mistree 2007)

5.2 Theoretical Structure Validation (Square 1)

The design method has an information flow similar to the original P&B, so the internal consistency will closely resemble the original systematic approach. The same core transformations will convert information into knowledge through the process. There is now a need to know what are the team divisions, what the teams are working on, and when they are going to meet with the other design teams. Therefore, there are some slight changes to how information moves through the process however, as demonstrated with the beginning of the embodiment phase in Figure 21.

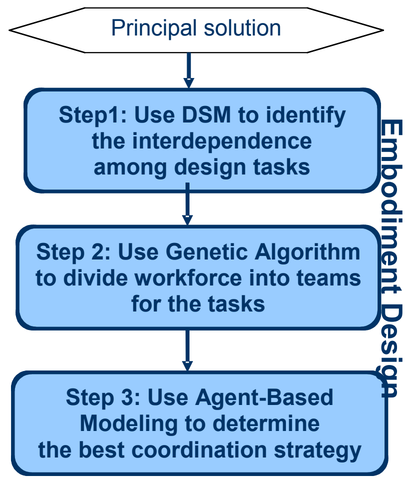


Figure 21: The new steps of P&B in the embodiment design.

5.2.1 Information Flow within the Method

To give a clear explanation of how the new information flows have been changed in the method, the steps, their requirements, goals and required tools for the **Conceptual Design phase** is shown in Table 13. Similarly, the steps, their requirements, goals and required tools for the **Embodiment and Detailed Design phases** are shown in Table 14.

Table 13: Information flow through the new Conceptual Design phase.

Transformation	**Requirements**	**Goals**	**Required Tools**
Step 1: Determine which designers are working on the project and find their skills		Find designers for the project and evaluate their strengths	MS Excel
Step 2: Divide workforce into teams for conceptualization	Know the available designers and their skills	Create teams to generate concepts	Genetic Algorithm
Step 3: Find the best coordination strategy	Know the teams and the estimated the amount of time for conceptualization	Determine which teams should coordinate and when they should coordinate.	Agent-Based Model

Step 1: Determine which designers are working on the project and their skills
1. Use internal company means to find designers

Step 2: Divide workforce into teams for conceptualization
1. Poll designers or have managers rank the individual's skills in these areas
2. Populate a person-task matrix
3. Run the genetic algorithm to find the optimal team breakdown using a fitness function based on the diversity of the teams

Step 3: Find the best coordination strategy
1. Is it beneficial to share preliminary concepts with other teams? If so, select the degree of crossover of ideas in the conceptual phase.

Table 14: Information flow through the new Embodiment and Detailed Design Phases of the method.

Transformation	Requirements	Goals	Required Tools
Step 1: Use DSM to identify the interdependence among design tasks	Know the tasks/ components required in the design	Find concurrent and sequential tasks	DSM and a sorting algorithm
Step 2: Divide workforce into teams for the tasks	Know the available designers and their skills	Create teams to complete each of the tasks in the least amount of time	Genetic Algorithm
Step 3: Find the best coordination strategy	Know the number of teams and the estimated amount of time for the project	Determine which teams should coordinate and when they should coordinate.	Agent-Based Model

Step 1: Use DSM to identify the interdependence among design tasks
1. Find the correlations between the tasks by populating the DSM.
2. Use algorithm to find independent blocks, these clusters can be preformed one-after-another.

Step 2: Divide workforce into teams for the tasks
1. Poll designers or have managers rank the individual's skills in these areas
2. Populate a designer-task matrix
3. Run the genetic algorithm to find the optimal team breakdown
4. Find if combining teams would result in better times

Step 3: Find the best coordination strategy
1. Find the amount of time a meeting is likely to need. Use this to get a Meeting Cost variable.
2. Run the ABM to find when meetings should be generally held between teams.

If there is a reason to change any of the teams or their coordination in the Detail Design Phase, then the designer can jump back into this flow anywhere where it is deemed necessary to make the change.

5.3 Empirical Structural Validation (Square 2)

To validate the design methodology, evidence must be provided to show that the examples used for the Empirical Performance Validity test the method's strength in different situations. Unfortunately, in the limited about of time that the group had, we were only able to use the method on one example. This example was to design a Hybrid Car, such as that seen in Figure 22.

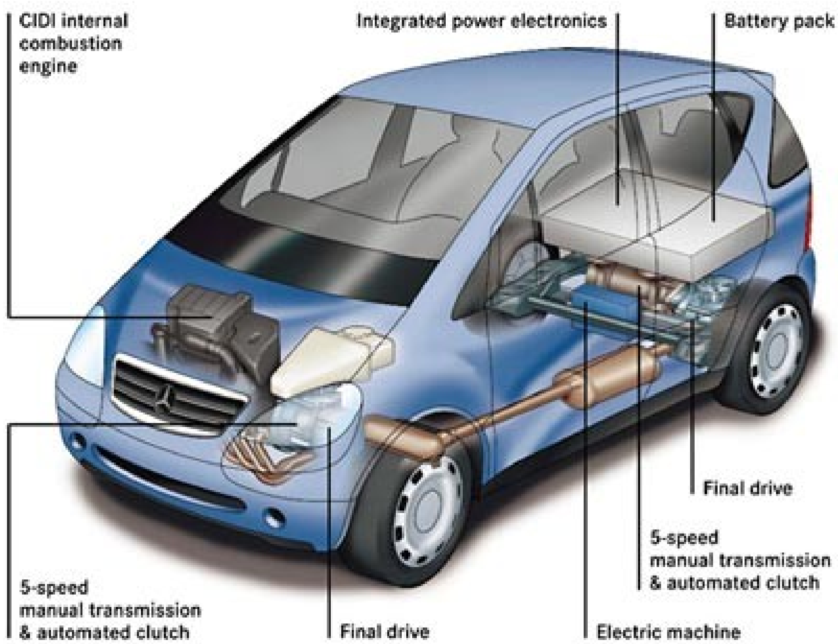


Figure 22: Hybrid Car Example used for Empirical Structural Validation [howthingsworks.com].

This example is a good one for a number of reasons. Our method is best suited for complex engineered systems and the car contains a number of interrelated tasks that designers from multiple disciplines will be required to work together on. Furthermore, the design of hybrid vehicles will be required in the year 2030, so the example is an excellent choice.

5.4 Empirical Performance Validation (Square 3)

The steps involved in the conceptualization phase are similar to the embodiment design and detailed design steps in the method. Therefore, we have selected to go through the embodiment phase step by step to demonstrate how the new steps in the augmented design method can be used in the world of 2030 to design a complex engineered system.

From the conceptualization phase we have an idea that there will be 13 tasks: 6 mechanical engineering related, 3 electrical engineering related, and 4 related to controls. These are shown in Table 15.

Table 15: Components of the Hybrid Car design.

Component	Abbreviation
Gas engine	GE
Transmission	T
Fuel system	FS
Wheels/axels	WA
Chassis	C
Brakes	B
Batteries	Bat
Electric Motor	EM
Generator	G
Battery vs. Gas Control	BG
Climate Control	CC
Transmission control	TC
Throttle/Cruise Control	TCC

5.4.1 Step 1: Use DSM to identify the interdependence among design tasks

1. Find the correlations between the tasks by populating the DSM.

The tasks abstracted from the conceptualization are then placed in a Design Structure Matrix (DSM). This matrix was then populated with the interdependencies between the tasks as shown in Figure 23.

	GE	T	FS	WA	C	B	Bat	EM	G	BG	CC	TC	TCC
GE	-	x	x										
T	x	-		x				x				x	
FS	x		-										
WA		x		-	x	x							
C				x	-								
B				x		-							
Bat							-	x	x				
EM		x					x	-					
G						x			-	x			
BG	x						x	x		-		x	x
CC										x	-		
TC		x										-	
TCC	x		x					x		x			-

Figure 23: The DSM with interrelated tasks shown by an x.

2. Use an algorithm to find independent blocks, these clusters can be preformed one-after-another.

For this example, the team used a JAVA-based "Triangularization Algorithm" (Kusiak, 2007) created at the University of Iowa to sort the tasks in the DSM. This sorted DSM is shown in

Figure 24. It should be noted that another DSM sorting algorithm can be found for Matlab online (DSM 2007).

	GE	T	WA	C	B	G	Bat	EM	BG	TCC	TC	FS	CC
GE	-	x										x	
T	x	-	x					x			x		
WA		x	-	x	x								
C			x	-									
B			x		-								
G					x	-			x				
Bat						x	-	x					
EM		x					x	-					
BG	x						x	x	-	x	x		
TCC	x							x	x	-		x	
TC		x									-		
FS	x											-	
CC									x				-

Figure 24: The sorted DSM. Only the Climate Control can be broken into a sequential task.

3. Find the estimated amount of time to complete each of the tasks.

The experts should be consulted to provide estimates for the amount of time each of these tasks will take to complete. The estimates will be more accurate for variant and adaptive designs, because people will have already completed the designs in the past. For this example, the completion time has been scaled up so the numbers are easier to compare in the GA. This is shown in Table 16.

Table 16: Estimated amount of time to complete each of the tasks in the hybrid car design.

Task	Abbreviation	Estimated time to complete task in months	Scaled time to completion
Gas engine	GE	8	400
Transmission	T	5	250
Fuel system	FS	4	200
Wheels/axels	WA	4	200
Chassis	C	6	300
Brakes	B	3	150
Batteries	Bat	6	300
Electric Motor	EM	8	400
Generator	G	6	300
Battery vs. Gas Control	BG	3	150
Climate Control	CC	2	100
Transmission control	TC	4	200
Throttle/Cruise Control	TCC	2	100

5.4.2 Step 2: Divide workforce into teams for the tasks

In this example we have presumed that there will be 40 designers working on this project. 18 are mechanical engineers, 14 are electrical engineers and 8 are controls people.

1. Poll designers or have managers rank the individual's skills in these areas

In this case we have given the designers more-or-less random skills on a 1 to 5 scale for each of the tasks in their discipline areas.

2. Populate a designer-task matrix

The designer-task matrix can be seen in Figure 25. Each of the designers have rated themselves or their colleagues and managers have provided this information on their behalf.

3. Run the genetic algorithm to find the optimal team breakdown

For this hybrid design and designers, there is no reason to run the electrical engineers with the rest of the group because they have completely separate skills and tasks from the rest of everyone else. This means that the Designers 19-32 can be input into the GA along with the design tasks: Battery Design, Electric Motor Design and Generator. Since there are 2 mechanical engineers with some controls background, they could work on the controls tasks, but by analyzing the problem and running different trials through the GA it was found that the mechanical tasks were the most costly for time (like a limiting reagent), and therefore, the mechanical and controls tasks could also be run individually through the GA. This is helpful because it drastically reduces the size of the design space. To run all the designers in the GA at the same time means that there are $13^{40} = 3.6\text{x}10^{44}$ possible combinations of the design teams, whereas doing it this way, there are only $6^{18} + 3^{14} + 4^{8} = 1 \text{ x } 10^{14}$ possible team combinations, so the GA can find the solution much quicker and accurately.

The results are shown in Figure 25, with the designer assignments indicated with an orange color. The total skill in units of skilled-men/(time unit) are tallied in the "total skill" row. The scaled completion time is given below the skill tally in the "relative time" heading. The time is given in a non-dimensionalized time unit of the same scale as the skills, so when Relative Time is divided by Total Skill, we get the time. Those values are shown in the last row called "Total Time." The GA minimizes the maximum value of all of the total times.

4. Find if combining teams would result in better times

There is also some chance that teams could work together to complete their tasks in sequence as opposed to concurrently. This is an interesting effect that occurs when a designer is placed on a task that is not perfect for his or her needs. To handle this question in the hybrid car example, the GA has a sequential-checking subroutine that looks at the possibility of reducing the amount of total time.

In the case of the hybrid car this only happens once—with the combination of the designers assigned to the transmission/cruise control and the climate control. By making a 3-man team to work on the task sequentially they reduce the amount of total time from 20.0 to 19.6 time units. This is only useful if one of the tasks is not required in one of the concurrent blocks because there would be feedback needs. Luckily, the climate control design can be completed after all of the other tasks since the other tasks do not require information from the climate control to be designed.

All this means that the limiting factor in the design is the Fuel System and it will take 22.2 time units to be finished. If possible it might be in the companies' interest to find another designer to help speed up the fuel system design. In this example, we will keep our 40 designers to work on their tasks without additional assistance.

		400	250	200	200	300	150	300	400	300	150	100	200	100
		GE	**T**	**FS**	**WA**	**C**	**B**	**Bat**	**EM**	**G**	**BG**	**CC**	**TC**	**TCC**
ME	Designer 1	2	3	3	1	3	4	0	0	0	0	0	0	0
ME	Designer 2	3	1	1	2	2	2	0	0	0	0	0	0	0
ME	Designer 3	2	1	3	2	4	3	0	0	0	0	0	0	0
ME	Designer 4	2	1	2	1	4	3	0	0	0	0	0	0	0
ME	Designer 5	1	2	1	2	1	3	0	0	0	0	0	0	0
ME	Designer 6	4	5	3	5	3	5	0	0	0	0	0	0	0
ME	Designer 7	5	3	4	4	2	5	0	0	0	0	0	0	0
ME	Designer 8	5	1	1	3	1	2	0	0	0	0	0	0	0
ME	Designer 9	2	4	1	4	2	3	0	0	0	0	0	0	0
ME	Designer 10	2	5	1	5	2	1	0	0	0	0	0	0	0
ME	Designer 11	3	1	1	2	5	3	0	0	0	0	0	0	0
ME	Designer 12	2	1	4	5	5	3	0	0	0	0	0	0	0
ME	Designer 13	1	2	1	4	1	2	0	0	0	0	0	0	0
ME	Designer 14	5	4	4	4	1	3	0	0	0	0	0	0	0
ME	Designer 15	1	4	5	1	4	3	0	0	0	0	0	0	0
ME	Designer 16	2	1	3	2	2	5	0	0	0	0	0	0	0
ME	Designer 17	2	3	1	4	5	2	0	0	0	2	1	2	1
ME	Designer 18	3	1	2	1	2	1	0	0	0	1	2	1	2
EE	Designer 19	0	0	0	0	0	0	1	3	3	0	0	0	0
EE	Designer 20	0	0	0	0	0	0	2	5	2	0	0	0	0
EE	Designer 21	0	0	0	0	0	0	1	3	2	0	0	0	0
EE	Designer 22	0	0	0	0	0	0	5	2	4	0	0	0	0
EE	Designer 23	0	0	0	0	0	0	2	2	3	0	0	0	0
EE	Designer 24	0	0	0	0	0	0	5	3	5	0	0	0	0
EE	Designer 25	0	0	0	0	0	0	4	2	4	0	0	0	0
EE	Designer 26	0	0	0	0	0	0	4	2	5	0	0	0	0
EE	Designer 27	0	0	0	0	0	0	5	4	3	0	0	0	0
EE	Designer 28	0	0	0	0	0	0	4	2	3	0	0	0	0
EE	Designer 29	0	0	0	0	0	0	2	1	4	0	0	0	0
EE	Designer 30	0	0	0	0	0	0	3	2	4	0	0	0	0
EE	Designer 31	0	0	0	0	0	0	3	4	3	0	0	0	0
EE	Designer 32	0	0	0	0	0	0	3	4	2	0	0	0	0
CE	Designer 33	0	0	0	0	0	0	0	0	0	3	1	5	3
CE	Designer 34	0	0	0	0	0	0	0	0	0	1	1	2	5
CE	Designer 35	0	0	0	0	0	0	0	0	0	2	4	5	2
CE	Designer 36	0	0	0	0	0	0	0	0	0	3	2	2	3
CE	Designer 37	0	0	0	0	0	0	0	0	0	4	2	1	2
CE	Designer 38	0	0	0	0	0	0	0	0	0	4	3	2	5
CE	Designer 39	0	0	0	0	0	0	0	0	0	3	4	1	4
CE	Designer 40	0	0	0	0	0	0	0	0	0	5	2	1	1
	Total Skill	20	12	9	10	14	9	16	22	15	8	8	12	14
	Relative Time	400	250	200	200	300	150	300	400	300	150	100	200	100
	Total Time	20	20.8	22.2	20	21.4	16.7	18.8	18.2	20	18.8	12.5	16.7	7.14

Figure 25: Designer-task matrix. The orange cells indicate the tasks the designer was assigned to by the Genetic Algorithm.

5.4.3 Step 3: Find the best coordination strategy

1. Find the amount of time a meeting is likely to need. Use this to get a Meeting Cost variable.

For the design of a hybrid car we estimated a meeting between groups of these design tasks would take a day to complete. From the GA we are expecting the design to take 22.2 time units, but in the agent based model (ABM) it is calculated on a 1000 iteration scale. Additionally, the team estimated that the actual design of a hybrid would be one year or 250 work days. This means that a meeting between groups will take 1/250th of the time to complete the task and is therefore set as a 4 iteration penalty in the model. This means that when the agents "have a meeting" and adjust their parameters, they will have to add 4 time iterations to their total time to converge.

2. Run the ABM to find when meetings should be generally held between teams.

The agent based model was run with this meeting cost parameter and with some slight variations on it, to determine the robustness of the solution. These parameters estimate design time when the meetings take 0.5, 1.0, 1.5, and 2.0 days to complete. The results from the simulation are shown in Figure 26 and Figure 27.

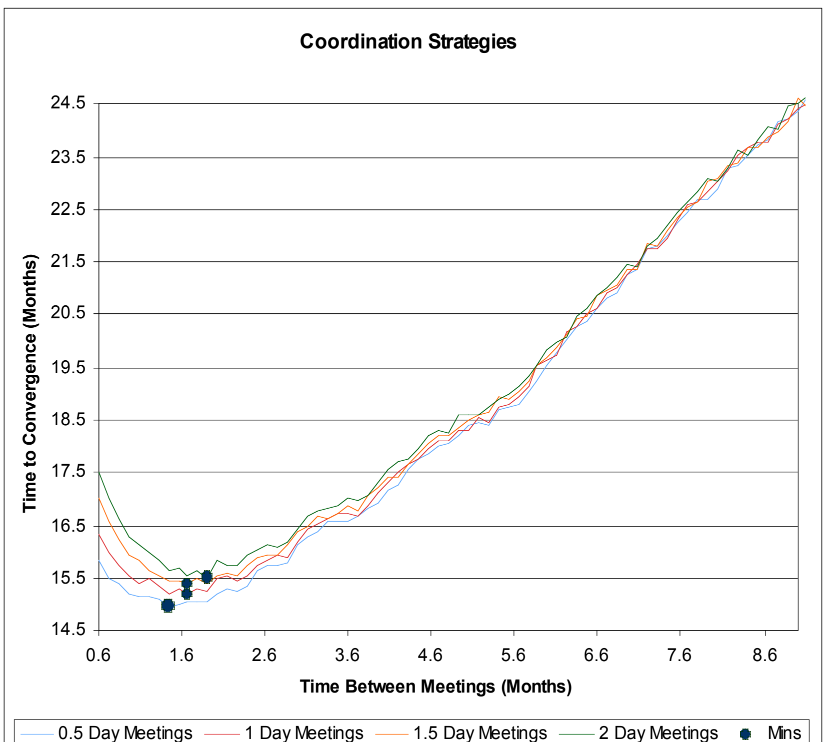


Figure 26: Design time vs time between meetings in months.

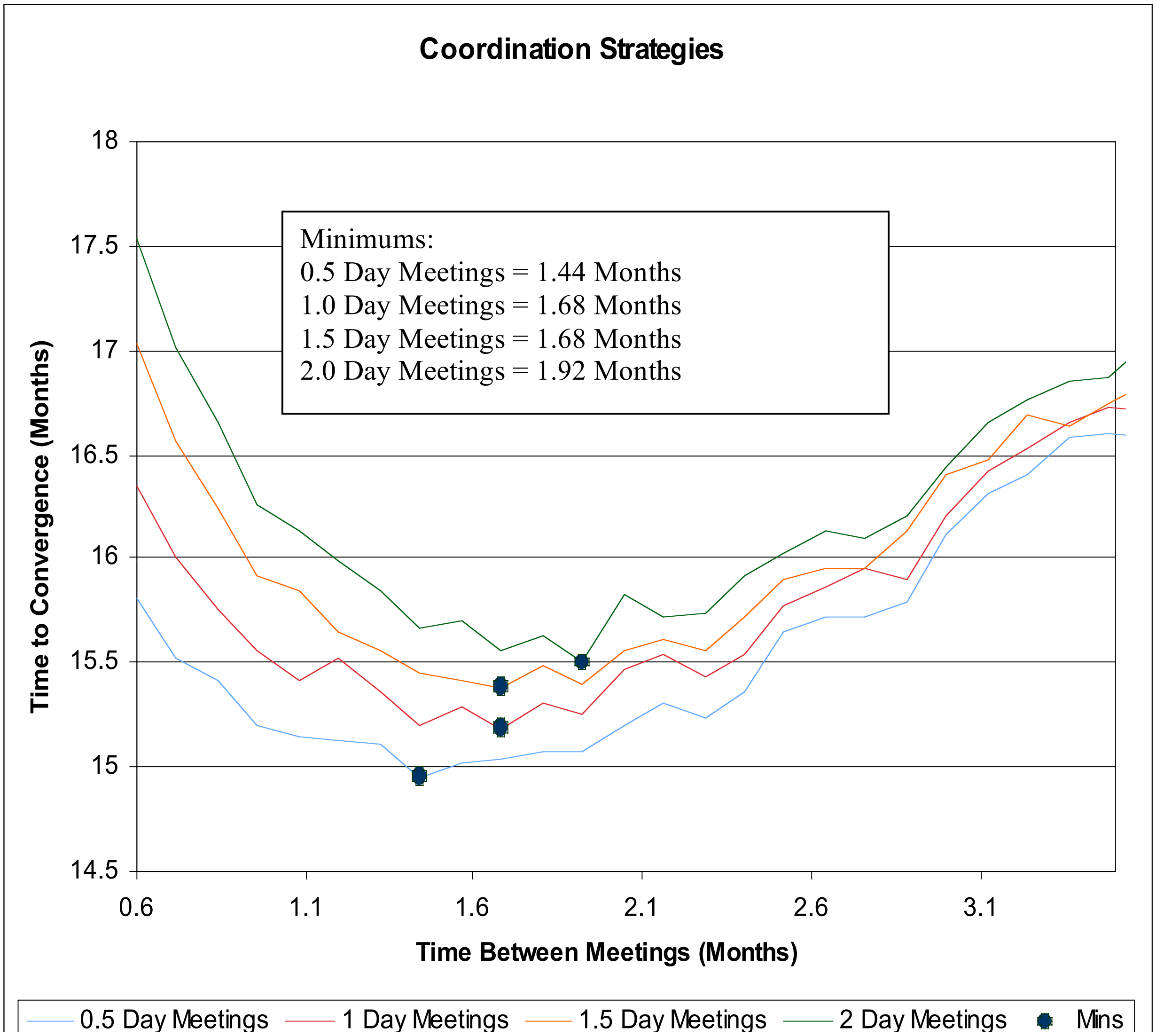


Figure 27: A closer look at the minimal design times and the estimated amount of time to complete the task based on 5000 iterations of the random walk simulation.

The agent based simulation indicates that the optimal meeting frequency is approximately every 1.7 months or about every 7 weeks, assuming the project takes 1 year to complete and a meeting would take approximately one day.

5.5 Theoretical Performance Validation (Square 4)

If our P&B method is theoretically sound, we have chosen good example problems and they have given good results, we can potentially jump to the conclusion that the method is valid for all design problems. In this case we have shown the consistency of the information in the model, but only looked at a portion of the design process for one example, and therefore are unable to fully validate our design method.

5.6 What aspects were verified using the Project?

In the validation section, we validated the theoretical structure by verifying our programs and carefully checking the flow of information through our method. We began the empirical structure and empirical performance validation by analyzing the hybrid car example and then taking it through the embodiment design phase of our augmented method. Due to the limited scope and time of our project our augmented method was only able to validate a small section of the empirical performance validity for one example. To fully validate this new method, many more pertinent examples need to be taken through the entire design process. At that point, barring poor performances, we could expect theoretical performance validation of our method.

5.7 Limitations of Augmented Method

As stated in the previous sections, our model is founded on many assumptions. The failure to satisfy these assumptions may lead to the ineffectiveness of our model.

The model of the designers is based on the evaluation of their skills. In real life this could turn out to be unrealistic if designers do not rank themselves appropriately or there is no effective measuring approach available. The modeling of workforce division and teams is a simplified process, which does not consider other more complicated issues such as the internal organization of the team, the workers' personal working preference, language barriers, and so on. Also, in the Agent-Based Modeling section, we only described the guideline of how this approach can be used to model the design coordination and only study the coordination mechanism between two agents working on two interrelated parameters. In real life, the coordination among more than two agents will be much more complicated.

However, the research work within engineering design is based on certain assumptions. Designers must understand how to handle these assumptions in the models appropriately in order to find good results.

5.8 Future Work and Research Questions

As stated above, our models are not perfect because of the assumptions and simplification we made. For future work, we recommend our model be changed to better represent the real life situation. In the model, we use DSM only to get qualitative information about the interdependence. To run the model more effectively, we need to get more quantitative information about the interdependence in order to answer these questions:

- How can we find the appropriate measure of interdependence among design tasks?
- How can we identify the role each design task plays in the overall interdependence map?

About modeling designers:

- What's the best way to find more effective and accurate evaluation measures to model designer skills?

About GA:

- Can there be more accurate methods to rank teams than the overall fitness?
- Could other searching techniques be used which are better?
- When design teams get too large to "fit in one room," what subroutines can be created to subdivide these teams into evolutionary or other design groups?

To apply the Agent-Based Modeling method to get the best design coordination strategy, much improvement is needed, mainly about how to broadly incorporate the real life coordination into the ABM modeling environment. In the future, we would like to know:

- how to define the conflict and compromise from a broader view in the coordination process in ABM environment.
- how to define agent activities in the ABM modeling iterations.
- how to define the overall coordination performance evaluation criteria of the system in ABM.
- how to model the coordination among more than two interdependent agents.
- identify potential effective coordination rules of agents through interdependence analysis.
- how to get the best coordination rules based on the combination of existing rules.
- How these rules can be translated into a real life coordination strategy.

6. Learning Experience

6.1 Team Goals

In order to come up with a set of target learning objectives and competencies, the team looked at our individual learning objectives and competencies. There were a number of common learning objectives and competencies which we were particularly interested in reaching and developing during this project.

6.1.1 Learning Objectives

The common learning objectives were:

1. **Learn and predict challenges and advantages involved in having a global engineering workforce. Investigate how management strategies and coordination mechanisms can compensate for the new difficulties.**

The project dove head first at this learning objective. It is clear that having the technological resources in the future to hire anyone in the world to do design work will help companies and assist the educated individuals from less fortunate countries, but how does that change the design? Some of the challenges we learned first hand. These would include trying coordinate efforts on the presentations or reports, keeping everyone in the loop on all the changes that were being made, and keeping everyone on top of the work that everyone else was doing. For instance, Todd and Jay would talk on Gtalk, about the GA and reports, but then Wuhao did not now about changes or the progress of the other teams members. We learned that we needed to coordinate more often to be sure that everyone knew what the others were doing and keep the influx of new ideas coming. We found personally that the best coordination strategy was to email everyone the changes, when changes were made; however this did not promise that all the team members would read or look at the information.

In the project, we found that with some simple assumptions, we can model the coordination of teams (or individuals) and that there is a “just right” point where there is not too much time spent meeting, but also not too little communication were people are left in the dark. This is found as a minimum in the agent based model, but in real life it certainly will not be that easy and managers will need to balance the needs of their teams. These tools are simply that: they are a means to assist in managing complex systems design in the future.

2. **Learn to use technology to accelerate and assist with the design process and find methods for creating autonomy in the design process.**

Again this can be seen from the personal and project points of view. From the personal view, we were able to create a new method, design computational tools, and create presentations and reports primarily through the use of Gtalk, email, MS office and Matlab. These tools have quickened the design of all of these projects.

From the point of view of the project, itself, we have learned to create models to automate the formulation of teams and their coordination. This is no small task! In fact, everyone on the team was shocked that we were able to get as far as we did, considering how ambitious the task was. When we were done everyone could see the advantages to using the GA over selecting designers by hand. Jay tried for some time to match the results of the GA, but was not successful, which means that the computer tool has created a superior and automated means to divide the teams. Likewise, before the ABM was created it was a matter of guessing when teams should meet, but now we have a reason for meeting every week vs. ever 2nd week.

3. **Learn strategies to work better with multidisciplinary and large teams that may consist of non-engineers.**

It is clear that Wu Hao has learned as much as Todd and Jay about working with designers with different backgrounds. We quickly learned that designers with different backgrounds have different skills, talents and motivations. One example is that the American University programs seem to place far more importance on computer tools than the Chinese, but the Chinese programs have a stronger background in mathematics.

In the project, it was clear that when the designers are multidisciplinary, there are entirely new problems that need to be sorted out. For instance, the GA does not work as efficiently if all the designers are input simultaneously because the search space is so large, and because only one of the disciplines will be the limiting reagent and cause improved fitness. Additionally, even though not directly tackled in this project, the team did learn that with large teams there will become the need to subdivide the groups. This was not discussed in the project and could cause new challenges the computational tools as well as the managers.

6.1.2 A0 Goals

4. **Ability to apply systematic design methods *in a future with a global engineering workforce.***

The group wanted to understand the changing global engineering workforce, and how that would affect the design process. We created computational methods which were inserted into Pahl and Beitz to yield better efficiency results. These results give a reduction of design time because the managers can do their jobs quicker and teams will collaborate more efficiently by having the correct number of meetings and the right designers on their teams. We gained the skills to apply our systematic design with all of these new advantages and caveats to the design of a hybrid vehicle (or anything else for that matter). We have learned how to apply new technologies to handle and take advantage of the global workforce.

5. **Ability to apply computational methods *in order to accelerate & assist with the design process.***

The group wants to be leading technology-based change in the future, so we have concentrated on applying the available (and ever increasing) computing power to the design process and building the competencies to do this. This project has been great to build everyone's skills with MS Office, Matlab, and other computer tools. I think everyone in the group learned something from another member of the group. Jay learned about the "paintbrush" for applying text formatting, Todd learned that Shift+Tab steps the bullet back, and Wuhao learned more about Excel and Matlab.

Even our project had us creating tools to accelerate the assist the design process. We are the only three people in the world who know how to use the GA and ABM that we created. These tools could save design projects hundreds of hours in the future. Agent based modeling can be used to model complex design problems, and then offer strategies to work out efficient coordination mechanism among design teams. And, the use of the DSM-GA-ABM tool combination allows for team collaboration methods to be derived in a systematic way. (In our case the Genetic Algorithm yields consistently superior results than we could find.)

6. **Ability to analyze multidisciplinary systems *and better work with multidisciplinary teams.***

Once again this can be broken down into what everyone learned by doing this work and from the actual results from the project. Everyone learned to deal with diversity in the group because we had very different backgrounds coming into this project. We learned to focus on the strengths of everyone and help each other out when problems cropped up. From the project we have learned how to create teams of multidisciplinary designers in the conceptual design phase and then divide the workforce into selective groups for the completion of their specialties in the embodiment and detailed design phases. All of us are coming away from this design project with more respect and understanding for the challenges and advantages of analyzing and harnessing multidisciplinary teams in the design process.

6.2 Personal Learning and Development

6.2.1 Jay's Learning

Learn and predict challenges and advantages involved in having a global engineering workforce. Investigate how management strategies and coordination mechanisms can compensate for the new difficulties.

Value > 1. I made a lot of progress in understanding the global engineering workforce situation by setting up this project, scaling it, then creating to tools to handle the new paradigm in design methods. It is a rare chance that we, as designers, sit down and look into our future lives. There are going to be many advantages to working in the globalized world. One example is that I was emailed today with an interview request. I had not heard of the company and I do not know how they got my resume, but they seem like an incredible company pushing CFD and CAE technologies. The point is that information about designers will be circulated and anyone can be employed by any company worldwide. Of course over the course of this project I've seen the darker side as well. There will no longer be that person-to-person interaction of designers and therefore, even the simplest of questions and meetings will be drawn out into more formal ordeals.

Learn the Pahl & Beitz method and then use it as a springboard for my own design ideas and my vision of the design world of 2030. I would like to focus on how to generate concepts and select the principal design, weighing in uncertainties and reliability concerns.

Value = 1. This work starts with the P&B foundation, and I have definitely launched my ideas off the P&B framework. I feel that the 2nd half of this learning objective was not fully realized through this project. With some help from Nathan and Todd, I setup the GA but there was no design process to weigh in uncertainty and reliability. These concepts have different connotations in software as well. The code does have some robustness, but there are other uncertainty and reliability concerns that still exist. The process is stochastic so there is always some chance the solution will not be the best. This is again one of the limitations of these tools. I created the random walk agent based model, again without much consideration for the alternatives, uncertainties or reliability concerns. It was also a little disappointing that our project did not work more extensively through the design process. This is tough when it requires a complex design to validate the model, but it would have been fun to see how all the steps fit together in the complete design of a hybrid vehicle.

Learn more about adaptive and variant designing processes. I want to efficiently use my predecessor's work in order to improve the design intelligently.

Value = 1. I used Nathan's presentations and report as a starting place for ours. It is great to have an outline of what I would like to accomplish so that I could pace the project and get it completed in time. This project has taught me a lot about using the work of others to give me and the team direction and to allow us to focus on what we feel are the most important issues in the proposal.

Learn to use technology to accelerate/assist with the design process and find methods for creating autonomy in the design process.

Value >> 1. The project in itself created a semi-automated management tool. I learned about the beauty and the ugliness that is hidden in automation tools. Yes, the tools find better solutions quicker than I can, but there is a lot of time and effort in setting them up right. The problems must be understood fully before the tools should be used. I learned that there are many areas where simulations and automated solution finding tools can be installed, but give exceedingly poor solutions. This is the danger of these tools. It is the same as giving undergrads CFD and FEA.

Learn strategies to work better with multidisciplinary and large teams that may consist of non-engineers.

Value > 1. I've learned in the small scale of our design team a few things. Working with Wuhao has opened my eyes to the differences in styles for approaching problems that exists between American and Chinese educational backgrounds—or we are just different people. I started off by trying a few things and building my knowledge from the basics of what I already knew. Wuhao on the other hand read paper after paper to understand that work that had already taken place. In this case these styles accompanied each other very nicely. My ideas were reinforced with Wuhao's reading background and we made excellent progress through the project.

From the project results in themselves, I learned that it will be highly challenging to manage a diverse group of designers. When designers only have a unidisciplinary skill, they stick in certain categories which lead to some tasks being completed much quicker than others. If this were to happen in the real world, the company has three options, let one component of the design be finished before the rest, pull designers off the quick tasks, or hire more people to work on the slower tasks. Hiring additional help may be the best option if design time is a design diver.

6.2.2 Jay's Competency Development

Mirroring my learning objectives, the competencies that I have focused on this semester are:

1. **Ability to apply systematic design methods in a future *with a global engineering workforce.***

Value > 1. From this project I have gained the ability to apply design processes in a global workforce. The GA and ABM tools that I have learned to use in this project will help me in my future work, and the design process that we created will be far more applicable in 2030 than P&B's method.

However, from the project results, it was fairly clear to me that the models of design processes in 2030 are going to have a number of limitations. I learned that in many cases they are delicate and it takes a knowledgeable designer to work the GA and ABM. Our method is not perfect and uses many assumptions. Design methods all use certain assumptions, it is our job as designers to be aware of these assumptions and proceed accordingly. I learned that teams are going to have to be carefully balanced and even more closely coordinated in the future to make sure that people stay together with the tasks. Even working on this report, the three of us made changes that were lost in all the versions. Without clear goals, groups dealing with 10 or even 30 people/teams will have an extraordinarily difficult time bring things together, even when there are perfect meetings.

2. **Ability to design products *considering the lifecycle of a product.* (*Ability to leverage ideas and integrate old and new concepts into adaptive and variant designs*).**

Value > 1. For the creation of the design tools it was a very interesting combination of adaptive and variant design that took place. I created what I thought was a GA for the team division, and it seemed to work, but then when I talked to Nathan, he described what I had done as a, “severely handicapped evolutionary strategy” and then gave me the background for real genetic algorithms. The Brownian Motion was inspired in part from a ISyE Simulation lecture and in part from game theory. The idea was that I have a team that needs to guess when to take a peek at the other team(s). If they see the other team’s way over there, then they’ll move closer, but if not, then they just keep on doing what they’re doing. Sort of like saying, “Ah, we’re in the same neighborhood, it’ll come together at the end.” It has evolved to look at all coordination frequencies primarily from Wuhao’s insights.

3. **Ability to model *complex systems* design.**

Value > 1. The research that Wuhao performed early in the project introduced everyone to DSM, and from there we looked at different methods for modeling the complexity of the design process. My biggest success of this project was creating a GA and an ABM which gave good results for our project and validation. To do this the team had to model the design complexity and then from that model spin off our requirements for a computational tool for designer division and modeling coordination vs time for the agents.

4. **Ability to apply computational methods *in order to accelerate/assist with the design process.***

Value > 1. There is no doubt that I have learned to apply computer tools to assist with this design. I have learned the ability to accelerate and assist management with the work that they must do at the initial stages of the design steps to organize the design teams. I also learned various other smaller skills with Matlab programming and standard windows programs. These tricks add up and can help me complete my work much quicker.

5. **Ability to analyze multidisciplinary systems *and better work with multidisciplinary teams.***

Value > 1. I have gained huge insights into the complexity of design and multidisciplinary systems. This project has allowed me to come to grips with the challenges that face engineers working with multidisciplinary systems and how they must communicate across knowledge barriers to the other teams. The project gave me a little sense of the difficulties when I worked with Wuhao on some of the programming, because he was not as familiar with Matlab as I was, but we have very similar backgrounds. When an industrial designer gets involved it will be even more difficult to explain the engineers needs to that person. From this project, I have a much better understanding of how to model and analyze multidisciplinary systems. Also, I feel that I can work better with multidisciplinary teams after this project, because I know how different backgrounds can conflict and compliment one another in the design process.

6.2.3 Hao’s Learning

Hao’s learning objectives

- ***Learn what the systematic design methods are like.***

Value>1

Through the project, we organize our augmented method to deal with complex design problem and then validate the method. As a saying goes, “knowledge comes from practice”, during this project, we use the augmented method and by reflecting on how the augmented design process proceed based on the major information flow I have a better understanding about how a systematic design method works.

- ***Learn the philosophy and methodologies of the design and then the abilities to personalize these methods according to my own use in the future.***

Value>1

The augmented method is basically built up to solve a personalized problem, the design for complex engineering system. In the project, I learn how to formulate the requirements for a specific problem and then how to make use of and augment available design methods to get the requirements satisfied.

- ***Learn the basic methods to carry out research work within this field.***

Value=1

This project is quire a research-oriented one. The work I have done is mainly about finding out the interdependencies among design tasks and identifying the coordination mechanism among design tasks. In the first stage, I went through the literature to identify the related previous work done by others and put forward the guideline of our project. During this process, I learned how to summarize what other researchers have done, how to formulate our problem, how to define what we should do for the problem.

- ***Learn relationship between design and other sections of industry.***

Value <1

The augmented method is mostly about organizing an augmented design for design complex system. Other issues, such as manufacturing, are seldom touched.

- ***Learn how to get the abilities to convert needs into specifications and then search for the method to achieve the specifications required.***

Value >1

During this project, we formulate the requirements for the complex design system and then search for the augmented method to achieve the needs required. This is a perfect practice to find the requirements first, then change them into specification and finally come up with solution.

6.2.4 Hao’s Competency Development

- **Ability to Apply a Systematic Design Method**

Value>>1
The idea of this project is to validate our augmented method. For validation, we apply the augmented method to the design of a hybrid car. In this way, we practice applying a systematic design method and the advance the competency.

- **Ability to convert users' needs into engineering specifications**

Value >1
Translating the needs for complex design into the specific requirements of our augmented method is the first step of our project, I found this procedure valuable because I learned how to abstract and synthesize the information about needs and then articulate them into engineering specification from professional view.

- **Ability to model uncertainty in design**

Value>1
The uncertainty and complexity in design always go hand in hand with each other. In this project, I learned how to model complexity and actually offered an approach to achieve this. To this extent, I believe I achieved value towards this competency.

- **Ability to generate ideas individually and as a group**

Value>1

From this group project, I learned how to do teamwork and how to learn from group members. Throughout the project, we work as a learning group and try to maintain effective communication. The discussions with others inspire many new ideas of mine. From our work process, I find the strength of others and learn from them. For example, Jay is quite good at programming, I learned from him and we worked together to work out the Agent-Based Modeling example. This kind of cooperation helps me to achieve effective learning through communication. Also, individual thinking played an important role in helping me put forward the roadmap of the project, as well as the actual implementation of ideas we have.

- **Ability to apply computational methods for design synthesis**

Value =1
In this project, we offered computational tools to divide the workforce with Genetic Algorithm and made use of a computational model to illustrate the application of Agent-Based Modeling. Through the project, I found out that I still need to try more effort to enhance my ability to apply computational methods.

6.2.5 Todd's Learning

- **I would like to take P & B and really understand how and more importantly why it works. I would love to be able to learn the process for modifying a system like this to work in the future.**

Value>1

During this project I spent a lot of time getting to understand all of the Pahl and Beitz method, and the information flow through the methodology. By spending a lot of time with Pahl and Beitz I developed a great understanding of its inherent strengths and weaknesses. Secondly I have seen how changes to a methodology can and should be applied; this ability to make these augmentations is extremely valuable.

- **I would like to learn how to identify the needs of multination/multicultural users. I would like to learn to develop manufacturing/ distribution systems for the futuristic world of 2030.**

Value=1

We did not focus on identifying the needs of multinational user, we focused on meeting these needs once they had been identified. The work we have done will make the development of these products more efficient. Lastly we have identified ways to best utilize a dispersed workforce. As time goes on it will be seen that this skill will be critical to surviving the competitive marketplace of 2030.

- **I would like to learn to design and implement systems that are based on cutting edge technology from many disciplines. I would like to be able to bring electrical, chemical, mechanical etc. together to develop truly cutting edge devices.**

Value >1

This is one area we explored in great depth, first how should complex design be broken up, second which designers should work on which task, and lastly how should they coordinate. I have made great strides toward understanding and overcoming the obstacles inherent with multidisciplinary design. We looked at Pahl and Beitz and saw this as a major weakness and took huge steps to strengthen this aspect of the design methodology. I am extremely happy with the strides I made regarding this objective.

- **I would like to learn a system for generating ideas both systematically and creatively. This means being able to generate ideas with out locking myself in a room and dwelling on something and hoping I have a "big bang" moment, where it all comes to me.**

Value=1

Although are project did not focus mainly on idea generation I still have made great strides in this direction. During this project there was a lot of coding involved (I am a novice coder), and I learned a lot from Jay about this process. Jay helped me apply some of the Pahl and Beitz concepts such as function structures, and sub functions to the coding process. With out this experience I would not have been able to contribute to the actual coding to the same degree I did. By breaking down a seemingly complex concept (genetic algorithm) we were able to build the program in small simple chunks. This really illustrates the power of breaking a problem down to its basic building blocks.

- **I would like to learn how to reflect internally on what I read, but more importantly I would like to learn how to present my thoughts:**

Value>1

This is a very personal goal and is seemingly unrelated to the project. However I feel I have made great strides in this direction through the course of the term. Working in a fast paced team environment really required that I share my ideas in a clear and concise manner. At the beginning of the project I think our team struggled with this, as time went on we were all more capable of expressing our ideas. It makes a huge difference in how a team operates if everyone can effectively share their own feelings.

6.2.6 Todd's Competency Development

- I would like to learn to utilize a systematic design method (Pahl and Bietz), with a globally dispersed workforce.

Value>1

This was a huge part of our project and it forced me to address many of the issues that globally distributed designers would face. The two big ones were team division and team coordination, both of which I have a far better understanding of. In the future we envision a lose of contact between management and employees, thus the two tasks become increasingly difficult. We have made changes to Pahl and Beitz to help management overcome these new challenges. Through the process of augmenting Pahl and Beitz I have with out a doubt come to a better understanding of how systematic design should be applied in the future.

- I would like to improve my ability to leverage what has been done in the past, and build upon it.

Value=1

Our project did not focus on this idea of integrating the new with the old, we focused on integrating multi disciplinary things together to create one product. However all is not lost ME6101 as a whole is based on the idea of building on what has been done in the past, this is known as leveraging. I have made great steps towards this concept of leveraging and using other peoples work as the foundation for my own. This concept allows people to avoid repetitive work and lets them head directly to what they are interested in working on. If leveraging is applied correctly it can lead to a better end result in less time.

- I would like to learn how to identify and fulfill the complex needs of consumers in the year 2030.

Value>1

Although we did not focus on identifying complex needs, we did focus on identify complexity and how to cope with it. Further, much of our project focused on dealing with complexity, how should it be quantified and how should it be overcome. We have decided to us the DSM as a means to do this, and I think it is extremely powerful. Regarding uncertainty we have applied techniques for dealing with the inherent uncertainty involved with complex design. For highly complex systems we promote the idea of using concurrent design to help reduce iteration times, caused by feedback. Unfortunately complexity by nature is terribly confusing and hard to model, I will have to continue to address this issue to grow my understanding to where I want it to be.

- I would like to learn a system for generating solutions both systematically and creatively, while fully harnessing computational tools.

Value>>1

Our project could not have been better suited to help me build this competency; we built software tools that accomplish this exact goal, it is very exciting. We have developed a method to divide our workforce into efficient and effective teams, secondly we offer recommendations as to how to coordinate these teams. These two tools will become increasingly important in the future, as the workforce becomes more dispersed. One area that we didn't' get a chance to look at his how to incorporate modeling tools (CFD, FEA etc). into the design process. This is something that I feel will be very important in the future…if I had more time I would like to explore it.

- **Ability to analyze and how to design multi-disciplinary systems with multidisciplinary design teams.**

Value>>1

Once again this is the core of what we have accomplished with our project. We can take a design problem with X number of tasks regardless of discipline and build and divide our available workforce into the most appropriate teams to complete the tasks quickly and efficiently. This covers both aspects of this competency "analyze multidisciplinary systems" and "work with multidisciplinary teams". I could not be happier with the progress I made towards attaining this competency. Not only do I have a terrific understanding of what is required to accomplish this goal, but I have computational tools to help me along the way.

6.3 Utility of Our Method

After completing this paper we as a team looked back and asked the questions: "How will our method be applied in the world of 2030?" and "Will it be effective?" We feel that our methodology lays the groundwork for a form of Pahl and Beitz that will be much more effective in future years. Our method overcomes two new obstacles of the future: how to effectively divide a workforce that managers may have never met and how managers coordinate teams that are geographically/culturally dispersed.

How have we changed the design world? Our methodology will allow for the corporate world to fully utilize a dispersed workforce—no longer will geography be an obstacle in team creation. This improvement will lead to two profound changes in the world. First corporations will be more efficient and effective, and hence, more capable of delivering better products much more cheaply to current markets. Second, areas of the world that were once trapped as 2nd or 3rd world countries will be able to work hand-in-hand with designers from the world, as new jobs and opportunities are offered to designers in these places. This second change will lead to market growth, which in turn will help corporations yield higher profits.

Additionally, this project has started to work with agent based models, which are growing in popularity in the design community. They are a new tool to model complex design and complex networks of designers, to attempt to gain an understanding of what different policies have on the global outcomes of the model. This was shown for a design process in this project, which will hopefully be used in future work, and spur more designers to uses similar models.

6.4 What would we do differently?

Again after completion our team has looked back to see what we have missed. We feel that our methodology may cause designers to loose touch with the overall goal: to design something. We focused so much on breaking the design into manageable design tasks, that we may have lost touch with the overall goal. Breaking a design into its core obstacles is an extremely effective way to develop solution and one in which Pahl and Beitz push throughout the design. This has one huge underlying limitation: designers may lose touch with the overall goal and not see the forest for the trees.

If we were to redo this entire project we would take steps to ensure that throughout the entire design process our designers would go back and look at the big picture. Not only will this help individual designers accomplish their own respective tasks, but it will help the design group as a whole move in the correct direction and converge to an appropriate solution more quickly.

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