AC 2009-1294: BIOENGINEERING PROCESS MAPS: ELEMENTS USED TO PRODUCE INNOVATIVE DESIGNS

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Bio-Engineering Process Maps: Elements Used to Produce Innovative Designs and Prototypes

This paper describes initial results from an ongoing study on how bio-engineering teams create innovative product designs as part of a larger NSF sponsored project. Specifically, it documents progress on a descriptive study of two groups of bio-engineering "inventors" – senior capstone bio-engineering teams and teams who entered the BME-Idea competition using process maps as a method of comparison. During the 2007-08 academic year nine bio-engineering teams from the University of Pittsburgh volunteered to develop process maps describing their capstone project. Utilizing the same approach, 27 process maps were collected from student entrants of the BME-Idea competition.

Each team's map describes the particular design process it followed that resulted in a working prototype. To assure consistency, each team used a comprehensive set of product development elements (developed from an earlier study) to describe their process. The teams were asked to first select those elements/activities that they actually used in their process and then arrange them temporally to reflect the team's design and product development process. The resultant maps were then analyzed through a series of comparisons between the two sets of design teams. Both groups were compared relative to their utilization of the elements, and which elements they had classified as being critical, time-consuming and/or problematic to the design process. Following this comparison, a path analysis was conducted to determine if teams approached process design activities in a similar manner. We provide a description of the overall approach, our analysis and results; and suggest how process maps might be used to evaluate the effectiveness of the overall design artifact in meeting its design specifications and purpose.

1.0 Introduction

In this paper we provide an initial descriptive study of how different teams of bioengineering "inventors" navigate the design process from idea conception to prototype. Nine bioengineering capstone teams from the Swanson School of Engineering Department of Bioengineering and 27 teams from throughout the U.S. who entered the BME-Idea national competition each reflected upon and diagramed their experiences via process maps that captured their engineering design and product development activities. Although many of the BME-Idea projects also resulted from bioengineering capstone projects, several others were either NCIIA funded "e-teams," or were graduate bio-engineering students. Hence, the two groups were kept separate. Here, we investigate several research questions associated with engineering design and product development and their potential implications for engineering education. Specifically, do bioengineering design teams utilize similar activities when developing their designs/prototypes or is the process specific to the particular design? As a follow on, do teams utilize similar paths when creating their designs/prototypes and is this indicative of design instruction at their particular institution? Further, and potentially more important, do certain activities and/or process paths relate to the overall quality (or rating) of the design?

The 2007 – 08 bioengineering teams who developed a design/prototype were asked to reflect upon and explain their experiences by developing a concept or process map.[1-2] The use of process maps allows teams to not only show the relative importance of the various elements in their process, but also to clearly indicate the relationships among these elements. This process mapping technique has been successfully used to investigate the differences between academic and corporate inventors in the RFID technology sector and to identify activities that university technology transfer offices might adopt. [3]

In the following sections, the conceptual model with its comprehensive set of elements (or activities) that bio-engineering teams used to create their maps is described. The process by which the teams created their maps and the quantitative and qualitative methods used to analyze the maps and address the research questions are then described. Finally, a discussion of results and potential implications for engineering education are presented.

2.0 A Conceptual Model of the Design and Product Development Process

Substantial research concerning the design and product development process[4-6] has resulted in a number of design and product development models [7-12]. In a prior research effort, the literature and models were combined to form a five stage model of the development process: opportunity identification, design and development, testing and preproduction, introduction and production and life cycle management. Elements that were not specific to any one stage were then grouped into a sixth "on-going" stage.

The model is delineated as follows:

- Stage one involves conceptualization of the product/technology, the identification of a potential target market, and competitor benchmarking. The project scope is then defined, resources are allocated, and technical feasibility and financial evaluations are conducted.
- Stage two involves the design and physical development of the technology. A critical activity is an assessment of customers' needs and specifications. Finally, a detailed design is created and a prototype(s) is developed.
- The third stage ensured functional capability and design for manufacturability. Prototype testing is completed to achieve reliability and operability by projected users in the intended environment.
- The fourth stage involves taking the technology from pilot to full scale and product launch.
- The fifth and final stage involves managing the life cycle of the technology.

Although the product design and development proceeds through the five stages, most, if not all prototypes developed by the bioengineering teams did not traverse the entire product development process since their final requirement was a working prototype. Consequently, fifth stage elements were not presented to the groups, although fourth stage elements were included in case there were teams who were taking their prototypes from pilot to product launch.

From the literature, an initial 99 process elements were identified that span each of these six stages. Because this article was interested in how bioengineering groups traverse the design and product development process, the individual elements were further grouped into six categories. These categories included: technological issues, human issues (referring to those aspects related to the development team), competitor issues, financial issues, strategic aspects, and societal aspects (referring to those aspects related to the product's use). These six sub-categories are similar to ones proposed by Mohanty [13] for classifying issues involved in implementing a new technology. This conceptual model was then pilot tested [14], resulting in additional elements being identified. In developing the process maps, neither the stages nor the categories were revealed to the bioengineering teams. Table 1 provides a listing of the elements in the model.

Table 1. Stages and Elements of the Design and Product Development Process

Opportunity Identification	Design and Development	Testing and Preproduction	Introduction and Production
Technological Issues (8)	***Technological Issues (14)***	***Technological Issues (18)***	***Technological Issues (4)***
Create Product Description	Produce 2 and 3-Drawings	Develop a Product Manufacturing Plan	Consideration of Product Service Opportunities
Preliminary Research	Design For Manufacturability	Product Test Method Definition	Pilot Scale Operational Testing and Evaluation
Generate Multiple Product Alternatives	Design For Assembly	Prototype Testing	Production Line Design and Setup
Choose Product Design From Multiple Alternatives	Design For Automation	Testing Data Analysis, Evaluation and Reporting	Full Scale Operational Testing and Evaluation
Incorporate Available Technologies to Improve Functionality, Safety, Etc.	Finalization of Technical and Physical Requirements for Design	Beta Testing – Product Works in Customer Operations	***Strategic Issues (2)***
Define Product's Performance Requirements	Evaluate / Select CAD Tools	Pilot/Prototype Review	One, Three and Five Year Product Plans
Evaluate Potential Time to Market Requirements	Product Functional Analysis	Reliability Testing, Test to Failure, Limit Testing	Documentation of Lessons Learned
Technical Risk Assessment	Optimization of Conceptual Design	Final Design Approval	***Financial Issues (2)***
Strategic Issues (8)	Product Component Tradeoffs and Optimization	Alpha/In-house Testing	Actual Versus Planned Cost Evaluation
Define the Market and Its Growth Potential	Reverse Engineering Protection	Product Packaging and Protection	Final Financial Reviews
Construct a House of Quality	Modeling and Simulation to Study Design	Refine Tests and Models	***Human Aspects (1)***
Create a Schedule for the Product	Optimization of Detailed Design	Gamma Testing / Actual User Testing	Creation of Data Management System
Define the Product Scope / Statement of Work	Prototype Development	Product Bill of Materials	
Intellectual Property Awareness	Software Development	Operator/Training/Assembly Documentation	
Cost Estimate Projections	***Strategic Issues (9)***	Design Manuals Written	**Life Cycle Management**
Product Risk Assessment	Product Advertising Plan	Patent Prosecution	***Technological Issues (3)***
Product's Mesh With Vision and Objectives	Product Marketing, 3 C's, 4 P's	Site Surveys / Installation Considerations	Part/Product Cost Reduction
Financial Issues (6)	Licensing In Considerations	Production Pilot Review	Product Quality Reviews, TQM, SQC
Create a Product Financial Plan	Licensing Out Considerations	***Strategic Issues (5)***	Concurrent Engineering Principles
Determination of Product Cost	Situational Analysis	Identify Potential Future Innovations	***Strategic Issues (1)***
Determination of Investment Req. / Potential Profit	Identify Primary Innovation	Develop Peripheral Innovation(s)	Determination of Product Phase-out / Divestment
Determination of Product Retail Price	Patent Filing Initiated	Pretest/Pre-Launch Forecasting	***Financial Issues (1)***
Funding Considerations	Create a Part Sourcing / Partnership Plan	Limited Rollout, Test Marketing	Life Cycle Cost Analysis
Financial Risk Assessment	Supply Chain Management	Quality and Process Reviews	***Societal Aspects (2)***
Societal Aspects (6)	***Financial Issues (1)***	***Financial Issues (2)***	Reaction to Customer Response
Conjoint Analysis of Customer Needs	Sales Forecasting	Estimate / Predict Customer ROI	Product Warranty
Target Customer Determination	***Societal Aspects (10)***	Proposed Design within Target Costs	***Competitor Aspects (1)***
Product Need Based on Development Time	Customer Needs Analysis	***Societal Aspects (5)***	Evaluation of Competitor Reactions
Product Feature Determination	Quality Function Deployment	Evaluation of Insurance Risks due to Errors	
Strength, Weakness, Opportunity, Threat Analysis	Determination of Product Positioning	Train / Transfer Technology, Actual User Training	**Ongoing**
Stakeholder Analysis	Ergonomic Evaluation	Product Meets Actual User Needs	***Technological Issues (4)***
Human Aspects (9)	Evaluate Prior Art (Similar Patents)	Product Use / Knowledge Dissemination	Design Modifications
Create Communication Plan Among Team Members	Identify Litigation Issues and Ways to Avoid	Customer Service and Logistical Support	Design Reviews
Develop a Human Resources Plan	Sought Guidance From Outside Sources	***Competitor Aspects (1)***	Technical Problems Arising During Development
Create Communication Plan For Briefing Management	Design For Environment (Is Product Recyclable, Reusable, Reducible, Disposable?)	Anticipate Competitor Responses	Documentation of Design Work in Technical Memorandums
Team Brainstorming	Product Design to Meet Government Mandate		***Strategic Issues (2)***
Multifunctional Team Development	Regulatory Certification / Compliance		Corporate Strategy Change
Resource Requirements			Schedule / Cost / Technical Summaries
Staffing Levels and Turnover Considerations			***Societal Aspects (4)***
Develop a Work Breakdown Structure			Customer Feedback Evaluation
Individual Brainstorming			Forces of Nature Effect
Competitor Aspects (1)			Interaction With Support Groups
Competitor Benchmarking			Determination of Changing Customer Needs / Market Requirements
			Human Aspects (2)
			Corporate Infrastructure Changes
			Re-scope Development Team
			Competitor Aspects (1)
			Continuous Competitor Monitoring

3.0 Approach to Develop Process Maps

Upon completion or near completion of their design and prototype, teams collectively met and were given scripted instructions to develop their process map. Teams were asked to recall as a group their development process. They were asked to think about where their idea came from (e.g., from research, provided by a faculty advisor or a team member, etc.), as well as the initial motivation for choosing to develop the idea. As a group, teams read each element (presented in alphabetical order) that were individually printed on labels (1 x 3 inch easy peel adhesive labels) and determined whether the element/activity was incorporated into their development process. For reference, a complete definition sheet was provided to each team. The teams then started to organize the selected elements of the process on a large sheet of paper starting with the left side of the paper to denote the beginning of the process and moving across the sheet to the right until the development process became complete. Using blank labels provided, teams were permitted to add additional elements, where necessary (although this was the exception rather than the rule). Once the team was satisfied with the process, they taped the labels to the sheet of paper and drew arrows between the elements to show the flow of activities from start to finish (teams could draw feedback loops, as well). Teams also commented on their map, providing descriptions of the process flow, such as interactions or influences that the team felt were important to note. Finally the team labeled critical, time consuming and problematic elements on the map. In all, the time to develop a process map averaged around 90 minutes. To give an overall perspective of what a complete process map might look like, an example is shown in Figure 1 (note - individual elements are not legible).

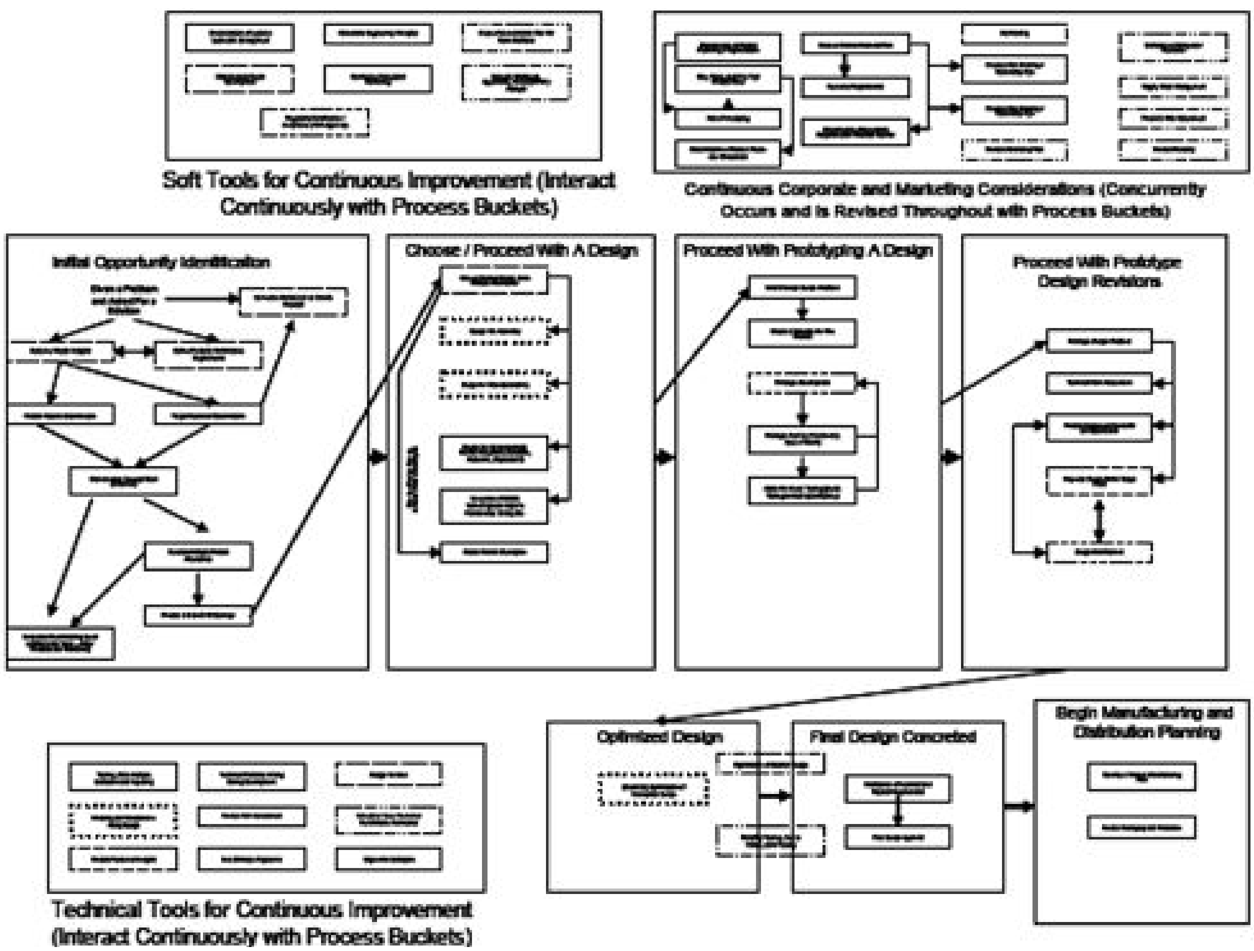

Figure 1. Example Depiction of a Process Map

In addition to the maps, each resulting design and prototype submission was reviewed and rated. For the Capstone teams, the designs/prototypes were rated by the instructor; and for the BME-Idea submissions, a panel knowledgeable in bioengineering design rated the designs and prototypes using a rating instrument developed for that purpose.

The resultant maps were then analyzed through a series of descriptive and categorical comparisons between different design groups. Separate investigations were conducted according to the research questions that were posed; the two groups were kept independent for several reasons. First, the quality of the prototype ratings between the two groups was substantially different. The instructor graded the projects based on course requirements and how well the design fulfilled customer needs. The BME-Idea panel rated the projects based on a five attribute scale that was then summed across the raters. Second, the time period for the Capstone projects was two semesters. The time period for the BME-Idea projects was relatively unknown and most likely varied among the projects; certainly some projects would have been similar in length to the Capstone projects, but others may have been shorter or longer in duration. Finally, the level (i.e., senior capstone, graduate level, etc.) was not always certain in the BME-Idea participants.

4.0 Results

4.1 Research Question - *do bioengineering design teams utilize similar activities when developing their designs or is the process specific to the particular design?* Results to date indicate that for both groups of participants design teams do utilize similar activities, but that the activities become less consistent as the design process progresses through the stages of design/product development. Table 2 provides a list of those elements that appear on at least 77.8% of the maps (i.e., the element appears on at least 7 or the 9 of the Capstone maps and at least 21 of the 27 BME-Idea maps). Admittedly arbitrary, we believe that this value fairly captures the majority of the maps for each of the two sets.

It was found that for phase one 32% of the elements in this phase were utilized in the majority of the design processes. That is, there were 38 elements associated with phase one of which 12 elements were explicitly placed on at least 77.8% of the maps. While in phase two, 21% of the elements were utilized across all the maps, in phase three, only 13% of the elements met this criteria; and for phase four, there were no consistent elements used across any of the teams. For the "on-going" phase 33% of the elements were utilized in the large majority of designs. This suggests that although teams begin the design process in a consistent manner, it becomes more and more unique as each team progresses to final prototype.

Upon completion of their maps, teams were asked to identify those elements they felt were "critical", "problematic", or "time consuming." Teams could identify several elements, but were instructed to be judicious in selecting those particular elements. Table 3 provides the results for the two sets of maps. As shown in the table, *Prototype Development* and *Prototype Testing* appear on both sets as being critical to the process; and both of these elements/activities are also identified as being time consuming. Further, *Prototype Development* is also identified as being problematic. Though not surprising, it is noteworthy that these two elements are highly important to the design/product development process. Additionally, *Preliminary Research* is known to be a time consuming activity for both sets of maps. Finally, it was observed (and expected) that *Technical Problems Arising during Design* was common to both sets of maps. Interestingly, although a substantial number of BME-Idea participant teams conducted a *Customer Needs Analysis*, this was not prevalent with the Capstone teams. Upon discussion of the results with the BME-Idea organizers, they were pleased to see that *Customer Needs Analysis* was considered a critical item as incorporation of customer needs is intended to be an important dimension of the contest (which is focused on entrepreneurial development).

Table 2. Elements Utilized in at Least 78% of the Maps

Element Name	Phase
Choose Product Design from Multiple Alternatives	1
Create Product Description	1
Define Product's Performance Requirements	1
Define the Market and its Growth Potential	1
Define the Product Scope / Statement of Work	1
Individual Brainstorming	1
Multifunctional Team Development	1
Preliminary Research	1
Product Risk Assessment	1
Target Customer Determination	1
Team Brainstorming	1
Technical Risk Assessment	1
Element Name	**Phase**
Design Modifications	On-going
Design Review(s)	On-going
Technical Problems Arising During Development	On-going

Element Name	Phase
Customer Needs Analysis	2
Evaluate Prior Art (Similar Patents)	2
Finalization of Technical and Physical Requirements	2
Identify Primary Innovation	2
Product Functional Analysis	2
Prototype Development	2
Sought Guidance From Outside Sources (Experts)	2
Element Name	**Phase**
Identify Potential Future Innovations	3
Pilot/Prototype Review	3
Prototype Testing	3
Testing, Data Analysis, Evaluation and Reporting	3

Table 3. Elements that Teams Identified as Most Critical, Time Consuming, and Problematic - Number of Maps in Parentheses

Critical	Time Consuming	Problematic
Capstone		
Design Modifications (4) Design Review(s) (5) *Prototype Development (5)* *Prototype Testing (5)* Sought Guidance From Outside Sources (Experts) (5)	Design for Assembly (4) Design Modifications (3) Optimization of Detailed Design (3) *Preliminary Research (4)* *Prototype Development (6)* *Prototype Testing (3)* Refine Tests and Models (3) Team Brainstorming (5)	Define the Product Scope/Statement of Work (3) Design for Assembly (3) Design Modifications (4) *Prototype Development (4)* Prototype Testing (4) Refine Tests and Models (3) Team Brainstorming (3) *Technical Problems Arising During Development (6)*
BME-Idea Participants		
Customer Needs Analysis (11) Preliminary Research (7) *Prototype Development (10)* *Prototype Testing (8)*	*Preliminary Research (9)* *Prototype Development (12)* *Prototype Testing (13)* Testing, Data Analysis, Evaluation and Reporting (9)	Modeling and Simulation to Study Design (6) *Prototype Development (8)* *Technical Problems Arising During Development (14)* Testing, Data Analysis, Evaluation and Reporting (6)

Table 4 provides a summary of those elements that appeared on all the maps. On the Capstone maps there were several activities that spanned across the nine groups, where there were only two activities/elements that appeared on all of the BME-Idea maps – *Product Functional Analysis* and *Prototype Development.* Many of the elements seen on the Capstone maps are requisite in the class requirements. In discussing the results with the instructor this was consistent with the intended pedagogy. As a result, although specific elements were independent of the class, their clear inclusion in the design process validated for the instructor that these activities were carried out by the student teams.

Table 4. Elements Appearing in All Maps

Aspect/Issue	Element
Capstone	
Human	Team Brainstorming
Social	Sought Guidance from Outside Sources (Experts) Target Customer Determination
Strategic	Create a Schedule for the Product Define the Product Scope / Statement of Work Product Risk Assessment
Technical	Create Product Description Define Product's Performance Requirements Design Modifications Design Review(s) Incorporate Available Technologies to Improve Functionality, Safety, etc., Preliminary Research Produce 2-D and 3-D Drawings *Product Functional Analysis* *Prototype Development* Prototype Testing Refine Tests and Models Technical Problems Arising During Development Testing, Data Analysis, Evaluation and Reporting
BME-Idea Participants	
Technical	*Product Functional Analysis* *Prototype Development*

In sum, teams do use similar activities as they begin their design process but as the teams progressed through the design/product development process the similarity of the activities wanes. Further, we have noted several elements associated with *Prototype Development* and *Prototype Testing* to be either critical, time consuming or problematic consistently across the two groups.

4.2 Research Question - *do teams utilize similar paths when creating their designs and is this indicative of design instruction at their particular institution?* In a previous but unrelated research effort, an algorithm was developed to evaluate process maps that described the development of school districts' K12 educational initiatives [15]. That algorithm looks for common paths across different process maps, as demonstrated via the connecting arcs (arrows) between nodes (elements). This same algorithm was applied to the bio-engineering design/product development process maps. In doing this, some maps had to be eliminated because the teams failed to draw a sufficient number of arcs between their elements. Only eight of the nine Capstone and 13 of the 27 BME-Idea maps could be assessed by the algorithm (21 maps in total out of 36).

With regard to whether or not teams use similar paths, it was found for both the Capstone and BME-Idea teams that there were few repeating paths or patterns (i.e., one element leads to another element which leads to another element, etc.) across multiple maps; and what repeating paths did occur only contained two or three elements.

For the Capstone maps, there were a total of 53 repeating paths of two elements; however, for the majority of these short paths, most were found on just two of the eight maps. Table 5 provides insight as to the type of activities that were repeated in three or more maps. Table 6 provides paths of three elements; and as noted these paths were only observed on two of the eight maps.

Table 5. Capstone Repeating Paths of Two Elements (8 Maps Total)

# of Maps	From Element 1	To Element 2
4	Refine Tests and Models	Prototype Testing
3	Customer Needs Analysis	Define Product's Performance Requirements
3	Identify Primary Innovation	Define Product's Performance Requirements
3	Identify Primary Innovation	Preliminary Research
3	Prototype Development	Technical Problems Arising During Development

Table 6. Capstone Repeating Paths of Three Elements (8 Maps Total)

# of Map	From Element 1	To Element 2 and Then	To Element 3
2	Design Modifications	Refine Tests and Models	Testing, Data Analysis, Evaluation and Reporting
2	Customer Needs Analysis	Define Product's Performance Requirements	Situational Analysis
2	Optimization of Conceptual Design	Prototype Development	Technical Problems Arising During Development

Tables 7 and 8 provide paths of two and three, respectively, for the BME-Idea Competition maps. As with the Capstone maps, there were few maps that displayed similar paths of lengths two and three. Although several repeating paths were created, they were shared among two maps at most.

Table 7. BME-Idea Competition Repeating Paths of Two Elements (13 Maps Total)

# of Maps	From Element 1	To Element 2
6	Preliminary Research	Evaluate Prior Art (Similar Patents)
5	Prototype Development	Prototype Testing
5	Generate Multiple Product Alternatives	Choose Product Design from Multiple Alternatives
5	Evaluate Prior Art (Similar Patents)	Intellectual Property Awareness
5	Target Customer Determination	Customer Needs Analysis

In analyzing these results, two general but preliminary suppositions about design teams have been formed. First, because the repeating paths between elements are not shared by a majority of teams, this further demonstrates that the product design and development processes can be approached in a manner that is unique to each team's objectives and requirements. Second, because there are a large number of activities that can be conducted during the process, finding a consistent path among the various teams can be arduous. Further research is necessary to determine if this is indeed true among both novice (as is the case here) and expert design teams.

Table 8. BME-Idea Competition Repeating Paths of Three Elements (13 Maps Total)

# of Map	From Element 1	To Element 2 and Then	To Element 3
2	Prototype Development	Prototype Testing	Refine Tests and Models
2	Prototype Testing	Refine Tests and Models	Finalization of Technical and Physical Requirements
2	Create a Schedule for the Product	Preliminary Research	Evaluate Prior Art (Similar Patents)
2	Customer Needs Analysis	Team Brainstorming	Generate Multiple Product Alternatives
2	Team Brainstorming	Generate Multiple Product Alternatives	Produce 2-D and 3-D Drawings
2	Preliminary Research	Evaluate Prior Art (Similar Patents)	Intellectual Property Awareness
2	Team Brainstorming	Generate Multiple Product Alternatives	Choose Product Design from Multiple Alternatives
2	Concurrent Engineering Principles	Design Modifications	Prototype Testing
2	Incorporate Available Technologies to Improve Functionality, Safety, etc.	Design Modifications	Prototype Testing
2	Choose Product Design from Multiple Alternatives	Technical Risk Assessment	Modeling and Simulation to Study Design
2	Prototype Testing	Design Review(s)	Design Modifications
2	Individual Brainstorming	Team Brainstorming	Generate Multiple Product Alternatives
2	Testing, Data Analysis, Evaluation and Reporting	Optimization of Detailed Design	Final Design Approval

<u>4.3 Research Question</u> - *do certain activities and/or process paths relate to the overall quality (or rating) of the design?* We are just beginning to have sufficient data to address this research question. Table 9 gives the both average and standard deviation for the number of elements found on the maps for each aspect and issue. Two top scores and two low scores were provided for the BME-Idea participants; and a single top and low score was provided for the Capstone groups. As shown in the table, for both sets of low scoring maps (relative to design/prototype) all were below the average number of elements observed for the complete set. In contrast, for the highest rated maps for both categories, all utilized at least the average if not more than the average number of total elements. Certainly this suggests that statistically significant correlations would be found with larger sample sizes, something we are now collecting.

Table 9. Elements Categorized According to Mohanty's Aspects and Issues

	Competitive	Financial	Human	Societal	Strategic	Technical	Totals
BME-Idea Competition							
Average	*1.4*	*5.4*	*5.1*	*11.5*	*11.9*	*27.4*	*62.7*
Std Dev	*1.1*	*2.8*	*2.0*	*3.7*	*3.2*	*4.9*	*13.0*
High Score #1	0	6	6	11	12	28	63

	Competitive	Financial	Human	Societal	Strategic	Technical	Totals
High Score #2	1	6	7	12	13	26	65
Low Score #1	1	2	4	6	7	15	35
Low Score #2	0	6	4	8	12	24	54
Capstone							
Average	*0.7*	*3.2*	*5.4*	*11.6*	*9.7*	*29.1*	*59.7*
Std Dev	*0.7*	*2.3*	*1.7*	*2.2*	*1.7*	*4.8*	*10.6*
High Score	0	2	7	13	10	35	67
Low Score	0	1	4	10	9	24	48

Further, for the BME-Idea participants, the lower scoring teams documented substantially fewer *societal* elements on their maps than did their high scoring counterparts. This was not the case for the Capstone low scoring design/prototype. In discussing this result with the BME-Idea organizers, this is likely an important insight as to why such designs did not fare well in the competition.

So far statistical tests have not yet been performed to verify these considerations and not all maps have been fully analyzed for this particular hypothesis. Further, it should be noted that both potential rater and rating scale biases may have an effect on the results. Further the the quality of the design/prototypes between the two sets of teams are substantially different; hence, drawing conclusions across the two groups is very problematic at this point. However, such findings do warrant further investigation.

5.0 Discussion and Future Work

To improve design education, and in particular bioengineering design education, engineering educators need to better understand how teams navigate the design process from concept to prototype. Through our research, we are developing tools that enable both real time assessment as well as retrospective analysis of the design/product development process. The work presented in this paper provides a first descriptive analysis of the use of process maps as a retrospective group reflection tool. To date, we have shown that teams do consistently utilize many of the same design elements as they begin their design process, but that the set of similar activities wane as the process moves towards prototype development. Consequently, our initial work suggests that the "paths" teams take when developing their designs/prototypes are fairly unique. Finally, preliminary results indicate that there is potentially a relationship between types of elements used in the design/product development process and the quality of the rating that it received; however more investigation is needed to confirm and verify this result.

In addition to the team process maps presented here, we are acquiring additional maps from the 2009 BME-Idea competition as well as maps from this year's two term bioengineering Capstone course from a second institution. This larger pool of maps will help to validate our initial conclusions, while providing a sufficient number of maps to properly conduct statistical analyses. We are also in the process of developing a normative process map for the design/product development process by assembling an "expert panel" of successful academic bioengineering product designers to also help us address a second set of research questions.

Specifically, how do the design process (maps) of "neophyte" bioengineering design teams relate to the normative process (map) of more "experienced" designers? Are their particular activities that "experienced" designers consider critical or necessary for a good design that are not currently a focus in the Capstone maps or in BME-Idea Competition maps? As we continue our analysis and perfect the mapping tool, we expect to provide the bioengineering education community with a methodology for analyzing team effectiveness and accomplishments.

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