THE ANALYSIS AND MODELING OF THE ENGINEERING DESIGN PROCESS: FACTORS LEADING TO INNOVATIVE OUTCOMES

by

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University of Pittsburgh, 2012

Engineering innovation is essential to solve many of the 21st century's "grand challenges", as it plays a strategic role in competitive environments. Currently, most design practices in engineering education focus on aspects of "good" technical design. However, to meet the competitive environment, elements of innovation must also be incorporated.

This research has two overarching goals. The first is to determine the characteristics of teams and their design processes that lead to innovative artifacts. Regarding this, two research questions are explored. First, what attitudes and design activities do teams exhibit that are related to the innovativeness of their design artifact? Second, how do teams' attitudes and their design activities traverse over the design process from problem definition to working prototype? To address these questions, two investigations that identify differences between innovative and non-innovative teams are performed.

The first one, examining teams' design activities, is a quantitative investigation addressing whether the engineering design process has any influence on the innovativeness of the artifact. Stepwise regression and association mining analyses are applied to determine the activities utilized, when they are utilized, and how teams navigate the process as depicted by their iterations. The second, examining teams' attitudes about their progress, is a qualitative investigation that incorporates grounded theory and content analysis to examine the attitudes of teams and how this potentially affects the innovativeness of the artifact.

The second goal of the research focuses on developing an intervention tool to increase the likelihood of innovative outcomes in design settings given engaged activities. This tool is formulized by a Bayesian network model.

The results show that utilizing *marketing* activities in the early phase is essential; and *design communication* becomes critical in the late phase. Moreover, displaying a smooth iterative flow has a positive effect on the innovativeness of the artifact. This research also shows that the innovative teams act like problem solvers, as well as have the propensity to know what they do not know, and where to seek help. In close, the innovativeness of a design team is a function of both their chosen design activities and their attitudes.

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ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

Innovation plays an important role in any competitive environment. A recent article by Booz and Company suggests that although there is no correlation between the number of innovative products and expenditures in research and development (R&D), there is an increased annual trend in R&D spending by companies and nations [1]. The U.S. has a strong history for invention throughout the 20th century [2]; however, many industry leaders and researchers have indicated that the U.S.'s technological leadership is now waning along with its global competitiveness [3]. Although "U.S. engineers lead the world in innovation," states a 2009 report, "this resource is at serious risk because America has an engineering deficit" [4]. The U.S. has already lost its lead in higher education degrees [5-7]; and as a result, the Obama administration has proposed a national strategy that invests in the building blocks of U.S. innovation to include the next generation STEM workforce [8]. These reports have indicated that the engineers must be educated to be innovative for economic growth, as engineering innovation is necessary in addressing many of the "grand challenges" of the 21st century [9]. Innovation does not only depend on creative idea generation, but also relies on thoughtful engineering design and the product realization process. Engineering educators currently educate their students to be technically competent and to design systems, components and/or products; but now given these competitive urgencies, educators must also be cognizant of how to infuse certain practices that lead to more innovative products and artifacts. Herein lays the motivation for this research.

There is ample study that indicates a good design process and what makes for a quality design artifact. In addition, much literature has been devoted to the nature of innovation from the perspective of business. Yet, little has been done to investigate the design process itself for aspects that improve and contribute to innovation. In this research, engineering design processes leading to “good” design but also to “innovative” design, of which the two are only moderately correlated, are considered. In order to improve design, one needs to understand it in relationship to innovation; and from its characterization, it is possible to provide a model demonstrating paths leading to innovation [10]. Also, a recent NSF report [11] indicates that “empirical studies and computational models that explore the temporal dynamics of individual and group factors on creativity/innovation” is one of the research areas identified as critical in helping the process of innovation.

In this research, three separate investigations are performed to: (1) characterize how engineering teams conduct design processes leading to innovative outcomes, (2) determine the attributes of these teams; and (3) provide guidance on how one might improve the innovativeness of the resulting product. In particular, 26 senior capstone bioengineering design teams as they work from initial conception to working prototype are examined over a 23 to 24 week time period. From this, the extent to which innovative and non-innovative resultant artifacts are a function of the design process is determined.

1.1 RESEARCH SCOPE

Investigating innovation in the 'real world' is a difficult task; and such studies are often case-based in nature. Often the setting for evaluating design has been in undergraduate engineering settings, where the research perspective has been cognitive, behavioral, or affective, looking at how engineering students engage in design. This research is no exception, as it draws upon a National Science Foundation grant involving the creation of data gathering and assessment techniques that facilitate student reflection and engagement about the design process. As part of this work, data is collected on groups of engineering students designing a biomedical device from idea conception to working prototype over multiple terms; hence providing a "near-real" world experience of the product realization process by apprentice-like professionals (senior capstone students). From this data and the resulting assessment tools, aspects of good design are evaluated in a team setting. More importantly, insights on design process and team dynamics leading to innovation are examined. This research investigates the early portions of Ford et al.'s [12] process of innovation; i.e., invention and some parts of trial production.

Innovation typically refers to the characteristic of the output, whereas creativity is an act. Note in this research creativity is not a specific focus, such that it is not necessary to have design teams act creatively. Rather, this research attempts to capture those activities that teams engage in during the design process, which potentially influence the final artifact to be more innovative.

In this research, we use Schumpeter's [13] landmark definition of innovation, which encompasses the following:

- New applications of existing technology,
- An innovative use of materials and/or components,

- Innovative manufacturing processes, and
- Innovative design changes to reduce manufacturing cost.

Further, the term “innovative team” refers to a “team having an innovative artifact”, and similarly the term “innovative design process” is used to indicate a “design process leading to an innovative artifact”. Moreover, the term “iteration” is used to describe the teams’ movement among the various design categories.

1.2 RESEARCH GOALS AND QUESTIONS

A first goal of this research is to determine if teams display certain characteristics throughout the design process such that they yield innovative artifacts. In doing so, quantitative and qualitative empirical investigations are conducted about the characteristics and patterns of the design process leading to innovative artifacts. Thus, two primary research questions are explored:

1. What attitudes and design activities do teams exhibit that are related to the innovativeness and the non-innovativeness of the design artifact?

2. How do teams’ attitudes and their chosen design activities traverse over the design process from problem definition to working prototype, and are they different depending on the degree of innovativeness?

A second goal of the research is to develop an intervention tool that allows engineering design instructors a means to predict the innovativeness of the team given the activities they engage in, and provide guidance when teams do not engage in activities that lead to innovative artifacts.

1.3 THREE INVESTIGATIONS OF THE DATA

To address the two overall research goals, three separate studies using the same data set are conducted. The first goal is achieved through the first two studies. In the first study, stepwise regression and association mining analyses are used to describe how engineering teams navigate the design process and produce innovative or non-innovative products. In this study, what activities are utilized, when these activities are utilized, and how teams navigate the process as depicted by their iterations are investigated. In the second study, grounded theory and content analysis are used to examine the qualitative characteristics of teams and their influence on the innovativeness of the artifact. Finally, for the third study, addressing the second goal, a normative model is created and tested for robustness based on the activities that teams use throughout the design process. The intent of the model is to serve as an intervention tool by engineering educators (and potentially engineering managers) to monitor the design process and provide guidance during the process such that more innovative artifacts may be produced. Bayesian networks are employed as the underlying tool for this normative model.

1.4 ORGANIZATION OF THE DISSERTATION

The organization of the dissertation is as follows. Chapter 2 provides the literature background for this research. It includes six sub-sections on background literature pertaining to design and innovation, as well as methods for capturing aspects of individuals and teams engaged in design. The data collection techniques and overall methodology used for all studies are explained in

Chapter 3. Chapters 4 through 6 provide the specific methodology, analyses, results, validations, and discussion for the three investigations; i.e., quantitative investigation of the activities teams engage in, qualitative investigation of team reflections about the design process, and the Bayesian network model developed for engineering design educators. Chapter 7 summarizes the research and proposes contributions of this body of work to the literature. Finally, Chapter 8 discusses the limitations of the study and outlines potential future work.

2.0 LITERATURE REVIEW

The literature review encompasses six areas. The first area provides an overview of recent prominent research in the area of engineering design and product realization. The second area presents literature on innovation specific to engineering. Notably most of the literature has been focused in the area of business and marketing. A third body of literature is devoted to research current to cognition and the engineering education arena. The fourth section provides an overview of how innovation has been measured. Design journaling is discussed in the fifth part of the literature review; and the sixth section provides characteristics of high performing teams.

In this research Dym's respected definition of engineering design is used. He defines it as a thoughtful process for generating designs that achieve objectives within specified constraints [14]. His approach to design, shown in Figure 1, provides many of the stages that are incorporated in the early stages of the product realization process.

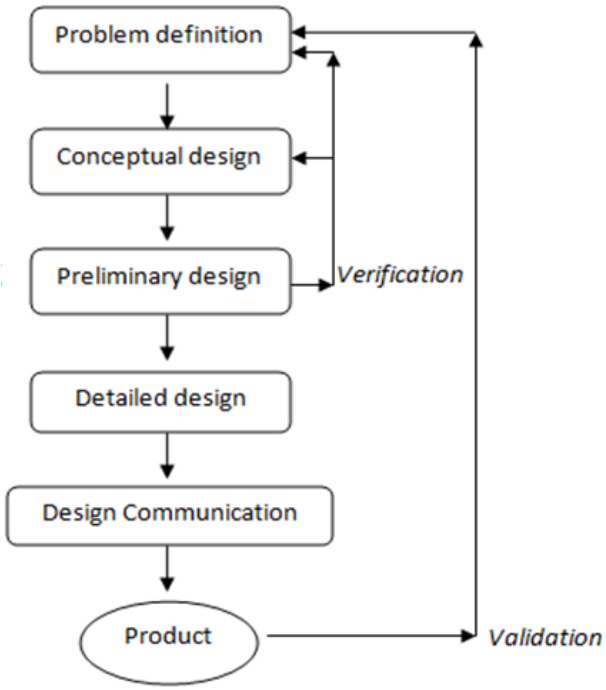


Figure 1. Feedback and iteration in the Dym's design process (see Reference 14)

As mentioned, product realization is the term used to describe the work that the organization goes through to develop, manufacture, and deliver the finished goods or services [15]. For this research, the first three areas of product realization that compatibly overlap with Dym's design process, that of idea, design and working prototype (i.e., Dym's product) are the focus.

2.1 THE ENGINEERING DESIGN/PRODUCT REALIZATION PROCESS

Design is a central and distinguishing engineering activity [16]. It is a complex process that has a collectivist nature [17] and thus a reason why the focus of this research is on engineering teams, instead of individuals. Further, Dym and Little emphasize that engineering design is a constrained process [14] and thus working in a reasonable time frame with a real client is an important aspect when studying design and innovation. In the analysis of design, a common approach is to generalize design activities into simpler activities. The major difficulty with this approach is its dependency on the information about the design activities and the fact that these activities often occur in cycles or iterations [18, 19]. In a prior study that investigates multiple design texts and articles, a list of activities by stage is compiled [20]; hence allowing one to recognize the activity s/he is working on, which can then be related to a particular stage of the design/product realization process.

In evaluating the design process, several researchers have investigated different aspects of design to help make improvements. Specifically, both Atman et al. [21] and Costa and Sobek [22] investigate the impact of the design process on project outcomes; thus providing some linkages between the independent variables of the process and the dependent variable of the quality of the artifact. Whereas Krishnan et al. [19] propose a mathematical model of engineering design iterations to minimize the expected duration of the product development time. In the same sense, Ha et al. [18] study the optimal timing of engineering design reviews, and show the benefits of concurrent engineering in shortening product development durations. The primary focus of this literature is aimed at reducing the duration of the design process and increasing quality. For the most part, these researchers have focused on identifying aspects of the process to obtain clues about how to improve the time or quality of the outcome; however, to the best known knowledge, no researcher has mentioned identifying behaviors and attitudes that potentially influence innovation in the final outcome.

Given the complexity and constructivist nature of design and product realization, another strand of research is related to successful design management. In their research, Yassine et al.

[23] identify four steps to manage the design process: (1) modeling the information and dependency structure of the design process, (2) providing a design plan showing the order of execution for the design activities, (3) reducing the risk and magnitude of iteration between design activities, and (4) exploring opportunities to reduce the project cycle time. In this research, the order of execution for the design activities is delineated for both innovative and non-innovative designs by using engineering capstone design projects.

2.2 INNOVATION AS IT RELATES TO DESIGN/PRODUCT REALIZATION

There is abundant research focused on managing and organizing for innovation [24-35], as well as marketing and economical aspects [36-38]. In particular, Hauser et al. [39] conduct a literature review of innovation in the management science literature and find over 16 topics that are synthesized into five research areas, one of which investigates prescriptive techniques for improving product development processes, which this research attempts to address. However, when describing innovative designs and prototypes, descriptions are often focused on the impacts of a particular innovation, as in the case of CNN’s “Top 25 Innovations” [40]. Given this, characterizing and measuring innovative designs has been left widely with an “eye for the future” value added, degree of newness [25], ornamentality, novelty, unobviousness [41] magnitude of impact, and competitiveness [42]. Measurable attributes do appear to exist for monetary and time-based metrics; however, such measures are likely more suitable for measuring entrepreneurship than innovative design [43] (see forthcoming section on measurements). Ford et al. [12] define the four components of innovation: invention, trial production, imitation, and diffusion (Figure 2).

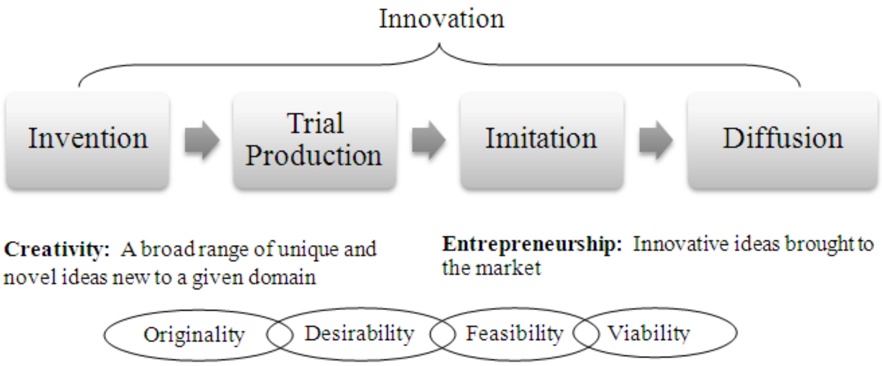


Figure 2: The components of innovation (see Reference 12)

This research investigates the beginning sections of the cycle including the invention and some parts of trial production.

More specific to this vein of research, Carlson et al., study technological innovation [44]; yet, it is not focused on engineering design. Rather, it is focused on the analytical and methodological issues arising from various system concepts. Moreover, Cagan et al. [45] explore the aspects of design innovation and advocate an integrated approach to product design, and emphasize how to integrate style into new products. Furthermore, Ohtomi and Ozawa [46] investigate innovative engineering design and information technology for electromechanical product development. They present the examples of design technologies that realize the innovative product development processes in Toshiba. However, they have not pointed to the characteristics of the design process leading to innovation.

2.3 DESIGN AND COGNITIVE CONSIDERATIONS IN ENGINEERING EDUCATION

From the engineering education perspective, among the eleven outcomes articulated by ABET, design is certainly one of the most complex outcomes. The criterion states that [47]:

"…graduating engineers should have acquired an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability."

McDonald et al. [48] state that engineering educators, who are concerned about rapidly changing industrial environment, need to focus not only on teaching the fundamentals, but also developing team, communication, and leadership skills, and provide a multidisciplinary perspective. To design a product, graduating engineers require a combination of science, mathematics, domain specific knowledge, experience and ability to work within constraints, to assess trade-offs, and to conform to the demands of the customer. Given these expectations, engineering design education has drawn substantial attention [17, 21]. Although not specified by ABET, it is conjecture that innovation also lies at the heart of good design.

The extent of most design studies in engineering education remain limited to the analysis of relatively short term (e.g., a few hours or a few days) design projects. For example, Atman et al. [21, 49-51] make a comparison of freshman and senior engineering design processes for short (roughly three hour) projects. Atman illustrates design (via having subjects design a fictitious playground) as an iterative and transformative process of revisiting and resolving aspects of a design task (e.g., gathering and filtering problem information, monitoring progress and understanding, and revising possible solutions). However, a real-life design and product realization process is far more complex and longer than a few hours or days.

Adams and Atman investigate the cognitive processes of iteration in engineering design to determine how engineers approach design problems. Their research seeks to characterize iterative behavior across levels of experience and performance as a means for exploring features of design learning [52]. In another study, Adams and Mosborg investigate problem prototyping (i.e., characterizing how engineers formulate design problems) with a goal to elicit underlying problem formulation schema [53].

Kavakli and Gero investigate differences between experts and novices through a case study approach investigating the structure of concurrent cognition [54] and find experts to be more organized and able to conduct concurrent processes when designing. Moreover, prior studies center on factors that influence successful design such as appropriate design selection [55, 56], factors leading to the failure of new designs [57], and the importance of good design [58]. One such factor, design fixation, has been investigated by Purcell and Gero to determine its relation to innovativeness of the final product [59]. Others have also investigated design fixation in the context of innovation. An example is provided in Linsey et al.'s study [60].

Notably design is also a collective social endeavor; hence it should be studied in a team environment. Literature in engineering education is growing but for the most part much of the design literature has been focused primarily on studying individuals. Roberts et al. have investigated design and its relationship to problem solving, specifically how students learn and problem solve in active and collaborative team based contexts [61].

This research takes an additional step to investigate where and how innovation potentially occurs along the design and product realization process. It considers longer, more realistic, two-term team based capstone projects that take design/product realization from idea conception to working prototype. By doing so, the complexity of the design process, as well as the collectivist and social nature of the process in a team based setting is considered; hence, allowing one to concentrate on the sequence of activities and their frequency of the design activities that potentially influence innovation.

2.4 MEASURING ASPECTS OF CREATIVITY AND INNOVATION

Currently, an overarching “innovation index” that can be readably used by researchers and engineering educators is not available in the design literature to measure innovation in student design projects [62]. This part of literature reports some innovation measurements (as well as creativity measurements). Stavridou and Furnham [63] propose that measurement of creativity and resultant changes should be framed on four aspects: students, processes used, artifacts created, and climate (or environment). Treffinger et al [64] suggest assessing innovative potential of individuals with the “Unusual Uses Task subscale of the Torrance Test of Creative Thinking” (TTCT), a widely used measure of divergent thinking ability [65], though it is not specific to engineering. Urban and Jellen’s “Test for Creative Thinking – Drawing Production” (TCT- DP) [66] is used to measure increased innovation in engineering students; as has Ragusa’s instrument, the “Engineering Creativity, Entrepreneurship and Innovation Inventory” [67]. To assess creative aspects of the work environment, Amabile et al.'s KEYS climate instrument [68] is specifically designed for engineers and scientists.

While several instruments can assess *artifacts*, the one by Shah et al. [69] provides a well researched engineering measure for artifact novelty, variety, and quantity. Unfortunately this instrument is a relative measure in that it assumes artifacts serve the same purpose (i.e., the product is the same). In our research, each design artifact or prototype is considered unique to the intended purpose and customer; and hence Shah et al.'s measuring cannot be used for this research.

Specific to engineering and the design process, Grenier and Schmidt [70] have created a design coding scheme to capture students' cognitive processes through phrases and sketches from design log books. To capture team innovative processes, this research capitalizes on the use of an online reflection system developed under an NSF funded grant in bioengineering [71, 72]. This reflection system allows students in near real time to record their specific design and product realization activities, as well as reflect on how they believe their design and team is progressing and whether or not they have had any innovative moments.

2.5 CAPTURING STUDENTS' REFLECTIONS OF THE DESIGN PROCESS

Reflective journaling, which is commonly used in engineering design research, has been demonstrated to be an effective tool for students [73], in particular, engineering students [74]. Adams et al. [75], Atman et al. [21] use students design reflections to characterize the engineering students' design processes, and to determine the design behaviors between freshman and senior groups. Genco et al. [76] also use students design reflections to compare freshman and senior students' innovative behaviors by looking at their concept generation exercises.

Moreover, Kosta and Sobek [22] analyze the students' design reflections to understand the relationship between engineering design and the quality of the outcome; and Moore et al. [77] investigate the use of student reflections to enhance engineering design education. Many researchers investigate the use of reflection tools, both individual (e.g., sketching, journaling, SmartPens) as well as those that are team-based (e.g., wikis, weblogs); and find such tools can improve ideation and conceptual design [70]. Here, engineering capstone students have used weekly reflections of their overall experiences throughout the design process (i.e., each Friday), as well as indicated any moments that are particularly innovative from their perspective.

2.6 HIGH PERFORMING TEAMS

Design is a complex process and distinguishing engineering activity [16, 17]; and thus, why engineering teams, and not individuals, should be studied is rationalized due to the social nature of the process. Given the complexity and constructivist nature of design and product realization, another strand of research is related to successful design management, as well as team work. Literature in engineering education is growing, but for the most part, it remains limited regarding teams and design practices. Roberts et al. have investigated design and its relationship to problem solving, specifically how students learn and problem solve in active and collaborative team based contexts [61].

Further, literature in the area of high performing teams is well studied specific to attributes and characteristics that describe team performance. Katzenbach and Smith [78] identify that high performing team members take individual responsibility. In addition, they are supportive, self directed and focused. Ammeter and Dukerich [79] note that high performing teams complete their projects 10%–15% under budget, on schedule or ahead of schedule (i.e., up to 18%), and typically have diverse functional backgrounds. Further, Blanchard et al. [80] describe the seven characteristics of high performance teams. These are as follows.

1. *Purpose and values:* Members of high performing teams have a common purpose, and clear strategies.
2. *Empowerment:* Members feel confident about their abilities to overcome obstacles.
3. *Relationship and communication:* Members have good relations with each other, and are committed to open communication.
4. *Flexibility* Members are flexible, and can perform different tasks.
5. *Optimal productivity:* Members get the job done properly and on time.
6. *Recognition and appreciation:* Members recognize and celebrate milestones.
7. Morale: Members are motivated and optimistic about the future.

In this study, teams producing innovative artifacts have demonstrated several of these characteristics, which may contribute to their overall innovative performance.

3.0 DATA COLLECTION AND OVERARCHING FRAMEWORK

In this section, we first give an overview of the research grant proposed for developing the data gathering instruments. Then, we describe the data collection and analysis techniques as well as the framework used for modeling the design process.

3.1 DESCRIPTION OF THE NSF GRANT - DEVELOPMENT FOR DATA GATHERING INSTRUMENTS

This research is a part of a project funded by National Science Foundation (NSF). As part of the grant, engineering design process maps are created, on-line reflections about the engineering design process are collected, and a design rating scale is used by faculty instructors to determine the overall innovativeness of the senior capstone projects. As seen in Figure 3, this study investigates innovation by developing empirical and normative models based on the “On-line reflections” and “Design Rating Scale”.

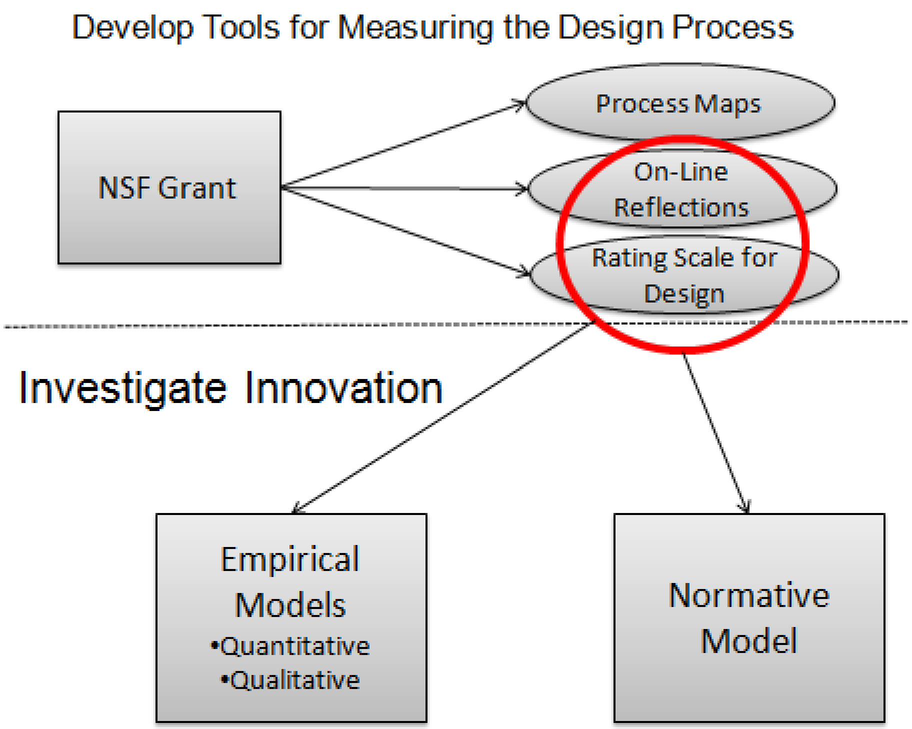


Figure 3. Develop tools for measuring the design process

A web-based system is used to deliver questionnaires to participants and save their responses for on-line reflections. A modified version of On-Line Student Survey System (OS3), which is initially developed by Besterfield-Sacre and Shuman at the University of Pittsburgh to conduct cross-institutional data on engineering student attitudes [81-83], is used for this study. Hosted by an Oracle database server, the OS3 requests participants to take periodic surveys via email. Both open and closed form questionnaires can be easily handled by this system.

3.2 DATA COLLECTION

The data used in this research has two primary sources. The first is the data collected under the mentioned NSF grant, which includes two data sets. The first set includes students' quantitative twice per week selections of the design activities they engaged in as they progress from idea generation to working prototype. The second set of data includes students' once per week qualitative reflections about their design progression.

A rating scale, which is used by faculty to grade the teams' final artifact, is used in this research. Further, as part of the NSF grant, bioengineering experts (from academia and industry) rate the design activities in terms of their importance.

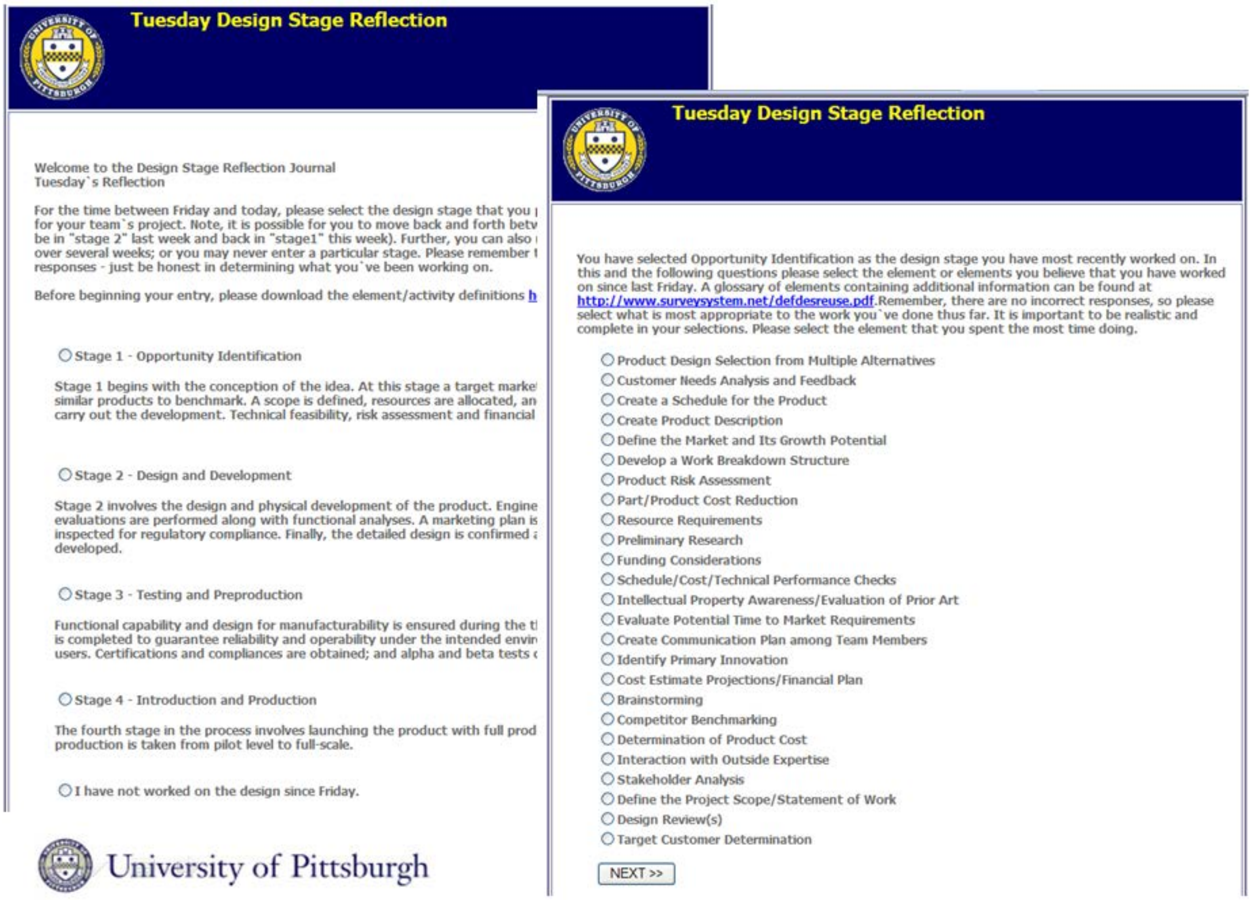
Expert opinions from capstone faculty and design experts on the design duration has been also collected, but not used in this research as insufficient number of responses is acquired.

3.2.1 Source 1: Data collected from students

The data is collected from bioengineering students' senior capstone projects during the 2007-08 and 2008-09 academic years (The descriptions of some artifacts are provided in Appendix A). Eighteen teams from the University of Pittsburgh and eight teams from the Rose-Hulman Institute of Technology participate in the NSF study. The number of students per team varies from three to five students; and the students are paid for their participation.

3.2.1.1 Twice per week activities

Students are surveyed twice per week (Tuesdays and Fridays) through the secure online system. The students are surveyed about the design stages they believed they are engaged in. This survey, as shown in Figure 4, includes four main stages of the product realization process: (1) opportunity identification, (2) design and development, (3) testing and preproduction, and (4) introduction and production. If the student has not worked on their capstone project since the last email, s/he can select “I have not worked on the design”. Within each stage, the student can select up to three activities they worked on. This number is arbitrarily set, but it is believed to be sufficient given the three to four day interval between emails. The entire set of activities is determined by Golish, Besterfield-Sacre and Shuman [84]; and is further reviewed and revised by the capstone instructors. The final set used by the students contains 89 activities (see Appendix B). Students are trained about the meaning of each activity and provided a definition list for easy reference.



Tuesday Design Stage Reflection

Welcome to the Design Stage Reflection Journal
Tuesday`s Reflection

For the time between Friday and today, please select the design stage that you
for your team`s project. Note, it is possible for you to move back and forth bet
be in "stage 2" last week and back in "stage1" this week). Further, you can also
over several weeks; or you may never enter a particular stage. Please remember
responses - just be honest in determining what you`ve been working on.

Before beginning your entry, please download the element/activity definitions h

○ Stage 1 - Opportunity Identification

Stage 1 begins with the conception of the idea. At this stage a target marke
similar products to benchmark. A scope is defined, resources are allocated, an
carry out the development. Technical feasibility, risk assessment and financial

○ Stage 2 - Design and Development

Stage 2 involves the design and physical development of the product. Engine
evaluations are performed along with functional analyses. A marketing plan is
inspected for regulatory compliance. Finally, the detailed design is confirmed
developed.

○ Stage 3 - Testing and Preproduction

Functional capability and design for manufacturability is ensured during the t
is completed to guarantee reliability and operability under the intended envi
users. Certifications and compliances are obtained; and alpha and beta tests

○ Stage 4 - Introduction and Production

The fourth stage in the process involves launching the product with full prod
production is taken from pilot level to full-scale.

○ I have not worked on the design since Friday.

University of Pittsburgh

Tuesday Design Stage Reflection

You have selected Opportunity Identification as the design stage you have most recently worked on. In this and the following questions please select the element or elements you believe that you have worked on since last Friday. A glossary of elements containing additional information can be found at http://www.surveysystem.net/defdesreuse.pdf.Remember, there are no incorrect responses, so please select what is most appropriate to the work you`ve done thus far. It is important to be realistic and complete in your selections. Please select the element that you spent the most time doing.

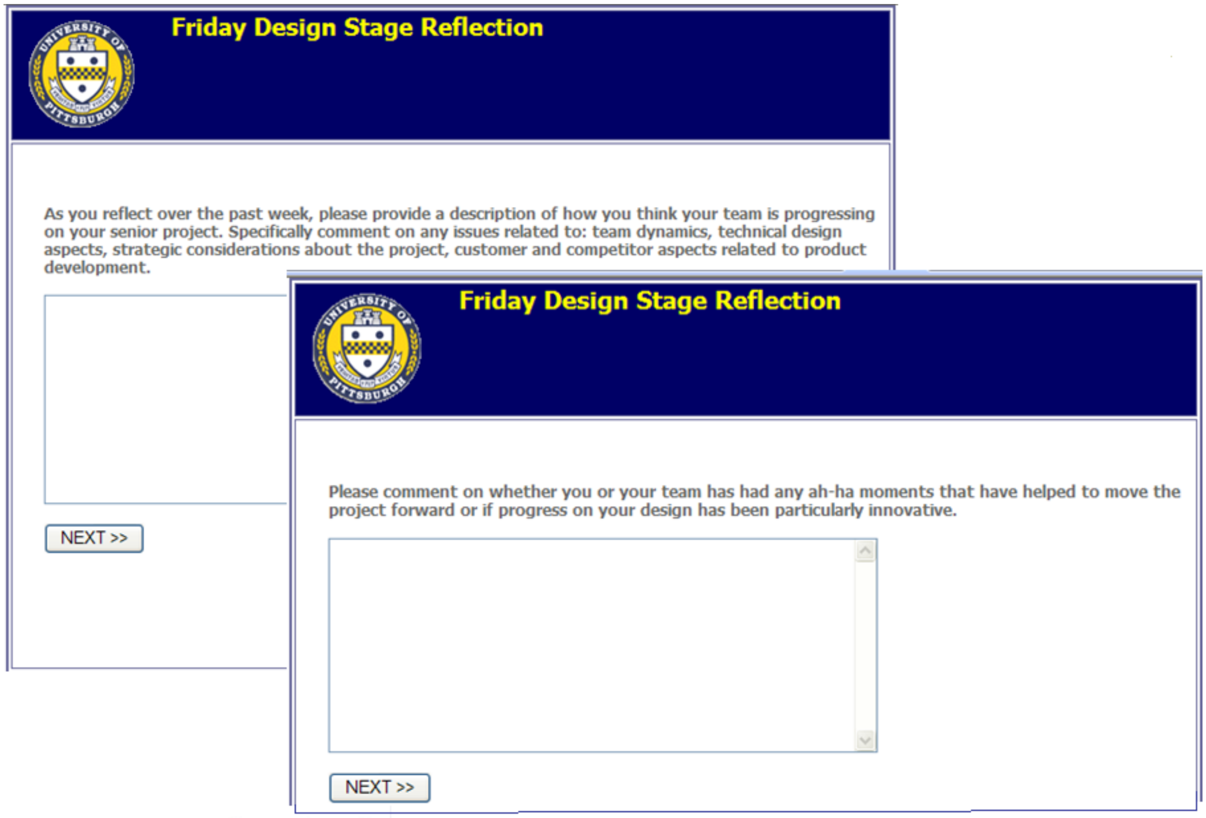
○ Product Design Selection from Multiple Alternatives
○ Customer Needs Analysis and Feedback
○ Create a Schedule for the Product
○ Create Product Description
○ Define the Market and Its Growth Potential
○ Develop a Work Breakdown Structure
○ Product Risk Assessment
○ Part/Product Cost Reduction
○ Resource Requirements
○ Preliminary Research
○ Funding Considerations
○ Schedule/Cost/Technical Performance Checks
○ Intellectual Property Awareness/Evaluation of Prior Art
○ Evaluate Potential Time to Market Requirements
○ Create Communication Plan among Team Members
○ Identify Primary Innovation
○ Cost Estimate Projections/Financial Plan
○ Brainstorming
○ Competitor Benchmarking
○ Determination of Product Cost
○ Interaction with Outside Expertise
○ Stakeholder Analysis
○ Define the Project Scope/Statement of Work
○ Design Review(s)
○ Target Customer Determination

Figure 4. Tuesday and Friday activity survey

The students at the University of Pittsburgh completed the survey 48 times; and the students at the Rose-Hulman Institute of Technology completed it 45 times. From the twice weekly reflections, quantitative data is collected about the activities of each team member. Appendix C gives an example of the quantitative data.

3.2.1.2. Once per week reflections on progress and ah-ha's

In addition to the twice per week activities, the Friday survey provides students with two additional open-ended questions as shown in Figure 5. The first question is about the team's achievements and overall progression since the prior week. Students are asked to reflect on team dynamics, technical design aspects, strategic considerations, problems faced, and customer and competitor aspects related to their product development. The second question asks students if they have any "ah-ha" moments that helps the team move the project forward or if progress on the design was particularly innovative.



Friday Design Stage Reflection

As you reflect over the past week, please provide a description of how you think your team is progressing on your senior project. Specifically comment on any issues related to: team dynamics, technical design aspects, strategic considerations about the project, customer and competitor aspects related to product development.

Friday Design Stage Reflection

Please comment on whether you or your team has had any ah-ha moments that have helped to move the project forward or if progress on your design has been particularly innovative.

Figure 5. Friday survey

The students at the University of Pittsburgh completed the survey during two semesters for 24 weeks (once a week); and the students at the Rose-Hulman Institute of Technology completed it during three quarters for 22 weeks. From those weekly reflections, qualitative data about the design process and any particularly innovative moments is captured. Collecting the data over a sustained period is shown to provide a robust data set [85].

In total 101 students (parsed into 26 teams with an average of four persons per team) participate in the research, and the students are surveyed during 23 weeks on average. Capstone is typically a 4-credit course. It is assumed that each student spends approximately 12 hours per week; hence a team could likely spend over 1,100 hours on their design. In this study we consider 16 teams based on expert ratings (see section 3.2.2). Thus, our data extends across 17,600 hours.

In this research, it is assumed that students are honest in selecting the activities and answering the open-ended questions. It is our belief that students were honest in providing data for multiple reasons. During their initial training session, students were informed that their answers would not be shared by the instructors and would not affect on their grades. Students also had the option to select “did not work”, which was chosen 129 times during the project timeline. Further, while reviewing the data, students appeared to be selecting logical activities and writing detailed reflections. Their responses did not appear to be cursory in any manner.

3.2.2 Source 2: Data collected from faculty and experts

Although each design is graded according to the instructors’ course criteria, both institutions also rate the projects using a common rating scale consisting of five criteria. The rubric is derived from the National Collegiate Inventors and Innovators Alliance (NCIIA) BMEIdea Competition [86]. Using this as a starting point, the instructors of the bioengineering capstone courses iteratively revise the rating scale to arrive at an agreed upon set of defined attributes and scale. The rating scale contains five criteria: technical performance and standards (TP), documentation, innovation, working prototype (WP), and overall impact (on the market or to the client) (OI). Each criterion also contains sub-criteria. The sub-criteria are determined based on the literature that the instructors collectively agree upon. The rating values ranged from “1” (poor) to “5” (excellent). For this research, teams having a score of “4” or “5” on the innovation criteria are considered as innovative; and conversely, teams having scores of “1” or “2” are considered as non-innovative. Overall, there are eight innovative teams and eight non-innovative teams for our observations of the 26 teams.

In addition to the instructors’ ratings of each of the 26 projects, ten biomedical design experts from academia and industry are asked to evaluate and rate the importance and criticality of the activities used in the design and product development process. The activities are then ranked according to the average importance scores. As a result, 15 activities are deemed as “the most important” for the design process. Although these activities are analyzed, no significant results are found; and hence not included in the overarching results.

3.3 OVERARCHING FRAMEWORK OF THE DESIGN PROCESS

Engineering design and product realization are multifaceted subjects. Clarifying objectives and translating them into appropriate forms (words, pictures, rules, etc.) are essential elements of design [14]. Students, who completed the twice weekly surveys, have a large variety of activities encompassing the entire design and product realization process. Hence, it is necessary to have a rigorous theoretical model to simplify the data. To achieve this, Dym’s five-stage descriptive model that identifies feedbacks and iterations among the design categories, as shown in Figure 1, is selected over other design process models in engineering and engineering education literature

[14], as this model traverses both fields and is suitable to the data collected. In Dym's model each phase consists of several design categories, as follows.

- *Problem Definition:* clarifying objectives, establishing user requirements, identifying constraints, and establishing design functions.
- *Conceptual Design:* establishing design specifications and generating design alternatives.
- *Preliminary Design:* modeling, analyzing, testing and evaluating conceptual designs.
- *Detailed Design:* refining and optimizing the chosen design.
- *Design Communication:* documenting the completed design.

The arrows in Figure 1 indicate the general sequence among steps. Dym and Little note that they are not presenting a recipe for completing a design; but rather, they are describing the design process [14].

For this research the focus is not only design, but also product realization; hence, Dym's model is expanded by adding *marketing* and *management* categories as many product realization activities incorporate these aspects. For example, defining the market and its growth potential, determination of production cost, identification of target customer and market can be considered as parts of the engineering design process. The management aspects are also crucial since the projects are conducted by teams. Dym and Little emphasize the importance of *marketing* and *management* in the design process, but do not include these two categories in their core five-stage, prescriptive model. Dym's expanded model is used as a framework for the quantitative analyses and development of the Bayesian model.

3.4 PARSING THE DATA FOR ANALYSIS AND MODELING PURPOSES

As mentioned, the student survey collects two types of data: quantitative data (Tuesday and Friday activity survey), and qualitative data (Friday survey) and is shown in Figures 4 and 5. Quantitative and qualitative models are proposed based on empirical data to identify the aspects of the design process leading to innovation.

Time is an element of this research. To have more explanatory results, the project timeline is divided into three phases: early phase, mid-phase, and late phase. Further, a five-date transition period is allowed between consecutive phases to prevent rigid borders between phases; thus, resulting in two transition periods. Depending on the study, parsing the data and usage of the transition periods are changed. The specific details are found in complementary chapters.

4.0 INVESTIGATION #1 – ANALYSIS OF QUANTITATIVE DATA

In this section, we first investigate the relationship between the design process and the innovativeness of the artifacts using quantitative analysis techniques, specifically stepwise regression analysis and association mining. In doing so, the primary research questions related to teams' actions are investigated. Specifically,

1. What design activities do teams choose that relate to the innovativeness and the non-innovativeness of the design artifact?

2. How do teams' chosen design activities traverse over the design process from problem definition to working prototype; and are they different depending on the degree of innovativeness?

Specifically, are there certain design activities that are significantly used by innovative teams, but not used by non-innovative teams? Where do these differences occur along the design process from initial problem definition to working prototype? Further, do the two types of teams differ in how they matriculate to different stages of the design process?

4.1 METHODOLOGY

We propose descriptive statistical models to analyze the aspects of the design process that leads to innovation. To do this the activities that students select twice per week are coded according to Dym's model. To determine if the two types of teams are significantly different, two quantitative techniques are applied to the coded data; and robustness of the results is tested.

To code the data for analysis, the various activities are first categorized using Dym's expanded model of the design process. In particular, the 89 activities, which are used by students in the twice per week surveys, are collapsed into the eight categories of the Dym's expanded model based on the experience of the research team (consisting of five individuals) in the field of design and product realization. The research team members individually and then collectively arrange all activities into Dym's model. Discrepancies between members are then moderated to determine the best fit of the activities to the categories. For some cases, it is determined that certain activities can be conducted in multiple categories.

As seen in Figure 6, a five-day transition period is used between the early, middle, and late phases to prevent rigid borders. Note that certain activities could belong to more than one category depending on when they occurred in the process. A partial membership rule is applied for those activities observed in the transition period. For example, prototype development activity is a member of both *preliminary design* and *detailed design* categories. If that activity is seen in the early or mid-phase, it is categorized as *preliminary design*. Otherwise, it is categorized as *detailed design*. However, if it is seen in the transition period between the middle and late phases, it is both *preliminary design* and *detailed design*. If it is seen on the fourth day of the second transition, then it is given a weight of 0.2 for *preliminary design* and a weight of 0.8 for *detailed design*.

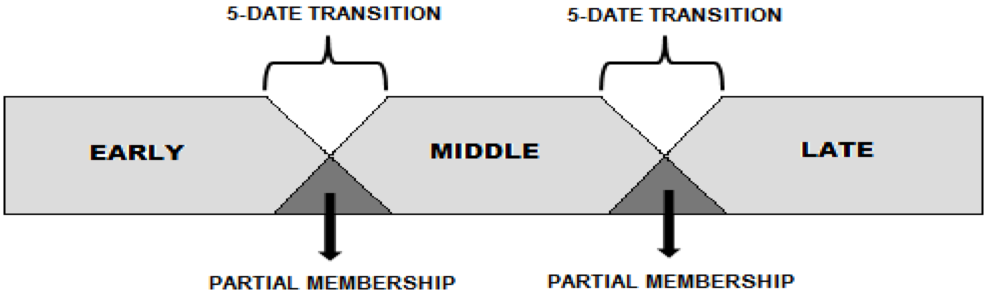
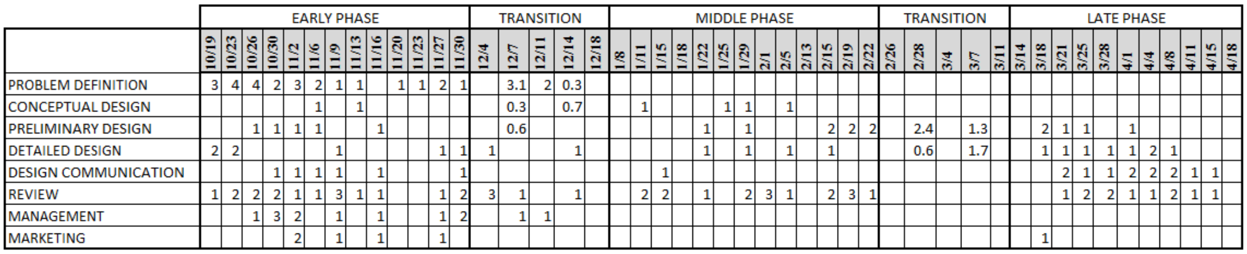


Figure 6. Timeline of the design process

After collapsing the activity data into the extended version of Dym's categorization, the frequency of activities in each category on each day is counted, as shown in Figure 7. The frequency of each category in a time phase is calculated by summing the daily frequencies. Because the number of students in each team varies (i.e., 3 vs. 5), the frequencies are normalized according to the team size. Furthermore, the numbers of survey days vary (i.e., 45 vs. 48) between the two institutions, thus the number of days is also normalized.



	EARLY PHASE													TRANSITION				
	10/19	10/23	10/26	10/30	11/2	11/6	11/9	11/13	11/16	11/20	11/23	11/27	11/30	12/4	12/7	12/11	12/14	12/18
PROBLEM DEFINITION	3	4	4	2	3	2	1	1		1	1	2	1		3.1	2	0.3	
CONCEPTUAL DESIGN						1		1							0.3		0.7	
PRELIMINARY DESIGN			1	1	1	1			1						0.6			
DETAILED DESIGN	2	2					1					1	1	1			1	
DESIGN COMMUNICATION				1	1	1	1		1				1					
REVIEW	1	2	2	2	1	1	3	1	1			1	2	3	1		1	
MANAGEMENT			1	3	2		1		1			1	2		1	1		
MARKETING					2		1		1			1						

	MIDDLE PHASE													TRANSITION				
	1/8	1/11	1/15	1/18	1/22	1/25	1/29	2/1	2/5	2/13	2/15	2/19	2/22	2/26	2/28	3/4	3/7	3/11
PROBLEM DEFINITION																		
CONCEPTUAL DESIGN		1				1	1		1									
PRELIMINARY DESIGN					1		1				2	2	2		2.4		1.3	
DETAILED DESIGN					1		1		1		1				0.6		1.7	
DESIGN COMMUNICATION			1															
REVIEW		2	2		1		2	3	1		2	3	1					
MANAGEMENT																		
MARKETING																		

	LATE PHASE										
	3/14	3/18	3/21	3/25	3/28	4/1	4/4	4/8	4/11	4/15	4/18
PROBLEM DEFINITION											
CONCEPTUAL DESIGN											
PRELIMINARY DESIGN		2	1	1		1					
DETAILED DESIGN		1	1	1	1	1	2	1			
DESIGN COMMUNICATION			2	1	1	2	2	2	1	1	
REVIEW			1	2	2	1	1	2	1	1	
MANAGEMENT											
MARKETING		1									

Figure 7. An example of calculated frequency

Finally, two data analysis techniques are applied on the coded data to draw descriptive conclusions: (1) stepwise multiple regression, and (2) association mining analysis. Stepwise regression is a commonly used statistical technique found in the educational literature; and is selected for this research as it highlights those variables that differ between the two team types.

Association mining is also selected to address the research questions, as it is used to identify iterations in Dym's design process. Iteration, in this research, is defined as the movement from one category to one other. This movement depicts the directional relationship between design categories. Furthermore, the frequency of these movements over time period provides information on the strength of the relationships. Because association mining analysis is somewhat less known, a description is provided here.

The association mining technique identifies the relationships between variables; and is commonly used by business enterprises (e.g., learning about the purchasing behaviors), medical diagnoses and bioinformatics [87]. In association mining analysis, relationships in the form of association rules or sets of frequent items can be uncovered. An association rule is an implication expression of the form $X \rightarrow Y$, where X and Y are disjoint events, i.e., $X \cap Y = \emptyset$. The strength of an association rule is measured by its support and confidence [87]. Support is the probability that two distinct categories appear consecutively throughout the design process; and confidence is the conditional probability that a particular category occurs after a given category. These two probabilities together are used to determine the degree of randomization in the data. Maps of the various associations are then created and tested to determine how teams iterate among the various categories of Dym's model over the three phases of the design process.

To check the robustness of the results, a method similar to the "leave-one-out" cross validation technique is employed to both the regression results and the association mining technique [88].

4.2 RESULTS AND VALIDATION

4.2.1 Stepwise regression analysis

Stepwise regression models are built to measure the significance of the categories in each time phase. Hypothesis testing is then applied to determine if there is a significant difference between the number of categorized design activities accomplished by innovative and non-innovative teams. As a note, a logistic regression is also applied; however, better explanatory results are obtained with multi linear regression utilizing the stepwise routine.

The eight categories of the Dym's extended model are used as predictors for our stepwise regressions. The innovation score (1 = innovative, 0 = non-innovative) is used as the dependent variable. Although the data is comprised of about 17,600 design hours, only 16 data records are available to build the stepwise regression models (i.e., eight innovative and eight non-innovative teams). Given this relatively small data set, a type I error of 0.10 is used to determine statistical significance.

Table 1 reports the summarized regression results for each phase (see Appendix D for the all regression results). A "(I)" means that teams having innovative artifacts utilize that particular Dym category significantly more than the non-innovative teams; and a "(NI)" means that the teams having non-innovative artifacts use those categories significantly more than the innovative teams. For example, in the early phase, the teams with innovative artifacts use more *problem definition* activities than do non-innovative teams; on the other hand, teams having non-innovative artifacts use more *preliminary design* activities than do innovative teams.

Table 1. Significant variables found by stepwise regression analysis

	Early	Middle	Late
Problem Definition	(I)		(I)
Conceptual Design	(I)		
Preliminary Design	(NI)		(NI)
Detailed Design	(I)		
Design Communication			(I)
Review			
Management	(I)		
Marketing	(I)		(NI)

As Table 1 indicates, several differences are found between the two sets of teams. First, teams with innovative artifacts use significantly more activities related to *problem definition*, *conceptual design, detailed design, managemen*t and *marketing* during the early phase of the design process. Hence, innovative teams strongly begin their design process with emphasis on several of Dym's categories. Regarding *marketing*, although the number of activities is small, innovative teams have significantly more of these activities in the early phase than do their non-innovative counterparts. Whereas non-innovative teams have significantly more *marketing* activities in the late phase of the design process; however, this finding is not fully validated (to be discussed). Regardless, involving *marketing* during the late phase intuitively does not make sense for innovation (unless it is a "re-visiting" of *marketing* activities), as understanding the marketplace in terms of the customer needs or potential new customers provides the impetus for a design.

Problem definition activities are also used significantly more by the teams with innovative artifacts in the late phase. Further, innovative teams used *design communication* activities significantly more in the late phase than do non-innovative teams. Thus innovative teams are working to document their work and their design much more so than non-innovative teams. Interestingly, non-innovative teams use more *preliminary design* activities in both the early and late phases. It may be inferred that non-innovative teams begin working on a particular design and in the late phase are regressing back to this phase, perhaps questioning their initial design.

As seen in the table, the middle phase is absent of any significant differences between the two types of teams. We speculate that both teams are busy working on the various categories of Dym's extended model, as there is evidence that both types of teams are utilizing many activities in each of the categories.

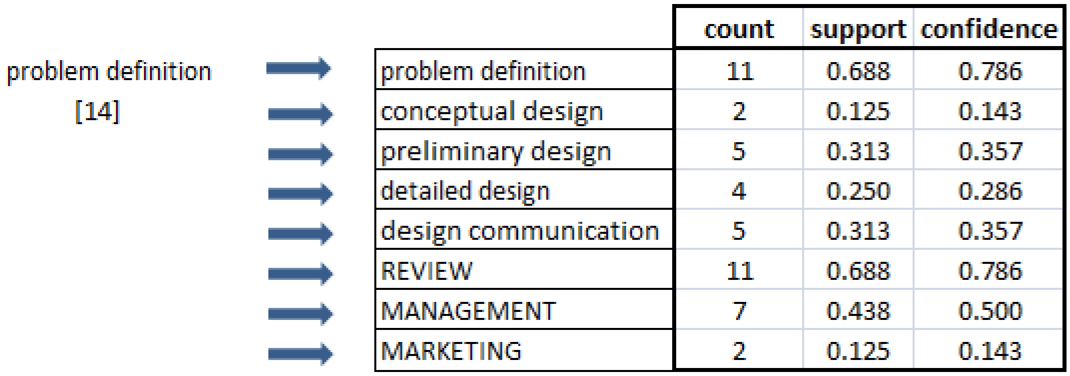
To check the robustness of the regression results, a method similar to the "leave-one-out" cross validation technique is employed [88]. The stepwise regression is run by excluding one innovative team and one non-innovative team leaving only 14 data records. All possible 64 combinations are exhausted. Table 2 provides the results of this analysis. Each cell in the table represents the percentage that the related category corresponds to the original significant result. For example, *problem definition* is found significant in 63 of the 64 cases, so the percentage is 98%. In all cases there is high consistency, indicating robustness of the results. The only exception is *marketing* in the late phase. In the late phase, only 44% of the stepwise regressions found *marketing* significant, indicating that there is no strong evidence to support that non-innovative teams conduct *marketing* activities significantly more than innovative teams during this phase.

Table 2. Robustness of the regression results

	EARLY	MIDDLE	LATE
Problem Definition	98.44% (I)		96.88% (I)
Conceptual Design	98.44% (I)		
Preliminary Design	89.06% (NI)		95.31% (NI)
Detailed Design	100% (I)		
Design Communication			100% (I)
Review			
Management	100% (I)		
Marketing	98.44% (I)		43.75% (NI)

4.2.2 Association mining analysis

The association mining technique is used to discover associations between the categories in Dym's model. We examine the associations between Dym's expanded model categories by counting the number of times category X is followed by category Y for each team during the project timeline. Figure 8 presents an example calculation of the support and confidence probabilities. This example is from the early phase in which the students take the survey 16 times. For the team considered in the example, *problem definition* appears 14 out of 16 times and *conceptual design* appears two times after *problem definition*; so the support probability from *problem definition* to *conceptual design* is 2/16 =0.125, and the confidence probability is 2/14 = 0.143.



problem definition
[14]

	count	support	confidence
problem definition	11	0.688	0.786
conceptual design	2	0.125	0.143
preliminary design	5	0.313	0.357
detailed design	4	0.250	0.286
design communication	5	0.313	0.357
REVIEW	11	0.688	0.786
MANAGEMENT	7	0.438	0.500
MARKETING	2	0.125	0.143

Figure 8. An example of calculated support and confidence probabilities

The support probability is used to identify the frequent events; and typically a threshold support is implemented to identify these events. That is, if a support is less than a certain level, then regardless of the confidence, that event is not considered. In this study, both *conceptual design* and *marketing* categories are lost when we apply any threshold (due to the low number of activities). To mitigate this, we use a new variable, Ω, which combines confidence and support probabilities (see, Table 3). In doing so, the bias in the relative data set is partially removed. After calculating Ω for all teams for each design category in each time phase, the average is calculated for innovative and non-innovative teams.

Table 3. Definition of Ω

Support (s)	**Confidence (p)**	**Ω**
$0.30 \le s$	$0.75 < p$	1
$s < 0.30$	$0.75 < p$	0.875
$0.30 \le s$	$0.5 < p \le 0.75$	0.75
$s < 0.30$	$0.5 < p \le 0.75$	0.625
$0.30 \le s$	$0.3 \le p \le 0.5$	0.5
$s < 0.30$	$0.3 \le p \le 0.5$	0.375
$0 \le s \le 1$	$p \le 0.3$	0

Based on Ω, the associations among all the categories can be classified as either weak ($0.3 \le \Omega \le 0.5$), moderate ($0.5 < \Omega \le 0.75$), or strong ($0.75 < \Omega$). Relationships less than 0.3 are not considered [87]. These associations are then graphed into maps, as shown in Figure 9. If the association is strong, then a bold and thick arrow is used to demonstrate the particular association; if it is moderate, then a bold arrow is used; and if the association is weak, then a light arrow is used.

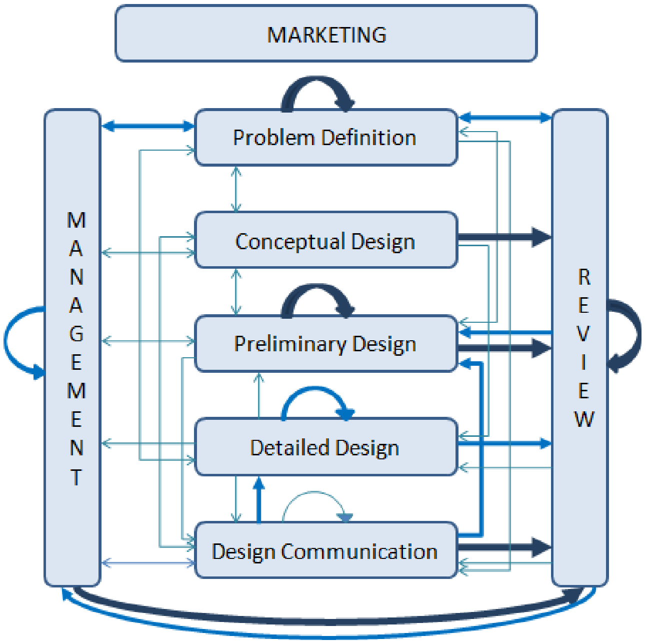


Figure 9. An association map example

In Figure 9, the example association map shows that there is no association related to *marketing* (i.e., no arrows enter and no arrows exit this category). To underscore a few associations, there is a strong association from *problem definition* to *problem definition*; and there is moderate association between *problem definition* and *review*. Using average Ω values, three maps are created for innovative teams and three maps are created for non-innovative teams, one each for the three phases. Figures 10, 11, and 12 present association maps for the early, middle and late phases, respectively, for both innovative and non-innovative teams.

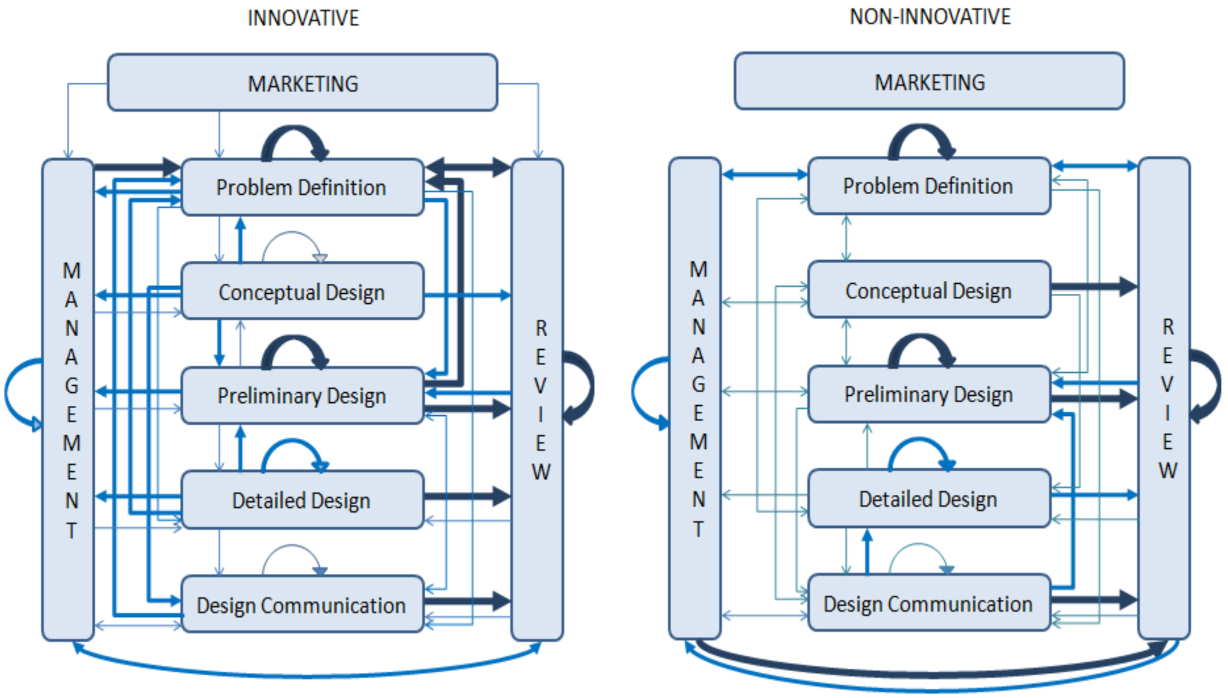


Figure 10. Association maps in the early phase

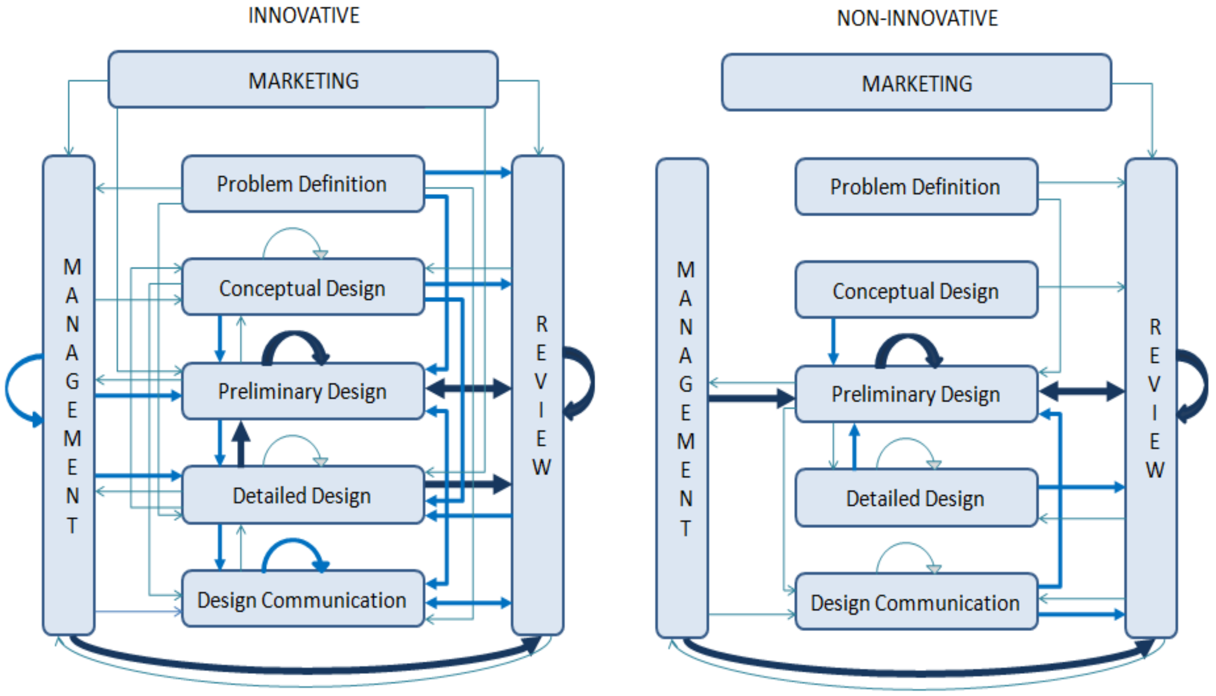


Figure 11. Association maps in the middle phase

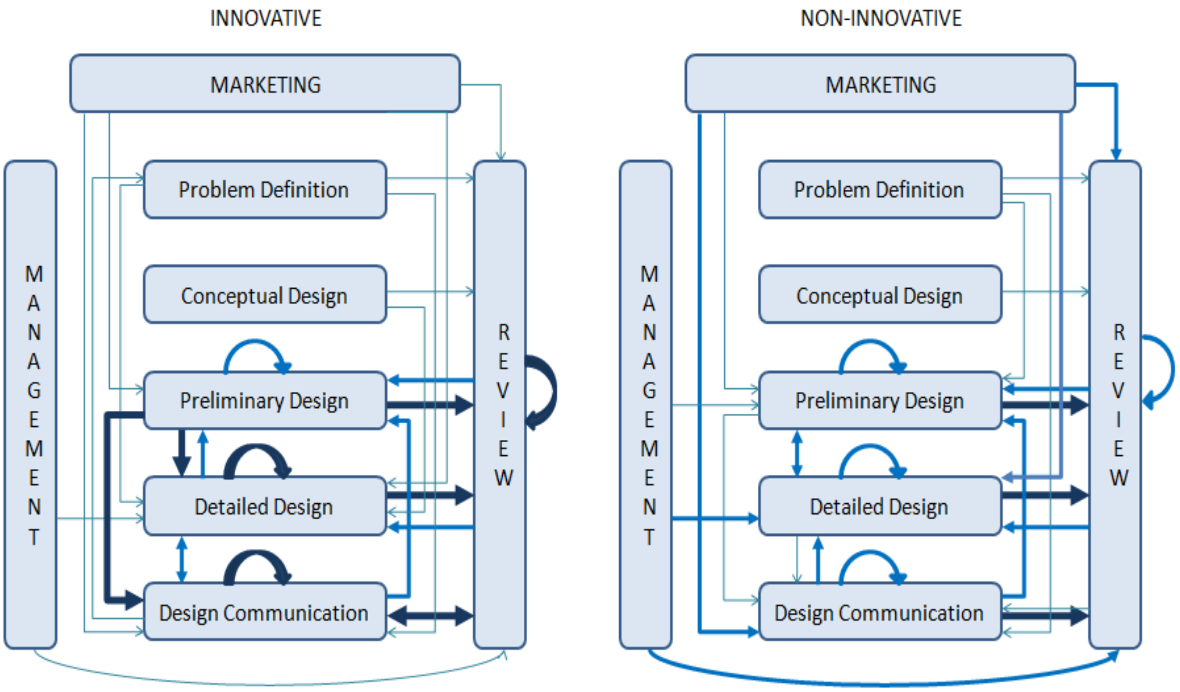


Figure 12. Association maps in the late phase

There are remarkable differences between the innovative and non-innovative association maps, as listed in Tables 4, 5 and 6. Many of the findings support the above regression results. For example, in the early phase there are associations, though weak, related to *marketing* for innovative teams, but there are no such associations for non-innovative teams. Teams are conducting *marketing* activities that then influence their move to *problem definition, review* and *management*, as shown in Figure 10. In addition, there are substantial associations to and from *conceptual design*, which are not readily found for non-innovative teams. To highlight an additional finding, during the early phase innovative teams are found to have more associations at and before *preliminary design* than do non-innovative teams. During the early phase, we surmise that innovative teams iterate around the early categories of Dym's model investigating perhaps several design options. Whereas, non-innovative teams may have acted more linearly [21] through the Dym's model categories.

Table 4. Association maps – comparing innovative and non-innovative teams (early phase)

Validation	INNOVATIVE	NON-INNOVATIVE	Validation
100%	There **are associations** related to *marketing*	There is **no association** related to *marketing*	100%
100%	**Stronger** *conceptual design* associations	**Weaker** *conceptual design* associations	100%
63%	The association is **strong** between *problem definition* and *review*	The association is **moderate** between *problem definition* and *review*	50%
100%	There are **more** associations at and before the *preliminary design*	There is **less** association at and before the *preliminary design*	100%

Table 5. Association maps - comparing innovative and non-innovative teams (middle phase)

Validation	INNOVATIVE	NON-INNOVATIVE	Validation
100%	The *detailed design* activities have **stronger** associations	The *detailed design* activities have **weaker** associations	100%
100%	There are **more** associations from *marketing* to others	There are **less** associations from *marketing* to others	100%
100%	There are **more** associations	There are **less** associations	100%

Table 6. Association maps - comparing innovative and non-innovative teams (late phase)

Validation	INNOVATIVE	NON-INNOVATIVE	Validation
100%	The **strong** associations take place at and after the *preliminary design*	The **strong** associations take place to *review*	63%
100%	**Weaker** associations from *marketing* to others	**Stronger** associations from *marketing* to others	100%
100%	**Weaker** associations from *management* to others	**Stronger** associations from *management* to others	100%

During the middle phase, innovative teams are found to have stronger associations around *detailed design* indicating that teams are iterating to and from this category from other categories. For non-innovative teams, there are only weak associations to and from *detailed design*. In general, it is found that innovative teams have more associations during the middle phase than do non-innovative teams, indicating that they are moving about through the various categories of Dym's model (i.e., iterating) more than non-innovative teams. Interestingly, there are more associations to and from *marketing* for innovative teams than for non-innovative teams. However, we know from the regression analyses that *marketing* is not a significant category during the middle phase; hence, even though the number of activities is not statistically different for the two groups, innovative teams iterate more around *marketing* than do their non-innovative counterparts.

Finally during the late phase, we find that non-innovative teams have strong associations involving *marketing* and *management* compared to their innovative colleagues. This means that these teams are iterating to and from the *marketing* and *management* categories during the late phase. We speculate that such teams are considering how to incorporate market and customer considerations into *detail design* and *design communication*, as well as *review*, as Figure 12 indicates moderate associations leaving from *marketing* to these design categories. Also, *management* activities of non-innovative teams seem to influence transitions to *detail design* and *review* activities during the late phase. Similarly to the early phase, innovative teams are found to have strong associations at and after *preliminary design*. Instead of iterating around the early categories of Dym's model, innovative teams are now iterating around the later categories of Dym's model. Such a finding does indicate that there is much movement to and from the categories both at the beginning and at the end of the design process. This does not seem to be as strong for non-innovative teams.

To evaluate the robustness of our findings, we repeat the association mining analysis eight times for the innovative teams and eight times for the non-innovative teams by leaving one team out each time. The percentages are reported in Tables 4, 5 and 6 under the adjoining robustness columns. The majority of the associations are found to be robust. The exceptions include associations between *problem definition* and *review* for both types of teams in the early phase, as well as associations to *review* by non-innovative teams in the late phase.

4.3 DISCUSSION OF RESULTS

The purpose of this work is to identify for innovative and non-innovative teams the design activities that are utilized, where these activities are utilized along the design process, and how the two team types navigate the process as depicted by their iterations among the various design activities. Using the two analyses, we state that certain activities and processes used by bioengineering capstone design teams do impact whether a resulting prototype is “innovative”. Notably, the value of the early phase in terms of the activities and types of iterations cannot be underestimated in contributing to the innovativeness of a design artifact. Further, although a focus on late phase activities seems unlikely to contribute to the innovation, there are certain aspects that are worth noting that can contribute to innovation. Each of these is discussed.

4.3.1 The importance of marketing and conceptual design in the early phase

Working across the early categories of Dym's model during the early phase is highly important. As noted, teams with innovative artifacts have more associations at and before the *preliminary design* in the early phase than their non-innovative counterparts. Further, performing *marketing* activities early in the design process can impact the innovativeness of a design. Literature suggests that companies that develop "internal marketplaces" are found to be more innovative [89], and this research potentially sheds light on how this same approach may be done in engineering education. Hence, engineering design educators need to emphasize and direct student designers to integrate more *marketing* activities during the beginning of the design.

Moreover, *problem definition* and *conceptual design* categories are found to be significant in the early phase for teams that produce innovative designs. These results make intuitive sense for any good design, but are also central for innovative design. In particular, *problem definition* indicates a need to understand the end use and need for a to-be-envisioned design. *Conceptual design* or "back of the napkin design" activities provide teams the critical opportunity to be creative and produce multiple ideas (again, introducing the internal marketplace) before selecting a few to test in *preliminary design*. Prior research on brainstorming indicates conflicting results as to the value or efficiency of brainstorming in design, citing that people who work in isolation actually produce more and better ideas than when working in a group [90]. However, this research would indicate that using *conceptual design* activities in the early phase and their associations to other design categories positively affects the innovativeness of the artifact for team based capstone projects. Hence, advice to engineering design educators is to allow extended time on these design categories to potentially increase innovativeness.

4.3.2 The late phase should not be underestimated

This research finds that during the middle phase all teams are working actively across the various design categories, but that innovative teams have more associations than do non-innovative teams meaning that profusion of movement between the Dym's categories is important to artifact innovation. This is further emphasized in the late phase where innovative teams have more associations at and after *preliminary design* (note the strong associations in Figure 12). When viewing the association maps across the three time phases, innovative teams have overall more complicated maps (i.e., more associations), yet they express a consistent flow across the three phases until the late phase where one sees strong associations between the *preliminary design*, *detailed design*, *design communication*, and *review*. Further, innovative teams revisit *problem definition* activities in the late phase significantly more than non-innovative teams. We surmise that this signifies the importance of circling back to the beginning to verify that the problem or opportunity has been fully addressed. This is followed by emphasis on completing the design process via *design communication*; hence, the importance of completing all phases of the design through proper documentation.

5.0 INVESTIGATION #2 – ANALYSIS OF QUALITATIVE DATA

In this section, we study the qualitative characteristics of teams and if these characteristics have any influence on the innovativeness of the artifact. Two research questions are explored:

1. What attitudes do teams exhibit and express that are related to the innovativeness and the non-innovativeness of the design artifact?

2. How do teams' attitudes traverse over the design process from problem definition to working prototype; and are they different depending on the degree of innovativeness?

Specifically, an empirical investigation is conducted on the data collected from the open-ended survey (Friday survey). These weekly reflections are coded across a number of attributes and claims are tested to determine if differences exist between those teams that produce an innovative artifact versus those teams that do not produce an innovative artifact. From this, teams' attributes across the design process that are related to innovation are determined.

5.1 METHODOLOGY AND ANALYSIS

The students' individual reflections are used to understand team perceptions and attitudes as they progressed through the design process. Given the nature of the data, qualitative analysis is employed to identify patterns that may distinguish differences between teams that produce innovative artifacts versus those that do not. That is, what are the teams' decision making processes, when and why do they take actions (or fail to take actions), and how do these actions potentially influence their design and ultimately its innovativeness? Furthermore, analysis of the qualitative data provides further support to the quantitative results and conclusion [85]; and thus serves as an additional level of robustness.

5.1.1 Coding of the data

A common procedure for analyzing qualitative data is to identify key themes, concepts and categories [91]. To do this, a grounded theory approach is applied to analyze the data. By using the grounded theory approach, emerging categories (or codes) and concepts are identified [92]. Each individual's complete set of reflections from the inception of the design project to the working prototype (i.e., roughly 23 reflections per person) are read, key points signposted, and then grouped. From this initial coding, an overarching framework of eleven categories is prepared, as shown in Table 7. It is assumed that the categories listed are independent of each other, such that a reflection may belong to one or more categories. Moreover, the categories listed in Table 7 are overarching and may contain several sub-categories, which are used to conduct more detailed analyses (see Appendix E for complete listing of the sub-categories).

Table 7. Qualitative analysis categories and explanations

Framework of Categories	**General Definition**	**Examples**
Timing	Any comments related to schedule	Keeping track of the schedule, taking time issues into account, etc.
Team Dynamics	Any comments related to team working	Complaining/blaming each other, ability to work in a group, etc.
Skill	Any comments related to ability/capacity to do the design	Students' strengths, abilities, etc.
Progress	Any comments related to design process	Testing, revising, ordering the materials, etc.
Problem	Any comments related to faced problems	Identification of the problem, solving the problem, etc.
Plan	Any comments related to planning of the design	Making plans, preparing a GANTT chart, etc.
Knowledge	Any comments related to familiarity or intellectual understanding of a topic	Learning a topic, figuring out how to use an equipment, etc
Getting help	Any comments related to asking consultant or for help	Getting help from experts, instructors, meetings with mentors, etc.
Emotional Assessment	Any comments related to student's feelings and emotions	Motivation, being pessimistic, etc.
Ah-ha	Any comments related to their "ah-ha" moments	Finding a solution, figuring out something important, etc.
Extra	Any comments which are not categorized here, but might be important	Considering source limitations, talking about their hopes, etc.

Following this, a content analysis, a research technique used to facilitate replicable and valid inferences [93], is conducted to further refine the set of codes, and subsequently apply these codes to reflections [92]. To code and conduct preliminary data analysis NVivo (version 8) Qualitative data analysis software is used [94]. Table 8 provides examples of how students' reflections may be coded to multiple categories.

Table 8. An example of how to code the data

Student Reflection	Category
"One team member never shows up for class, and is always late for meetings. It is really annoying"	Category: Team Dynamics Sub-category: Complaining
"We are falling behind due to lack of motivation"	Category: Team Dynamics Sub-category: Not motivated Category: Timing Sub-category: Behind /Worry
"We brainstormed ideas and then got together and combined them"	Category: Progress Sub-category: Brainstorming

A detailed code-handbook is prepared to maintain consistency when coding the reflections. The reflections are coded by one researcher; however, the code-handbook is reviewed by two researchers, and if an issue related to coding occurs, the reflection's placement is decided upon discussion. Moreover, the entire dataset is re-coded six months later. Further, the researcher has no knowledge whether the reflections are from innovative teams or non-innovative teams. After coding is completed, counts per each category (and sub-categories) can be easily determined by NVivo software.

5.1.2 Hypotheses regarding team work for design leading to innovative outcomes

Using the concepts that emerged from the data, several “claims” are made about innovative teams and their design process.

1. Innovative teams *“talk” about their progress* albeit positive or negative; however, non-innovative teams tend to complain without much explanation of their progress.

2. Innovative teams *act like problem solvers*, whereas members of the non-innovative projects spend time “realizing what the problem is” rather than solving it. When innovative teams realize their progress is slow moving, they resolve the issues; whereas, non-innovative teams continued to struggle.

3. Innovative teams manage their time, i.e., checking the time and making plans based on the time remaining; hence, they *strategize their time* and keep track of their schedule during the entire process. On the other hand, non-innovative teams realize "time issues" often too late to take corrective action.

4. Innovative teams *revise their designs*; but non-innovative teams (in general) focus and create one design/prototype prior to the deadline.

5. Innovative teams recognize when they do not have sufficient information and *recognize where to go for assistance*. The innovative teams get help from experts and mentors that make the teams more innovative.

6. Innovative team members *work as a group*; and their team dynamics are generally positive even when they are in a stressful situation.

7. Innovative teams *communicate with their customers* from the beginning of the project. This results in being able to define the problem according to customer needs.

5.1.3 Analysis of the hypotheses

By using the emerged concepts and the results obtained via NVivo queries, these hypotheses are tested. To achieve more comprehensive results, the design process timeline is taken into consideration: early phase, mid-phase, and late phase. A transition period is included between consecutive phases to prevent rigid borders between phases; as shown in Figure 13. For the two transition periods, the codes are counted twice (i.e., the codes appeared in the first transition period are counted for both early and middle phases; and the codes that appeared in the second transition period are counted for both middle and late phases).

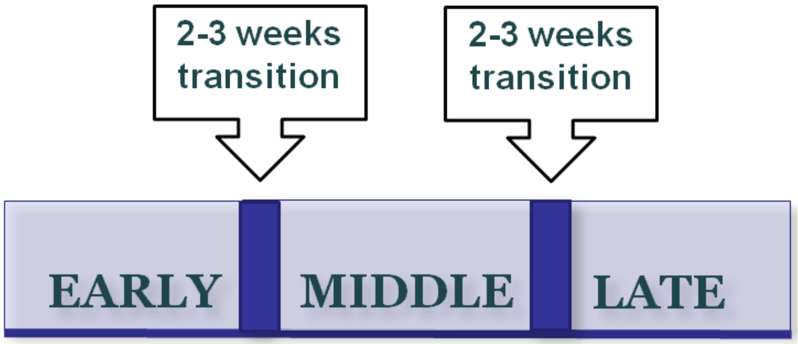


Figure 13. Timeline of the design process for qualitative investigation

The NVivo software allows for the coding of the qualitative responses to be summed, such that statistical analyses can be conducted. Three separate queries are prepared for each time phase and the frequencies of each category are obtained. The aim is to identify the differences between innovative and non-innovative team attributes. Two sample t-tests are conducted. Significant differences between innovative and non-innovative teams are presented in Tables 9, 11 and 13; and Tables 10, 12, and 14 provide explanations and examples for the significant categories and sub-categories. For the "ah-ha" moments, the same approach is conducted and results are provided in Table 8. An alpha level, α, of 0.15 is used as the data. This value is selected as the data has a relatively small *n* (i.e., 16 teams – eight innovative and eight non-innovative).

To investigate the robustness of the results, a method motivated from the “leave-one-out” cross validation technique is employed [88]. Each analysis is repeated excluding one innovative and one non-innovative team; therefore, each new test consists of seven innovative and seven non-innovative teams. From this, all possible combinations are tested and exhausted. As shown in Tables 9, 11, and 13, the robustness percentage is provided for each significant finding. Specifically, the percentage indicates the proportion of “leave-one-out” combinations tested that yielded the same results as the initial two sample t-test with all 16 teams. For all significant findings, robustness results are found to be 70% or higher.

5.2 RESULTS AND ROBUSTNESS

This section provides the results of each phase, as well as the “ah-ha” moments that student teams encountered.

5.2.1 Early phase

In the early phase, the foremost difference between innovative teams and non-innovative teams appears in problem solving. Innovative teams solve their faced problems significantly more than non-innovative teams. In addition, innovative teams express their need to work more than do non-innovative teams; hence, from the self-reflections, there is a propensity that innovative teams need to push themselves to work harder. Moreover, innovative teams articulate the re-doing of some of their activities related to team progress; and they state in their self-reflections getting help on financial aspects of their project. For the early phase, these particular categories are found to be significantly higher in the self-reflections than in the non-innovative teams. Table 9 summarizes the results, and Table 10 gives the explanations of the significant variables.

Table 9. Significant results in the early phase

Category	Sub-category	p-value	Robustness	High for Group
Problem	Solve	0.02	98.44%	Innovative
Team Dynamics	Need to Work	0.06	81.25%	Innovative
Progress	Re-do	0.12	73.44%	Innovative
Getting Help in	Financial	0.15	75.00%	Innovative

Table 10. The definitions of the significant variables in the early phase

Category	**Sub-category**	**Definition**	**Examples from Students' Reflections**
Problem	Solve	The students solve the problems faced during design process	“To solve this problem and to allow for it to hit with multiple magnitudes of force we made two pivot joints on the arm, one for angle variation and another for force variation.” *(from an innovative team)*
Team Dynamics	Need to Work	The students believe that they need to work on the design	"We SERIOUSLY need to get to work." *(from an innovative team)*
Progress	Re-do	The students re-do the design process before facing (or reporting) a major problem	"We re-designed one of our sub-systems for our simulation device.” *(from an innovative team)*
Getting Help in	Financial	The students got help in funding	"Our mentor has agreed to help us out financially." *(from an innovative team)*

5.2.2 Middle phase

When the results in the middle phase are checked, it is found that the innovative teams are still resolving the problems significantly more than the non-innovative teams. Further, from the frequencies of the self-reflections, it is found that innovative teams evaluate their progress significantly more than non-innovative team. Specifically, there are significantly more self-reflections from innovative teams that indicate brainstorming sessions and discussions with their team members about what might happen in the future based on their current situation. Also, innovative teams state in their reflections that their teammates' skills and abilities are considered before dividing the work, or while deciding design progress. Moreover, innovative teams reflect significantly more than non-innovative teams about their plans and progress; and state their developing strategies related to their progress.

Unfortunately, it is found that non-innovative teams choose the "no work" survey option significantly more than the innovative teams. Further, in the middle phase non-innovative teams begin to mention in their self-reflections their need to get help from their instructors (as opposed to the innovative teams indicating their need to get help in the early phase). Lastly, non-innovative teams mention significantly more progress reviews in their self-reflections than do innovative teams; i.e., they verify what they have done to date and at the same time they are addressing questions about aspects that they are confused about. The results and representative examples are presented in Tables 11 and 12.

Table 11. Significant results in the middle phase

Category	Sub-category	p-value	Robustness	High for Group
Problem	Solve	0.00	96.88%	Innovative
Progress	No Work	0.03	96.88%	Non-Innovative
Progress	Evaluation	0.04	96.88%	Innovative
Getting Help from	Instructor	0.06	96.88%	Non-Innovative
Skill	Consider	0.06	96.88%	Innovative
Plan	Progress	0.06	79.69%	Innovative
Progress	Review	0.08	87.50%	Non-Innovative
Progress	Strategy	0.15	73.44%	Innovative

Table 12. The definitions of the significant variables in the middle phase

Category	**Sub-category**	**Definition**	**Examples from Students' Reflections**
Problem	Solve	The students solve the problems faced during design process	"We bought the plastic washers to create our own bobbin." (This action solves the problem) *(from an innovative team)*
Progress	No Work	The students did not work, or they let the answer blank	"We haven`t worked on the project since last Friday." *(from a non-innovative team)*
Progress	Evaluation	The students talk about/interpret the progress.	"Deciding to just adapt the power source to an LED otoscope will save a considerable amount of money and time." *(from an innovative team)*
Getting Help from	Instructor	The students got help from their instructors	"Getting positive feedback on our design from our instructor was encouraging. It helps to know that we are on the right track." *(from a non-innovative team)*
Skill	Consider	The students consider/take into account their skills while taking actions.	"The projects we do have we are gaining more and more information on to determine which projects complement our team`s skill sets and which will provide us with the greatest design team-customer relationship." *(from an innovative team)*

Table 12 (continued).

Category	**Sub-category**	**Definition**	**Examples from Students' Reflections**
Plan	Progress	The students make plans for design progress.	"We are going to start the analytical testing of our device next week upon completion of Finite Element Analysis." *(from an innovative team)*
Progress	Review	The students review their design progress (revising the documents is excluded).	"We have been reviewing everything we have done and been getting consumer input and advice about how to make our product." *(from a non-innovative team)*
Progress	Strategy	The students apply a technique to overcome a problem.	"We are currently splitting up the different aspects of the design and doing a command and conquer approach since we have a lot to do." *(from an innovative team)*

5.2.3 Late phase

As the teams move into the late phase, it is observed that the non-innovative teams are expressing a significant number of complaints about instructors, mentors and experts, indicating that these resources are not available to meet (see "availability negative" in Table 13). During this phase, non-innovative teams announce that they are "refreshing" their team dynamics and "re-doing" several of their activities. These types of reflections occur significantly more for non-innovative teams than for innovative teams. “Re-do” activities may be a result of the significant increase in “review” activities during the middle phase.

On the other hand, innovative teams are getting help in technical topics (see “expertise” in Table 13) significantly more than non-innovative teams. Innovative teams reflect on their progress, simplifying what they need to do and then act upon their plans. Lastly, the innovative teams believe that they have the necessary skills to progress on their design significantly more than their non-innovative counterparts. Table 13 and 14 provide results and representative examples, respectively.

Table 13. Significant results in the late phase

Category	Sub-category	p-value	Robustness	High for Group
Getting Help in	Expertise	0.03	100.00%	Innovative
Team Dynamics	Refresh	0.07	75.00%	Non-Innovative
Getting Help in	Availability Negative	0.07	75.00%	Non-Innovative
Progress	Simplify	0.08	75.00%	Innovative
Skill	Positive	0.08	75.00%	Innovative
Progress	Re-do	0.15	75.00%	Non-Innovative

Table 14. The definitions of the significant variables in the late phase

Category	**Sub-category**	**Definition**	**Examples from Students' Reflections**
Getting Help in	Expertise	The students got help in technical fields from their mentors, instructors, customers etc.	"We met with Dr. X, who helped us find a pelvic trainer for testing and he showed us the trainer and we practiced and threw around ideas of the most effective way of testing our prototype compared to the current plastic models." *(from an innovative team)*
Getting Help in	Availability Negative	The students cannot arrange meetings because their mentors, instructors, customers etc. are not available.	"Our meetings were canceled by our mentors so we were unable to work on this project again this week." *(from a non-innovative team)*
Team Dynamics	Refresh	The students refresh their team dynamics.	"Our team dynamic seems to be almost fully repaired, with our problem member being very enthusiastic about making up for lost time." *(from a non-innovative team)*
Progress	Simplify	The students or experts assigned for that group simplify the design progress.	"He gave us a much simpler route than what we were going to do with our plates." *(from an innovative team)*
Skill	Positive	The students believe that their skills are suitable for their design actions.	"We realized that although we have many things to accomplish, one of us is an expert in almost each one of them" *(from an innovative team)*

Table 14 (continued).

Category	**Sub-category**	**Definition**	**Examples from Students' Reflections**
Progress	Re-do	The students re-do the design process before facing (or reporting) a major problem	“The bulk of this week was focused on redesigning our device to meet functionality requirements.” *(from a non-innovative team)*

5.2.4 Analysis of ah-ha moments

In addition to the weekly reflection question, students are asked to comment on any “ah-ha” moments they may have had over the prior week. These reflections, which occurred roughly 15 percent of the time, are categorized as being either a “real ah-ha” or a “student ah-ha”. A “real ah-ha” is a reflection that is related to progress by the team (e.g., a breakthrough on technology, solving a problem creatively). On the other hand, there are some reflections in which the student believes the particular week is important, but nothing innovative is discussed; hence the reflection is categorized as a “student ah-ha”. In addition, occasionally students joke and tease about their progress; as a result, these moments are also categorized as a “student ah-ha”. Below are a few examples of student reflections.

- Example 1: *“One of the members had a great idea for keeping the tubing submerged. It involves putting weights in the bottom of the pool and somehow attaching these to the tubing. The attachments would have lengths that allow the tubing to be at a constant depth.”* This reflection is coded under “Ah-ha Real”. *(from an innovative team)*

- Example 2: *"Not really ah-ha, but finally meeting with our mentor and playing around with an otoscope was really helpful."* This reflection is coded under "Ah-ha Student". *(from a non-innovative team)*

- Example 3: *"We`ve finally realized that the parts aren`t going to magically appear and assemble themselves. Yay."* This reflection is coded under "Ah-ha Student". *(from a non-innovative team)*

Table 15 represents the t-test results for each phase. The analyses are applied for "real ah-ha" moments, "student ah-ha" moments and "total ah-ha" moments (i.e., the sum of "real ah-ha" and "student ah-ha").

Table 15. Statistical results of "ah-ha" moments by phase

	Early	**Middle**	**Late**
"Ah-ha Real"	No differences	No differences	p = 0.039 High for innovative teams
"Ah-ha Student"	No differences	No differences	No differences
Total	No differences	No differences	p = 0.052 High for innovative teams

In the early and middle phases, no significant differences are found between innovative and non-innovative teams at $\alpha = 0.15$. In the late phase, however, innovative teams have significantly more "real ah-ha" moments than their non-innovative counterparts; and innovative teams have significantly more "total ah-ha" moments. Interestingly, innovative teams do not realize their innovativeness until the end of the design.

5.3 DISCUSSION AND CONCLUSIONS

As mentioned previously, seven claims are made regarding the differences between innovative and non-innovative teams based on their weekly reflections. In this section, each claim is re-examined with the documentation to either support or not support the claim. Specifically, a table is provided for each claim indicating the evidence (i.e., direct or indirect), along with the category (and sub-category).

Claim 1: Innovative teams *"talk" about their progress albeit positive or negative*; however, non-innovative teams complain. As shown in Table 16, there is evidence that innovative teams talk about their progress more than non-innovative teams, but it is only found to be significant in the middle phase. Hence, this claim is partially supported.

Table 16. Supports for claim 1: talk about their progress

Support Direct/Indirect	High for Group	Category	Sub-category	p-value	Robustness	Design Phase
Direct	Innovative	Progress	Evaluation	0.04	96.88%	Middle

Claim 2: Innovative teams *act like problem solvers,* whereas members of the non-innovative projects spend time "realizing what the problem is" rather than solving it. From Table 17, it can be seen that there is strong evidence during the early, middle and late phases that innovative teams recognize when their progress is moving slowly, and they resolve their pending issues significantly more than do non-innovative teams.

Table 17. Support for claim 2: act like problem solvers

Support Direct/Indirect	High for Group	Category	Sub-category	p-value	Robustness	Design Phase
Direct	Innovative	Problem	Solve	0.02	98.44%	Early
Direct	Innovative	Problem	Solve	0.00	96.88%	Middle
Direct	Innovative	Progress	Simplify	0.08	75.00%	Late

Claim 3: Innovative teams manage their time, i.e., they check the time remaining and revise plans based on the time remaining; hence, they *strategize their time* and keep track of their schedule throughout the first two phases, as shown in Table 18. Non-innovative teams do realize "time issues"; however, it is often too late for them to make proper corrections.

Table 18. Support for claim 3: strategize their time

Support Direct/Indirect	High for Group	Category	Sub-category	p-value	Robustness	Design Phase
Indirect	Innovative	Team Dynamics	Need to Work	0.06	81.25%	Early
Direct	Innovative	Plan	Progress	0.06	79.69%	Middle
Indirect	Non-Innovative	Progress	No Work	0.03	96.88%	Middle

As seen in the table, this claim is marginally supported as the late phase is not statistically supported for innovative teams. With that said, innovative teams continue to express time management issues in their weekly reflections during the late phase; however during this time non-innovative teams are also now recognizing the need to manage time, so there is no significant difference in the late phase.

Claim 4: Innovative teams *revise their designs*; but non-innovative teams, in general, focus and create one design/prototype prior to the deadline of the project. Interestingly, innovative teams are revising and re-doing their work in the early phase; however, reflections about revisions for non-innovative teams become significant during the middle and late phases. Hence, this claim is not supported as written, as it is initially believed teams that produced innovative artifacts would revise their designs throughout the process; and non-innovative teams would create one type of design and linearly progressed until it is completed. The results of this study, as shown in Table 19, indicate that innovative teams revise early in the process possibly testing various ideas, whereas non-innovative teams jump forward produce a design and then spend much of their time trying to improve upon the design during the later phases.

Table 19. Support for claim 4: revise their designs

Support Direct/Indirect	**High for Group**	**Category**	**Sub-category**	**p-value**	**Robustness**	**Design Phase**
Direct	Innovative	Progress	Re-do	0.12	73.44%	Early
Indirect	Non-Innovative	Progress	Review	0.08	87.50%	Middle
Indirect	Non-Innovative	Progress	Re-do	0.15	75.00%	Late

Claim 5: Innovative teams recognize when they do not have sufficient information and *recognize where to go for assistance*. As shown in Table 20, innovative teams reflect significantly more than non-innovative teams when obtaining help from experts and mentors. This contributes to the innovativeness of the artifact as the team recognizes what they know and what they do not know, but they know where to find assistance and improve upon their design.

Further, reflections indicate that they understand their skills, abilities; hence, such teams target assistance in areas where they have stated weaknesses.

Table 20. Support for claim 5: recognize where to go for assistance

Support Direct/Indirect	**High for Group**	**Category**	**Sub-category**	**p-value**	**Robustness**	**Design Phase**
Direct	Innovative	Getting Help In	Financial	0.15	75.00%	Early
Direct	Innovative	Skill	Consider	0.06	96.88%	Middle
Indirect	Non-Innovative	Getting Help from	Instructor	0.06	96.88%	Middle
Not Supported						
Direct	Innovative	Getting Help in	Expertise	0.03	100.00%	Late
Indirect	Non-Innovative	Getting Help in	Availability Negative	0.07	75.00%	Late

Further, non-innovative teams are also found to have significant reflections, particular to the middle and late phases; however, these reflections are not always positive in nature. In the middle phase the teams reflect about seeking help from their faculty mentors and instructor. Also, Table 11 shows that these teams review their progress. So, it can be concluded that they are conducting much review with their instructors, i.e., many of the reflections indicate that the non-innovative teams are ‘spinning their wheels’. In the last phase, non-innovative team reflections indicate that when help is sought there is little availability by mentors and instructors.

Claim 6: Innovative teams *work as a group*; and their team dynamics are generally positive even when the team faces stressful situations. Also, while parsing the work among the team, they consider their skills, and help each other with the work. As shown in Table 21, in the middle and late phases, innovative teams comment in their reflections about their team's skills and abilities and how to best use their abilities to further the design. However, this is not seen in the early phase; hence, this claim is only partially supported. Further, in the late phase non-innovative teams have significantly more reflections than innovative teams regarding comments about their team dynamics (e.g., "repairing" team interactions, getting the team back together again, etc.). Thus, one might conclude that some of the non-innovative teams may have had problematic interactions, but are trying to resolve them in the late phase.

Table 21. Support for claim 6: work as a group

Support Direct/Indirect	High for Group	Category	Sub-category	p-value	Robustness	Design Phase
Direct	Innovative	Skill	Consider	0.06	96.88%	Middle
Indirect	Innovative	Skill	Positive	0.08	75.00%	Late
Indirect	Non-Innovative	Team Dynamics	Refresh	0.07	75.00%	Late

Claim 7: Innovative teams *communicate with their customers* from the beginning of the project. From the evidence provided in the Friday reflections and ah-ha moments, there are no significant indications that innovative teams do better at communicating with their customers than do non-innovative teams. In study 1, it is found for the early phase that innovative teams did significantly more activities than their non-innovative counterparts related to *marketing*. However, the number of activities is small; hence, this may be one reason that teams did not provide any Friday reflections. Another reason might be that *marketing* includes not only the

customer communication activities, but also activities such as target customer determination, defining the market and its growth potential, etc.

In summary, the Friday reflections and “Ah-ha” moments that individual team members put forward about their team’s progress provide insights to the research questions posed: (1) What attitudes do teams exhibit and express that are related to the innovativeness and the non-innovativeness of the design artifact?; and (2) How do teams’ attitudes traverse over the design process from problem definition to working prototype; and are they different depending on the degree of innovativeness?

According to Schön, the reflective practitioner as designer interactively frames the problem and names the things, and makes “moves” toward a solution and reflects on the outcomes of these moves [75]. There is no question that teamwork plays a role in the success in any project or product design. The degree to which teamwork plays a role in innovation, though, is largely unconfirmed. This particular study investigates the attitudes expressed by team members that produced both innovative and non-innovative teams. Using grounded theory, coupled with content analysis, students’ reflections are coded and statistical hypothesis testing is conducted to determine if differences exist between the two types of teams. In the context of this research, reflections from teams that produce innovative artifacts do indeed have significantly different expressed attitudes across the three phases of the design process, as delineated by the significance of the claims.

What is striking about these results is that teams that produce innovative artifacts demonstrate many characteristics of high performing teams. Specifically, claims 2, 3, and 5 are fully supported by the statistical analyses of the students’ reflections. Innovative teams act like problem solvers throughout all phases of the design process. Further, they manage their time during the early and middle phases and continue through the late phase.

Finally, innovative teams know what they do not know; and they know where to go for assistance. Throughout the weekly reflections individuals on innovative teams indicate responsibility for their work both from an individual perspective as well as for the team; and as witnessed by their statements, students express the need to strategize time and to be productive. Further, innovative teams' reflections indicate understanding and knowing how to capitalize on their teammates abilities and skills. When the team lacked the skill or knowledge, they sought help. These traits are all critical characteristics of high performing teams [78-80].

It is important for engineering design educators to know that successful teams will need to act as independent self guided problem solvers knowing their own deficits and how to overcome these deficits. As seniors in their final capstone course, this is not a skill that is to be learned during the final course; however, instructors can provide meta-cognitive clues for students to recognize these important attributes for success. One aspect that instructors can assist student teams is in the importance of documentation early and often for development of the final product. Documentation provides a necessary reflective component to help rethink how to better their final product.

6.0 DEVELOPMENT OF A BAYESIAN NETWORK MODEL

In this part of the research, we investigate the feasibility of modeling the engineering design process as an intervention tool. The aim of the tool is to increase the likelihood of innovative outcomes in design settings. The model is built on the 16 teams used in this research and is verified on all 26 teams’ data; and although the model is specific to bio-engineering teams, it may be generalizable to any engineering capstone or in-depth design course. The model advises which design activity or activities should be conducted by a team to achieve more innovative artifacts. The goal is to help design instructors and managers to lead and track their design teams’ processes so that the teams display more innovative characteristics that, in turn, lead to more innovative artifacts.

6.1 SELECTION OF THE MODELING TECHNIQUE

In developing a model, a decision-based approach is required as engineering student teams continuously make decisions through the design process [95]. Furthermore, the model should keep the history because both past and current design activities are critical in determining future activities. Activity selection has influence on whether or not the artifact is innovative or non-innovative; however, it does not guarantee an innovative output. Thus, the proposed model has uncertainty. Lastly, given the data acquired and used, there are no immediate rewards but only a reward at the end, i.e., the final prototype and documentation scores. All these aspects, depicted in Figure 14, are considered when determining the appropriate modeling tool.

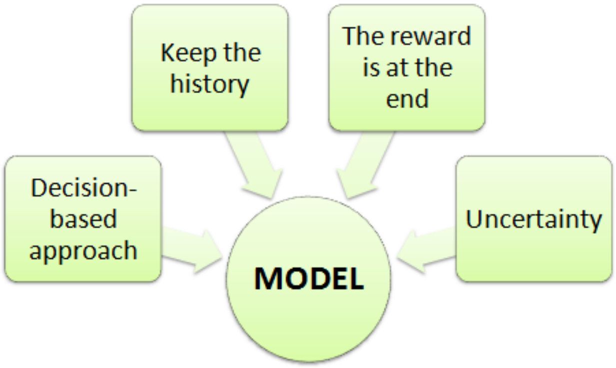


Figure 14. The properties of the aimed model

Markov chains (MC), Markov decision processes (MDP), as well as Influence Diagrams (ID) are evaluated as candidate modeling tools, as shown in Table 22. Note that the "the reward is at the end" and the "uncertainty" properties are not evaluated as all these models support them.

Table 22. Comparison of the potential modeling approaches

	Decision-based Approach	**Keep the history**
MC	x	x
MDP	+	x
ID	+	+

Influence Diagrams support all required properties. Specifically, a Bayesian network model is proposed as a special case of the Influence Diagrams.

6.2 METHODOLOGY AND APPROACH TO DEVELOP THE BAYESIAN NETWORK MODEL

A Bayesian network is a probabilistic model that represents a set of random variables and their conditional dependencies via an acyclic graph [96]. In this research, a Bayesian network is created to map how design teams traverse and use Dym's design processes across time to achieve a design artifact, albeit innovative or non-innovative. GeNie (Graphical Network Interface) software is used to create the model [97]. This software provides a development environment for building graphical decision-theoretic models.

There are eight variables used exclusively in the Bayesian model that correspond to the design activities based on Dym's five-stage descriptive extended model. The variables include: 1- Problem definition; 2- Conceptual design; 3- Preliminary design; 4- Detailed design; 5- Design Communication; 6- Review (verification and validation); 7- Management; and 8- Marketing. As seen in Figure 15, each variable is represented by a node in the model, and it appears in each time epoch (to be subsequently explained).

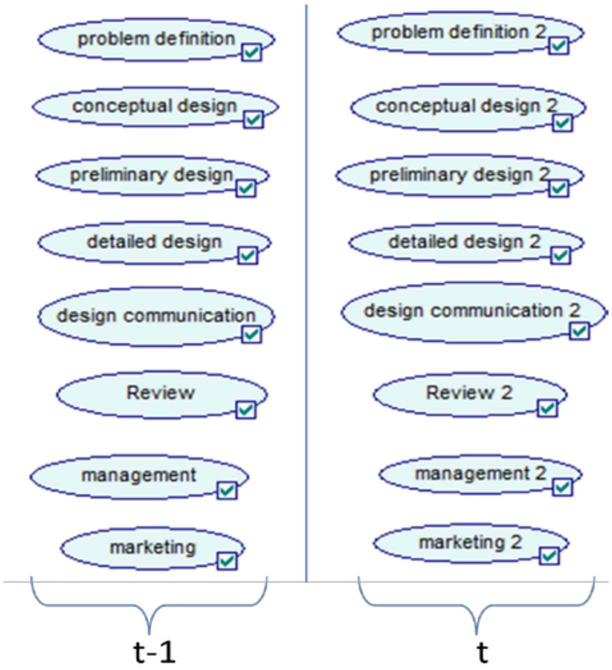


Figure 15. Bayesian network variables

Further, there are three primary assumptions in the model. The first is that activities utilized at time *t* are independent of each other; on the other hand, they are dependent on the activities utilized at the prior epoch (i.e., *t-1*). Second, we assume that the teams used in creating the model are either innovative or non-innovative. This assumption is based on our data as independent judges rated the resulting design artifacts in terms of their innovativeness. Third, if a design artifact is determined to be innovative (or non-innovative) as the final result, it is also considered innovative (or non-innovative) throughout the design process.

Typically Bayesian networks are formulated using only chance nodes. However, "decision nodes" are required in our model. As a result, the "set evidence" property of GeNie allows a probabilistic node to be treated as a decision node. Further, the final reward of this normative model is defined as a random variable consisting of two states: innovative and non-innovative. Given the relatively long time frame of the design process (e.g., two term capstone project), three separate models, representing the early, middle and late phases are created and tested.

Models for early and late phases have four time epochs; and the model for the middle phase contains five time epochs based on the descriptive model. Further, all three models are created using the same logic; therefore, the following explanations are expressed only for the early phase. Information related to the middle and late phases are provided in Appendix F.

Figure 16 shows the initial framework (without dependencies) of the early phase model. The design variables appear in all four time epochs. Finally, there is an output node (i.e., innovative or non-innovative).

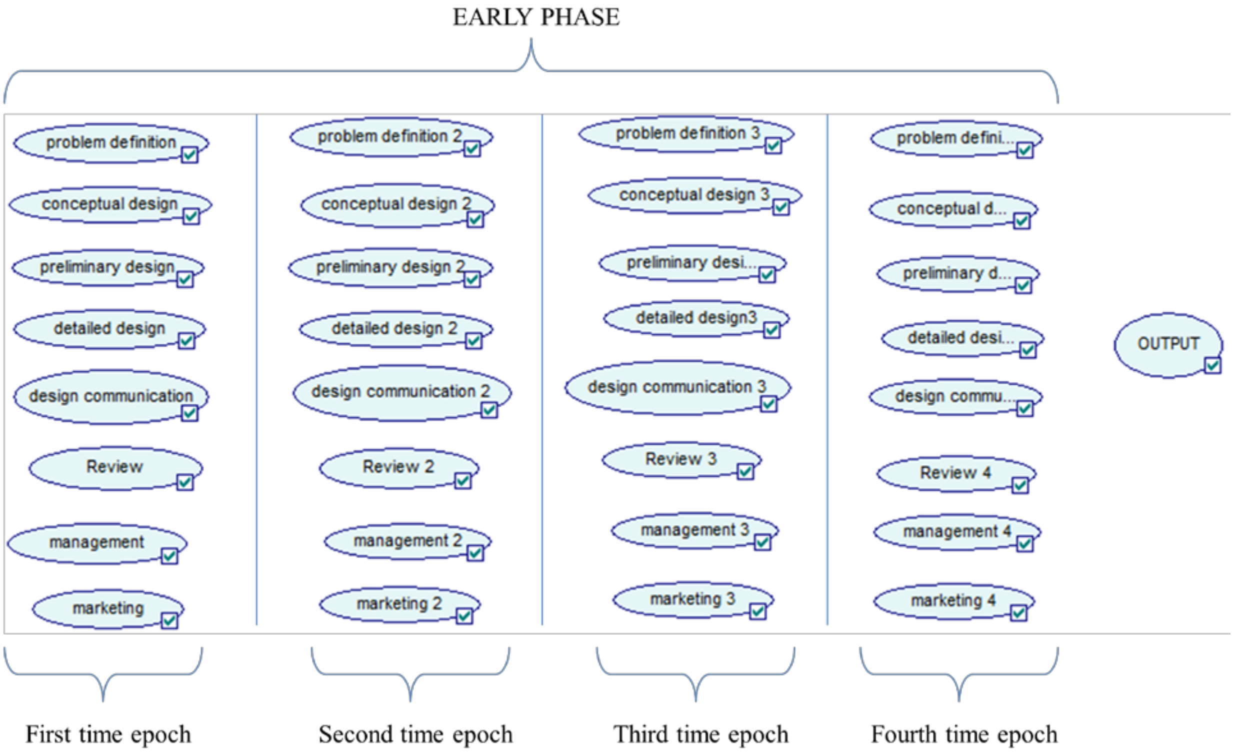


Figure 16. The framework of the GeNie model in the early phase

Dependencies between two nodes are represented by arcs. When all dependencies are added, the model becomes overly complicated and unwieldy. Furthermore, it is unnecessary to calculate all conditional probabilities with the available data (see Figure 17) as the majority of these probabilities are close to zero because there are too many scenarios while moving from one time epoch to the next one.

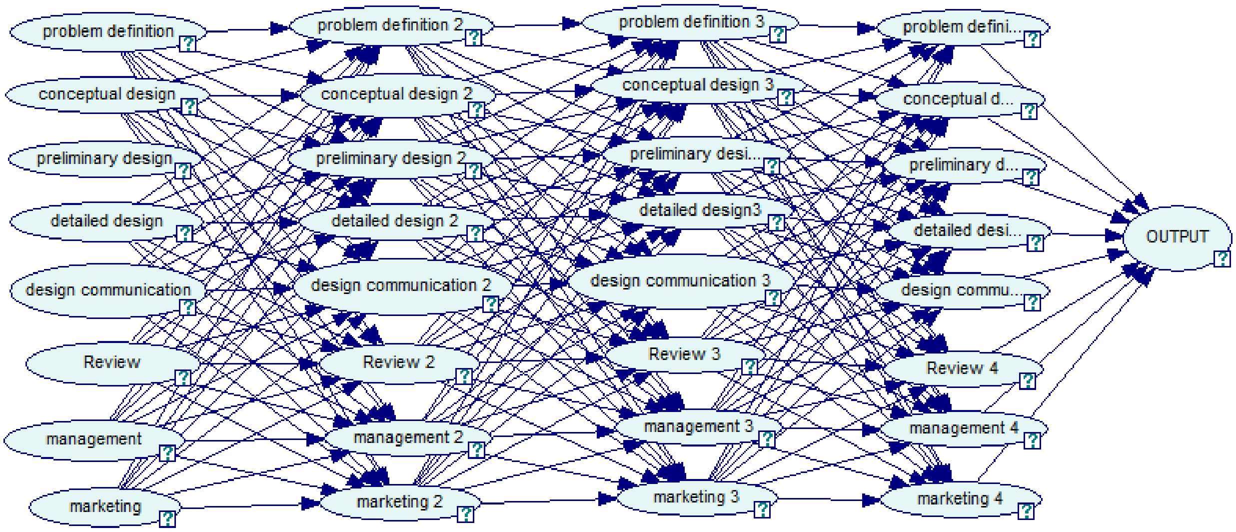


Figure 17. The framework of the GeNie model with all dependencies

To simplify the model, inter-nodes are added after each epoch with two states: innovative and non-innovative. In this version of the model the effect of predecessor nodes is lost when evidence is set. For example, the effects of the evidence in the first and fourth time epochs do not have the same influence on the “innovation 4” node, i.e., the final output of the phase. Moreover, when evidence is entered into the fourth time epoch, the effect of the previous time epochs are virtually lost. To rectify this issue, a value node, named “Output”, is added to the model, as seen in Figure 18. The value node provides a weighted-average score based on each time epoch.

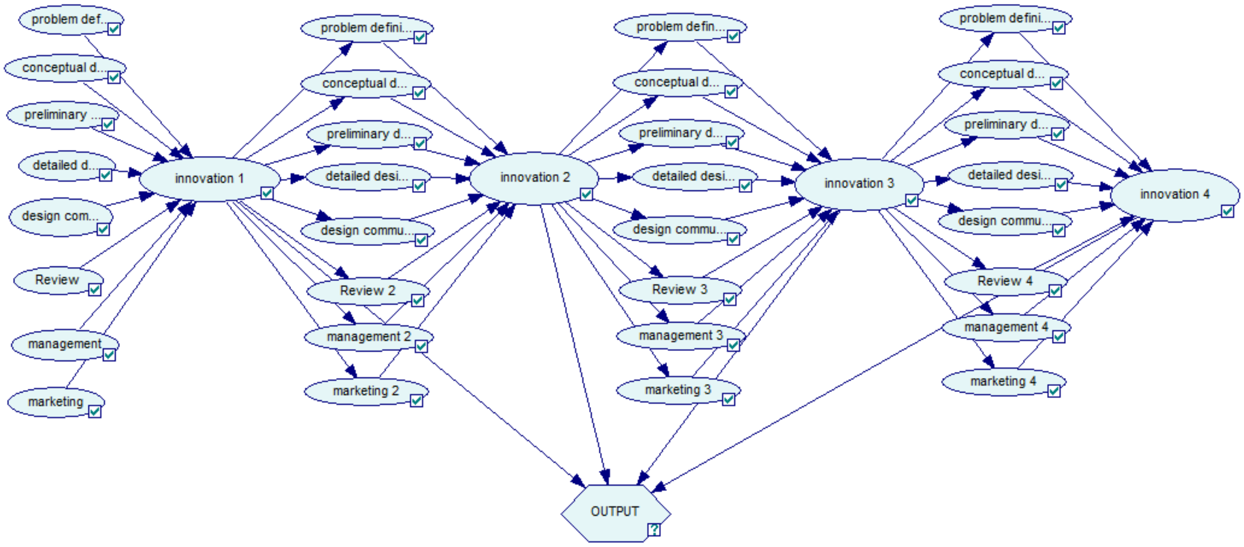


Figure 18. The early phase Bayesian network model with a value node

A second issue is also faced in the current model. As evidence at *t+1* is updated, the probability of the innovation node at *t* to be updated is inevitable because Bayesian networks do not consider time. Specifically, when new evidence is found in a node, all of its ancestor nodes are updated including the previous innovation nodes; hence this situation misleads the value node. To remedy this problem, innovation nodes with no descendants are created that preserve the information about the prior time epoch. Thus, these new innovation nodes (with no descendants) are collectively weighted with the innovation-4 node to create the output. This final model is used for the analysis, and is depicted in Figure 19.

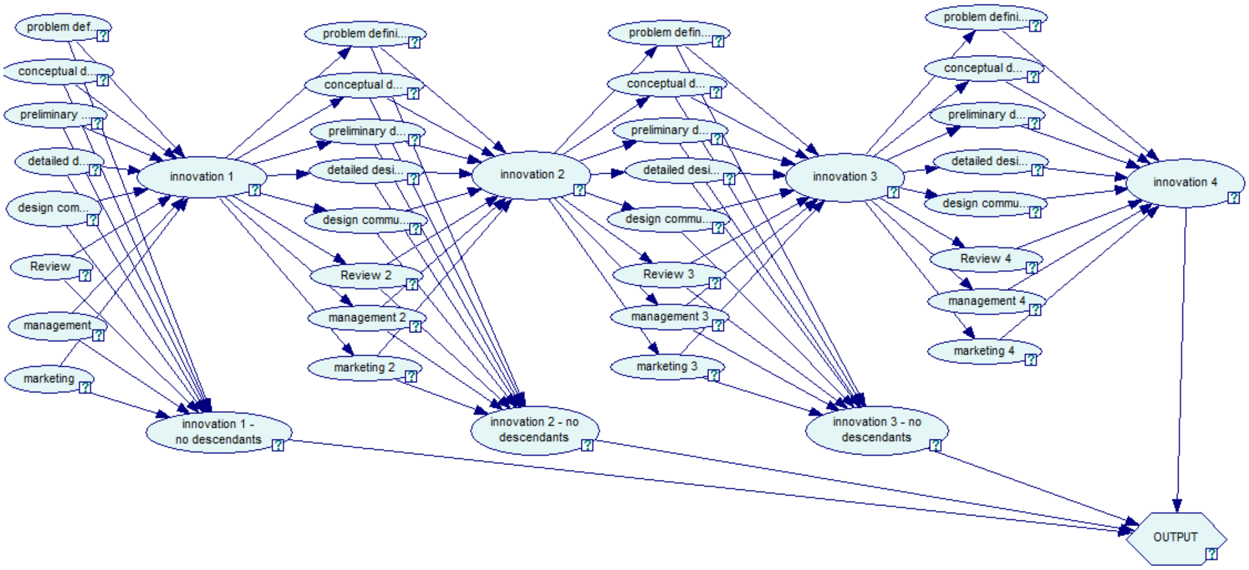


Figure 19. Bayesian network model

Each design category node has three states representing their level of usage by a design team: *low*, *medium* and *high*. The innovation nodes have two states: *innovative* or *non-innovative.*

6.3 PARAMETER ESTIMATION

Each design category is counted in each time epoch across all three phases (early, middle, and late). A clustering algorithm is then used to decide the extent to which categories are used (i.e., low, medium or high). The following example in Table 23 shows the number of *problem definition* activities. For example, Team 1 performed eleven *problem definition* activities in the first time epoch; and they did not perform any such activities in the eleventh time epoch. Both two-step and K-means clustering algorithms are applied to the counted data. It is observed that the K-means algorithm is better at capturing outliers, whereas the two-step algorithm yields more balanced results. As a result, the two-step algorithm is used.

Table 23. An example of counting the problem definition activities

	Time Epoch										
	Early Phase						**Late Phase**				
				Middle Phase							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Team 1	11	9	2	1	0	0	0	1	0	1	0
Team 2	19	11	7	8	0	0	0	0	2	1	1
Team 3	12	8	4	7	0	0	0	0	0	0	0
Team 4	11	0	5	4	0	0	0	0	0	1	0
Team 5	7	6	3	2	1	0	0	0	0	0	0
Team 6	12	10	5	5	1	0	1	0	1	2	0
Team 7	19	8	0	1	1	0	0	0	0	0	2
Team 8	8	13	6	7	0	0	0	1	0	0	1
Team 9	15	14	11	2	1	0	0	0	0	0	1
Team 10	18	2	0	0	1	0	0	0	0	0	5
Team 11	16	9	7	1	0	0	0	0	0	0	0
Team 12	39	8	8	1	0	0	1	0	3	5	7
Team 13	10	4	10	2	0	0	0	1	0	0	1
Team 14	15	4	9	2	2	0	0	0	1	0	2
Team 15	17	2	6	8	0	0	1	0	0	0	0
Team 16	10	15	5	0	0	0	0	0	0	0	0

For simplicity, the cluster number is limited to three for each design category (i.e., low, medium, and high). Using three clusters provided a higher cluster quality than two clusters. Table 24 reports the clustering results for *problem definition,* with a cluster quality for the three clusters of 0.822. For *problem definition*, if the number of activities is less than or equal to than three, then the team's state for *problem definition* is labeled low. If it is between four and eleven, then its state is medium; otherwise its state is high. Clustering results for the other design categories can be found in Appendix G.

Table 24. Two-step clustering results for problem definition

Number of problem definition activities	Cluster	Quality
0-3	Low	0.822
4-11	Medium	
12 – up	High	

The probabilities for each scenario are calculated for the different usage levels of all design categories.

$P(\text{being innovative}/\ Y_1 = s_j \cap Y_2 = s_j \cap Y_3 = s_j \cap Y_4 = s_j \cap Y_5 = s_j \cap Y_6 = s_j \cap Y_7 = s_j \cap Y_8 = s_j)$, and

$P(\text{being non-innovative}/\ Y_1 = s_j \cap Y_2 = s_j \cap Y_3 = s_j \cap Y_4 = s_j \cap Y_5 = s_j \cap Y_6 = s_j \cap Y_7 = s_j \cap Y_8 = s_j)$,

where

Y_1 is problem definition,

Y_2 is conceptual design,

Y_3 is preliminary design,

Y_4 is detailed design,

Y_5 is design communication,

Y_6 is review,

Y_7 is management, and

Y_8 is marketing.

Moreover, for $j=1$, s_1 represents the low state, for $j=2$, s_2 represents the medium state, and for $j=3$, s_3 represents the high state for the utilization level of design categories.

As mentioned, it is assumed that the design categories in the same time period are independent of each other. Therefore:

$P(\text{being innovative}/\ Y_1 = s_j \cap Y_2 = s_j \cap Y_3 = s_j \cap Y_4 = s_j \cap Y_5 = s_j \cap Y_6 = s_j \cap Y_7 = s_j \cap Y_8 = s_j)$

$= P\ (\text{being innovative}/Y_1=s_j)*P(\text{being innovative}/Y_2=s_j)*P(\text{being innovative}/Y_3=s_j)*P(\text{being innovative}/Y_4=s_j)*P(\text{being innovative}/Y_5=s_j)*P(\text{being innovative}/Y_6=s_j)*P(\text{being innovative}/Y_7=s_j)*P(\text{being innovative}/Y_8=s_j)$

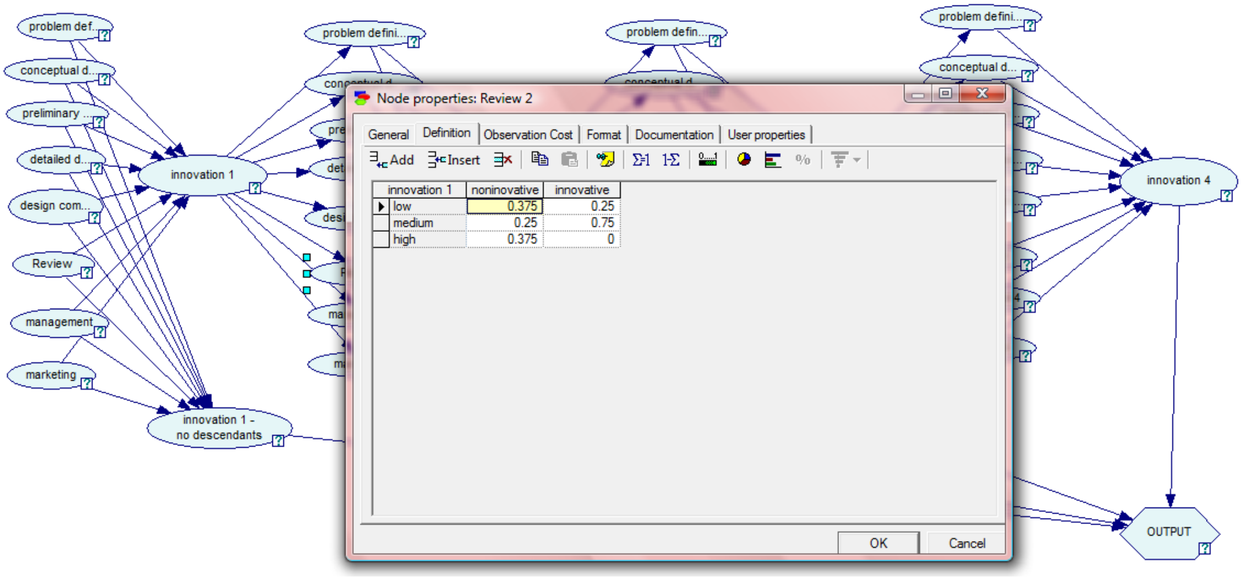
for $j = 1,2,3$.

To calculate $P(\text{being innovative}/Y_i=s_j)$ for $i = 1,2,3,4,5,6,7,8$ and $j = 1,2,3$, each state for each design category is counted over all teams, and the ratios are calculated for the innovative and non-innovative teams. For example, in the second time epoch, eight of the 16 *conceptual design* categories are labeled as "low". Five of these appear in the design process leading to non-innovative artifacts, and three of them appear in the design process leading to innovative artifacts. Therefore:

$P(\text{being innovative/conceptual design is "low"}) = 3/8 = 0.375$, and

$P(\text{being non-innovative/conceptual design is "low"}) = 5/8 = 0.625$.

After calculating the probability of being innovative and being non-innovative for a given scenario, the sum of the two probabilities is normalized, because the artifacts are assumed to be either innovative or non-innovative. All probabilities are then loaded into GeNie using the dialog box shown in Figure 20.



innovation 1	noninnovative	innovative
low	0.375	0.25
medium	0.25	0.75
high	0.375	0

Figure 20: Inserted probabilities in GeNie dialogue box

6.4 ENTERING DATA INTO THE MODEL

A goal of the Bayesian network model is to help instructors calculate the most likely retrospective scenario given the artifact is innovative. It can also be used to determine if a team is following a scenario that is non-innovative; and hence, allowing the instructor to intervene and put the team on a more “corrective” or “innovative” course of action.

In this section an example is presented on how to input data and use the model as an intervention tool. Suppose a team uses the categories provided in Table 25 in the first time epoch of the early phase model.

Table 25: The data of the first time epoch used in the example

Design Category Name	Level of Usage
Problem definition	High
Conceptual design	Low
Preliminary design	Low
Detailed design	Low
Design communication	Low
Review	Medium
Management	High
Marketing	Low

To set the evidence, an instructor would select the particular design node (i.e, right mouse click), select “set evidence” and determine the desired state (e.g., low, medium, or high). Figure 21 provides an example of setting evidence on “high” for *problem definition* in the first epoch. Upon establishing evidence, the lightning symbol is selected from the toolbar to update the model.

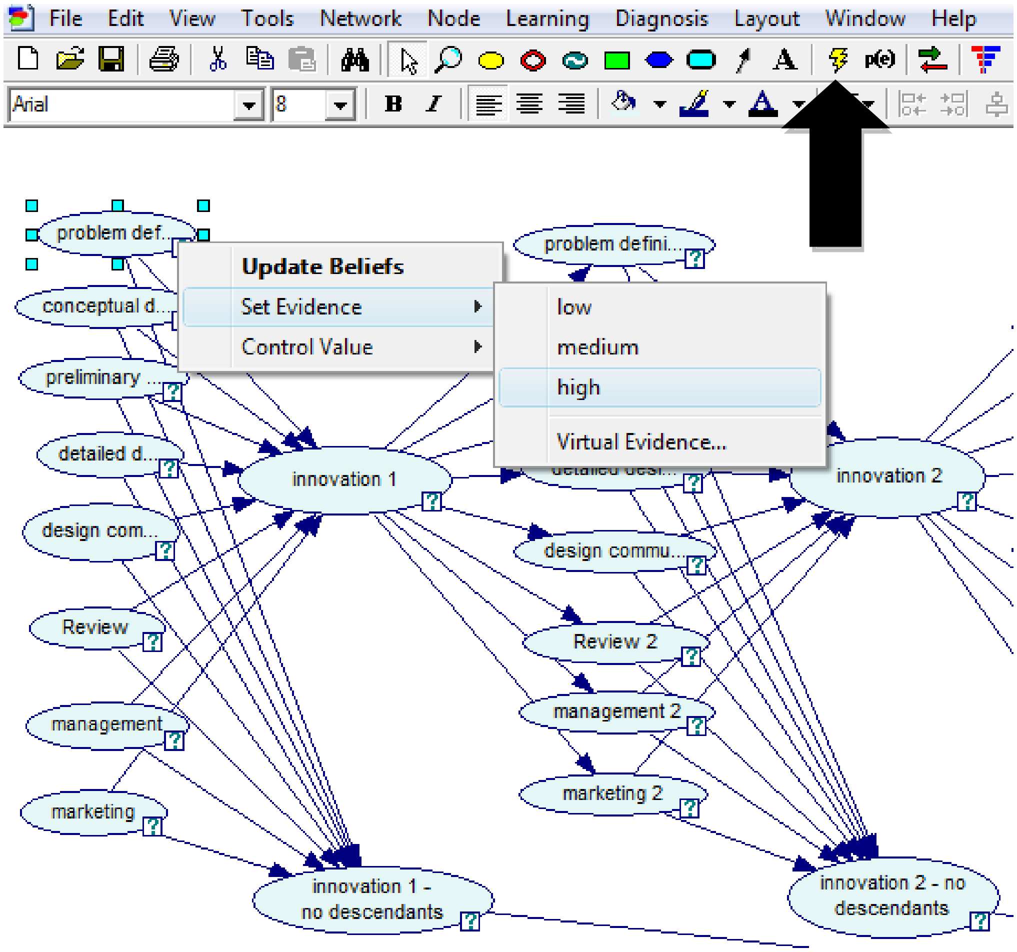


Figure 21. Setting an evidence in GeNie

Figure 22 illustrates this particular example. As shown, each innovation node is updated with a final output 0.664 given the evidence updated for the first epoch (it does not include updated evidence for the other three epochs). Updated evidence is denoted with "✓" marks.

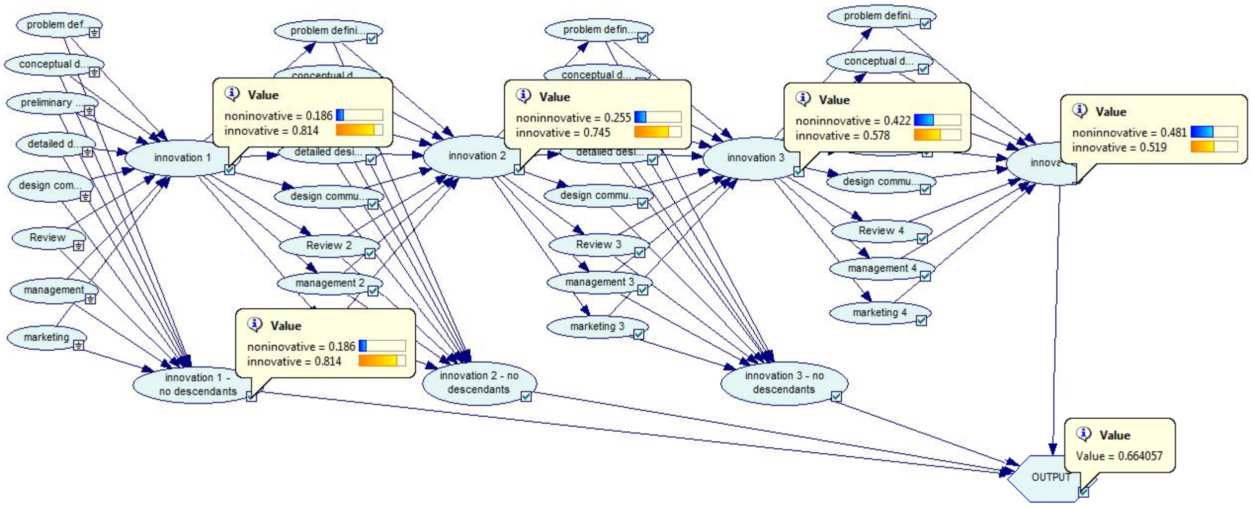


Figure 22. The updated model after entering the evidence in the first time epoch

As shown Figure 22, the probability of being innovative is 0.814 for the first innovation node. Further over the next three epochs, the probability of being innovative decreases (0.745 for innovation-2; 0.578 for innovation-3; and 0.519 for innovation-4) as the effect of the evidence from the design categories in epoch-1 decreases. Also note the values of “innovation-1” and “innovation-1 no descendants” nodes are the same. Given the evidence from just the first epoch, it is inconclusive if this team will be innovative by the end of the early phase given the output probability of the early phase is 0.664. As more evidence is received over the next few epochs, the interpretation of the output will be updated as more information is provided as to the predictability of a team’s innovativeness. Hence, one usage of this model is to determine the probability of being innovative based on which categories are utilized by a team.

6.5 VALIDATION

Out of the 26 total teams that participated in this study; eight are rated innovative and eight are rated non-innovative. The remaining ten teams are neither innovative nor non-innovative. In validating the model two approaches are used. First, data used to construct the Bayesian network are inputted into the resulting model to determine how well they performed. The second approach involves inputting the other ten teams to determine how well *they* performed in the model. It is predicted that these ten teams will have final results that are between innovative and non-innovative ratings. Thus, we compare the model results with the observed innovation ratings.

6.5.1 Validation with innovative or non-innovative teams

As mentioned, the model is parameterized using the data of the eight innovative and eight non-innovative teams. The results of the model for those 16 teams in the early, middle, and late phases are presented in Tables 26, 27, and 28, respectively. Data from all time epochs are inputted and the network results are calculated. The teams are sorted based on their probability of being innovative.

Table 26. Validation results for early phase Bayesian network model

Team	Rated as innovative?	Probability of being innovative	Probability of being non-innovative
Team 6	yes	0.838	0.162
Team 14	yes	0.764	0.236
Team 2	yes	0.749	0.251
Team 3	yes	0.732	0.268
Team 13	yes	0.702	0.298
Team 15	yes	0.663	0.337
Team 5	yes	0.622	0.378
Team 9	no	0.591	0.409
Team 12	yes	0.580	0.420
Team 8	no	0.431	0.569
Team 4	no	0.327	0.673
Team 16	no	0.269	0.731
Team 1	no	0.220	0.780
Team 7	no	0.214	0.786
Team 10	no	0.176	0.824
Team 11	no	0.054	0.946

Note that the model outputs a probability of being innovative on a continuous scale. Therefore, a threshold probability value should be used to determine the resulting model’s degree of innovation. Intuitively, a probability 0.5 serves as an appropriate threshold value; however different threshold values can also be used to pursue the same analysis.

As shown in Table 26, Team 9 is found to be more innovative than non-innovative. In general, though, the accuracy of the model is quite high accurately predicting 93.8% of the teams (i.e., 15 out of the 16 teams) during the early phase. In addition, its sensitivity is 100% (i.e., all eight innovative teams are correctly identified as innovative or with a probability greater than

50%); and its specificity is 87.5% (i.e, seven out of the eight non-innovative teams are correctly identified as being non-innovative with a probability of less than 50%).

Table 27. Validation results for middle phase Bayesian network model

Team	**Rated as innovative?**	**Probability of being innovative**	**Probability of being non-innovative**
Team 6	yes	0.855	0.145
Team 14	yes	0.838	0.162
Team 13	yes	0.813	0.187
Team 15	yes	0.726	0.274
Team 5	yes	0.682	0.318
Team 12	yes	0.647	0.353
Team 2	yes	0.549	0.451
Team 3	yes	0.512	0.488
Team 1	no	0.485	0.515
Team 4	no	0.368	0.632
Team 16	no	0.342	0.658
Team 9	no	0.333	0.667
Team 8	no	0.319	0.681
Team 10	no	0.252	0.748
Team 11	no	0.223	0.777
Team 7	no	0.093	0.907

Table 28. Validation results for late phase Bayesian network model

Team	Rated as innovative?	Probability of being innovative	Probability of being non-innovative
Team 5	yes	0.970	0.030
Team 13	yes	0.881	0.119
Team 12	yes	0.859	0.141
Team 14	yes	0.853	0.147
Team 2	yes	0.822	0.178
Team 3	yes	0.820	0.180
Team 15	yes	0.771	0.229
Team 6	yes	0.703	0.297
Team 1	no	0.421	0.579
Team 16	no	0.360	0.640
Team 8	no	0.359	0.641
Team 4	no	0.252	0.748
Team 10	no	0.235	0.765
Team 9	no	0.165	0.835
Team 7	no	0.080	0.920
Team 11	no	0.074	0.926

In Tables 27 and 28, the accuracy, the sensitivity, and the specificity of the model are equal to 100% for both the middle and late phases. Figure 23 compares the three phases together for all 16 teams. As seen in the figure, the late phase model produces stronger results such that innovative teams have probabilities closer to 1, and the non-innovative teams have probabilities closer to zero as compared to the early and middle phase models; hence the late phase model provides stochastic dominance over the other two models.

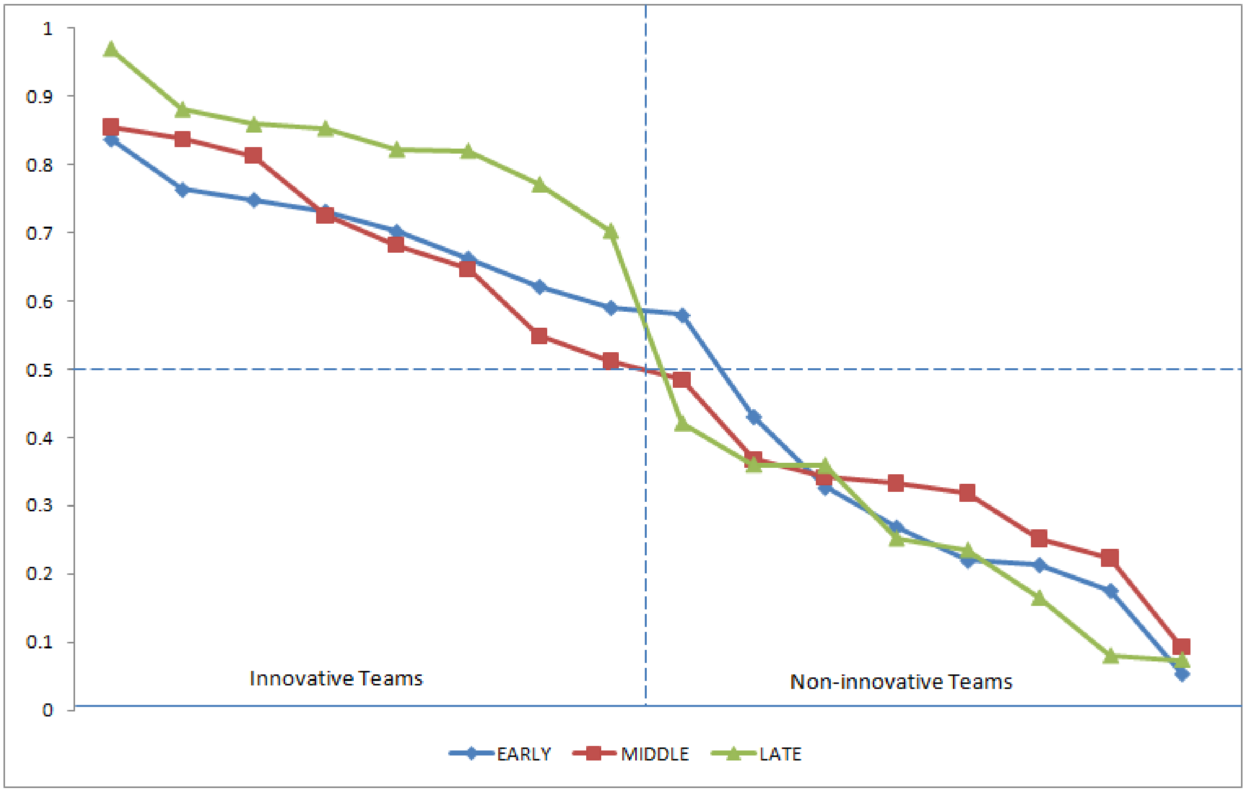


Figure 23. The comparison of the validation results in the early, middle, and late phases

6.5.2 Validation with neither innovative nor non-innovative teams

The reserved data of ten teams (those not included in the development of the model as they are neither innovative nor non-innovative) are inputted into the model as an external dataset; and their results are reported for the early, middle, and late phases as depicted Figures 24, 25, and 26, respectively. In Figure 24, the average probability of being innovative for all 10 teams is in between that of non-innovative and innovative teams in the early phase. As for the individual probabilities, probability for each team is between 0.3 and 0.7. Three of the teams have probabilities greater than 0.5; and the other seven teams have probabilities less than 0.5; hence, some of these teams could have been innovative and some would have clearly been non-innovative. However, among these “middle” rated teams, none display any strong indications of being innovative or non-innovative in the early phase. In fact, when regressing the data, the coefficient of determination, R^2, is 0.65 with a slope of 0.21. From this we conclude that there is a fairly moderate relationship between those teams that are rated in the “middle” of innovation, who are predicted by the Bayesian network to be in the “middle” regarding their innovativeness at the end of the early phase.

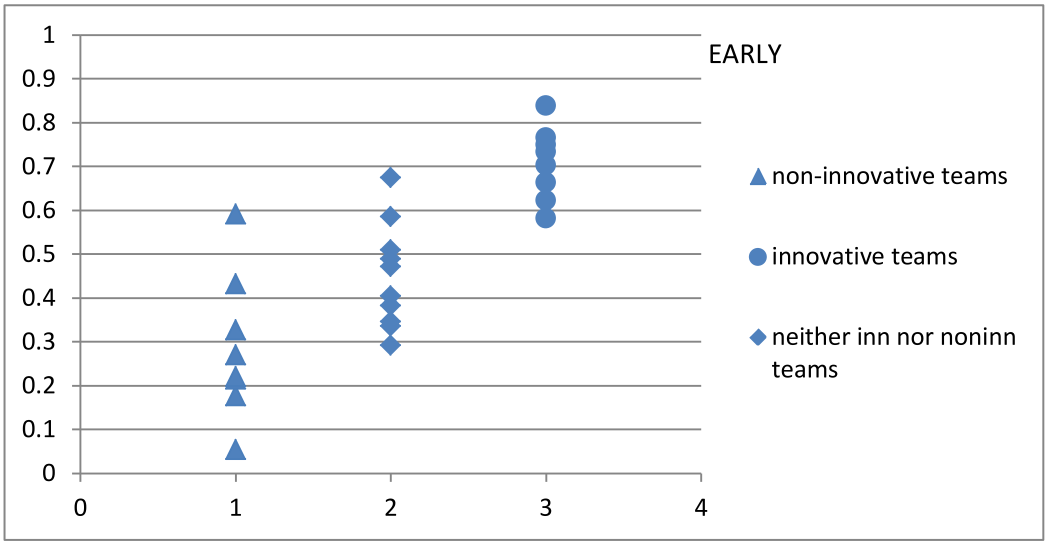


Figure 24. Testing the early phase Bayesian network model with the “middle” teams

In Figure 25 (the comparison for the middle phase model), the range of probabilities of the “middle” rated teams is smaller and covers 0.50. All but one team has a probability between 0.4 and 0.6. The probabilities of five teams are greater than 0.5, and the other four teams are less than 0.5. One team has a probability of 0.192, which is clearly non-innovative. Further, when regressing the data, the coefficient of determination, R^2, and slope remain relatively unchanged compared to the early phase model (i.e., $R^2 = 0.66$ and slope = 0.20). As a result, our conclusions about the relationship between how the teams are rated and the predictions by the Bayesian network remain the same as with the early phase model.

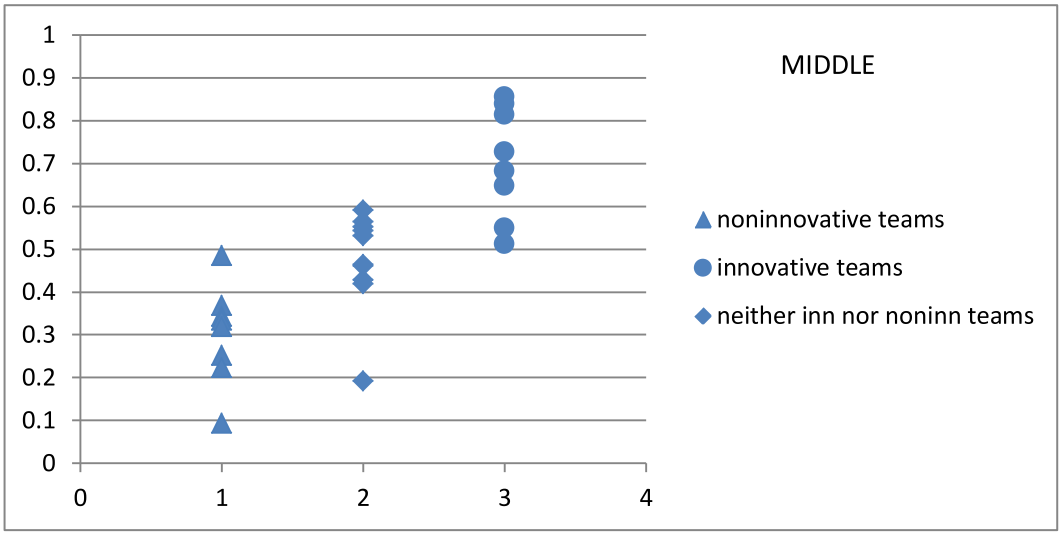


Figure 25. Testing the middle phase Bayesian network model with the “middle” teams

In Figure 26 (the results for the late phase model), the clusters for non-innovative, “middle” and innovative teams are more distinctive and non-overlapping. Probabilities for eight of the ten “middle” teams are in between 0.4 and 0.6 in the late phase. Interestingly, the probabilities for being innovative are higher than that of the middle phase. Specifically of the ten teams, seven teams have a probability greater than 0.5, and the other three teams have a probability less than 0.5. This is a switch from the early phase in which these same teams tended to have probabilities closer to a non-innovative outcome. Here, the distinction in how the various groups are predicted by the Bayesian network becomes magnified. The coefficient of determination, R^2, increases to 0.84 and the slope increases to 0.30. Thus, we are certain from the late phase model that the Bayesian network does an exemplar job of correctly predicting the outcome using the external data (i.e., those teams that are rated in the “middle” of innovation).

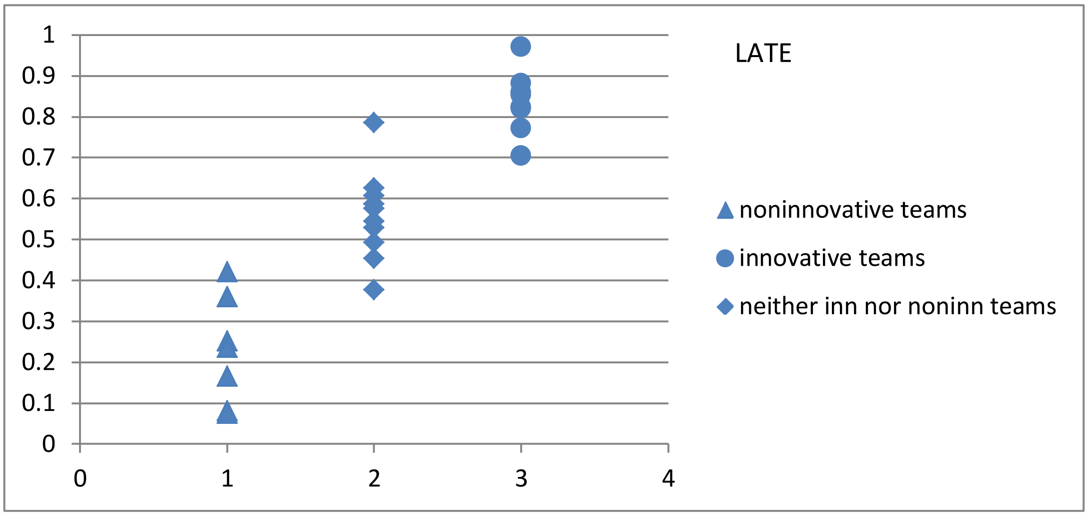


Figure 26. Testing the late phase Bayesian network model with the "middle" teams

The "middle" teams typically have probabilities within 0.4 to 0.6 range. For those that fell out of this range, it is observed that their probability is not always consistent for all phases. That is, these particular teams sometimes displayed innovative team tendencies in one phase and sometimes displayed non-innovative team tendencies in another phase. In general, innovative teams and non-innovative teams act consistently in three different phases.

6.6 SENSITIVITY ANALYSIS

The model is designed based on clustered data. In this section, a sensitivity analysis is conducted by changing the upper and lower bounds of these clusters. For each variable (i.e., design category) four cases are evaluated as shown in Table 29. Note that when the upper bound of the "low" cluster is changed, the lower bound of "medium" cluster changes by default. Further, when the upper bound of the "medium" cluster is changed, the lower bound of the "high" cluster is also changed.

Table 29. Cases of sensitivity analysis

Case	Bounds	Change	Magnitude
case 1	The upper bound of cluster "low"	decrease	by 1
	The lower bound of cluster "medium"		
case 2	The upper bound of cluster "low"	increase	by 1
	The lower bound of cluster "medium"		
case 3	The upper bound of cluster "medium"	decrease	by 1
	The lower bound of cluster "high"		
case 4	The upper bound of cluster "medium"	increase	by 1
	The lower bound of cluster "high"		

Three innovative (Teams 3, 6 and 12) and three non-innovative (Teams 1, 9 and 16) teams are selected to conduct sensitivity analysis. These particular teams are selected as being potential borderline cases (e.g., an innovative team with a relatively low probability such as 0.703). Figures 27 and 28 report the sensitivity analysis results of the early phase model. The horizontal axis shows the six different teams (i.e., “1” shows *Team 6*, “2” shows *Team 12*, “3” shows *Team 3*, “4” shows *Team 9*, “5” shows *Team 1* and “6” shows *Team 16*). The red diamond represents the probability obtained by the original clustering. Cases 1, 2, 3 and 4 are represented by the light blue, green, purple and dark blue diamonds, respectively. As seen in the Figures 27 and 28, there is no strong differentiation between the probabilities of the original clustering versus the four new cases; and hence one might conclude sensitivity analysis conducted on these six teams indicates a fairly robust model as fluctuations are minimal. Given six teams, eight categories, and four cluster cases there are 192 possible outcomes; only three percent changed in the output. Specifically, the *Management* category yields the most fluctuation in the output in that there are three instances in which a particular team (Teams 9 and 12) changes from innovative to non-innovative (see Figure 28). In Figure 27, *conceptual design* category, one can note that there are two instances in which Team 9 changes from innovative to non-innovative. Finally, in Figure 27, Team 9 again changes from innovative to non-innovative for *detailed design* category in one instance. Clearly, Team 9 is a borderline case of innovativeness.

The results of middle and late phases yield similar results; and are provided in Appendix H.

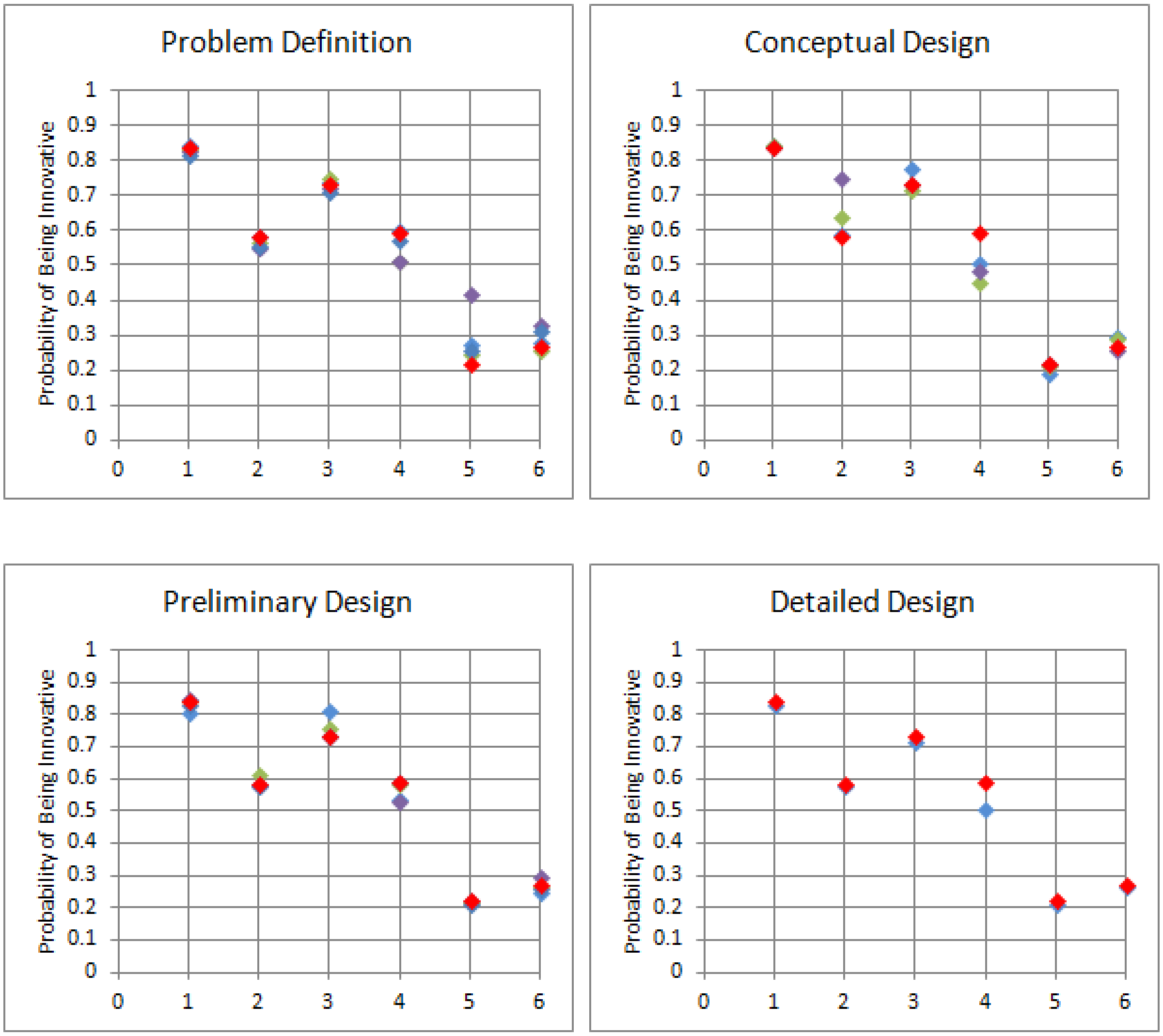


Figure 27. Early phase sensitivity analysis results for all design categories for all cases - 1

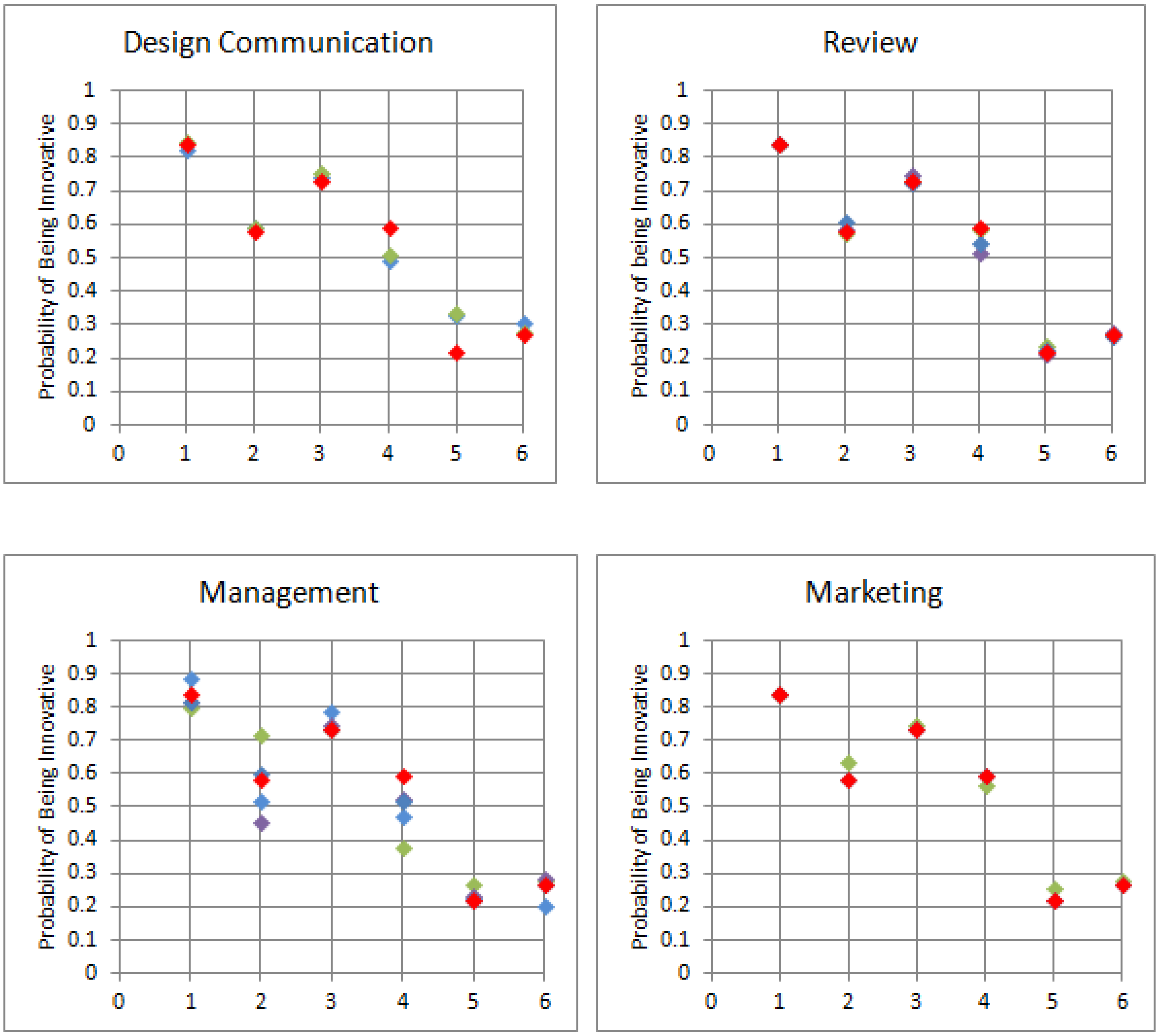


Figure 28. Early phase sensitivity analysis results for all design categories for all cases - 2

6.7 AN EXAMPLE OF HOW MODEL MIGHT BE USED AS A TOOL BY ENGINEERING EDUCATION FACULTY

As previously mentioned, an objective of this Bayesian network is to assist instructors in determining likely scenarios that lead to innovative artifacts. Such a model can help instructors redirect or intervene when teams need to take a more “innovative” course of action. As such, this developed model enables design supervisors and faculty to track teams, and make recommendations based on their current progress.

The GeNie software contains a “backward scenario” property that allows a faculty to instruct what activities need to occur based on what a team has already performed. To explain this, we provide a demonstration of the Bayesian network in practice. After entering the evidence of a team into the model, the innovation nodes without descendants are set to “innovative” as shown in Figure 29, and subsequently updating the model such that the output value is equal to one (i.e., the probability of being innovative is 100%). Note that inter-nodes are not set to any value because their role is linking the information between the time epochs within a phase. The output node is linked directly to the innovation nodes without descendants.

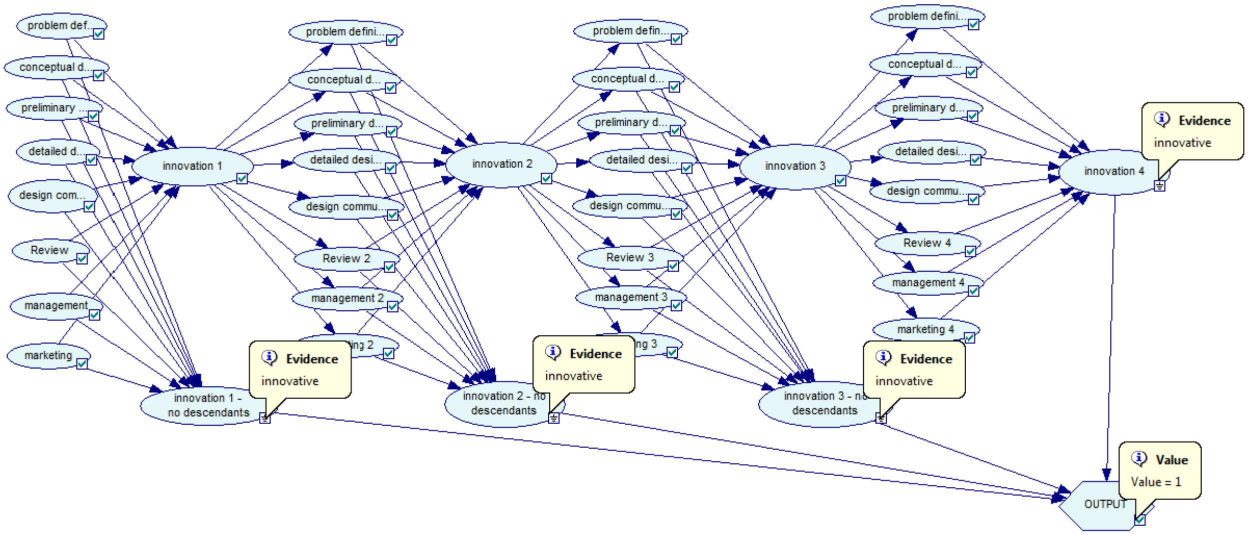


Figure 29. The specific nodes are set as "innovative"

Figure 30 shows the most-likely utilization levels for a portion of the categories to design an innovative artifact when the probability of being innovation is 100%. Note other categories are changed, but not displayed in the figure. The categories shown here are known to be important for innovation.

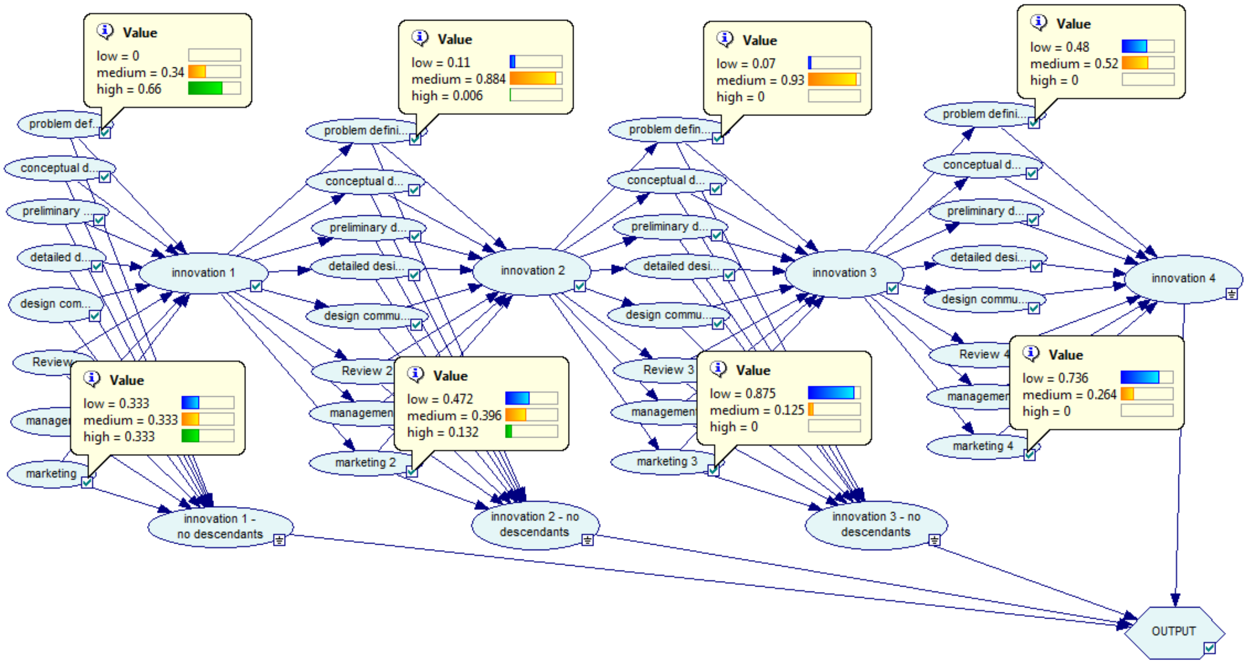


Figure 30. Design category utilization levels to get an innovative artifact

For the next step, the design instructor sets the innovation nodes without descendants to “non-innovative”, so that the output value is equal to 0 (i.e., no chance of being innovative), as shown in Figure 31. This figure shows the most-likely utilization levels of design categories when the probability of being innovative is 0%.

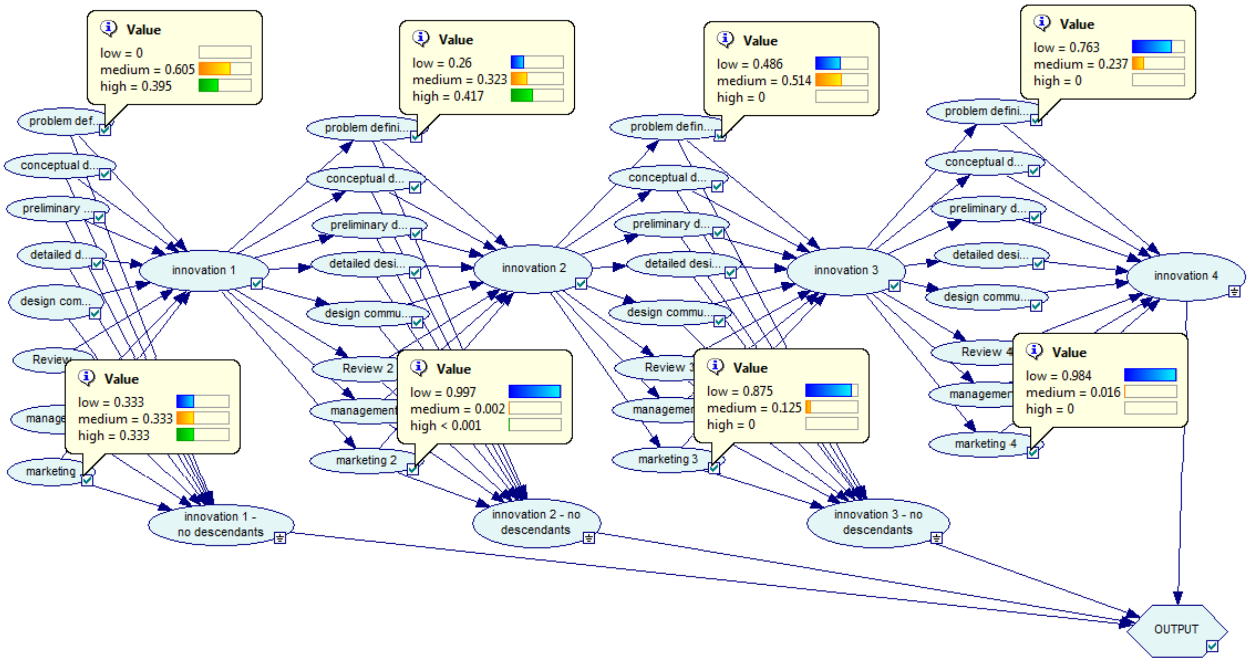


Figure 31. Design category utilization levels to get a non-innovative artifact

After observing the utilization of activities in the non-innovative case, the instructor can make recommendations to the design team by comparing the design category utilizations (e.g., *problem definition* in epoch 3 for innovative versus *problem definition* in epoch 3 for non-innovative). Consider the following example. Before the team performs any activity, it is recommended that there be a high utilization of *problem definition* activities in the first time epoch, and then reducing it to medium utilization in the following time epochs. Further, it does not matter the degree of utilization of the *marketing* activities in the first time epoch; however, thereafter, it should have at least a medium utilization in the following time epochs.

Following this example, consider that the team is now at the second epoch where evidence exists from the first epoch. Suppose that in the first time epoch, a team's utilization levels are the following:

- *problem definition* and *management* → high,

- *conceptual design*, *preliminary design*, *detailed design*, *marketing* and *design communication* → low, and
- *review* → medium.

Then, to increase the likelihood of designing an innovative artifact, the team should, in the second epoch, utilize *problem definition* at a medium level and *marketing* at either at medium or high level (as depicted in Figures 32 and 33).

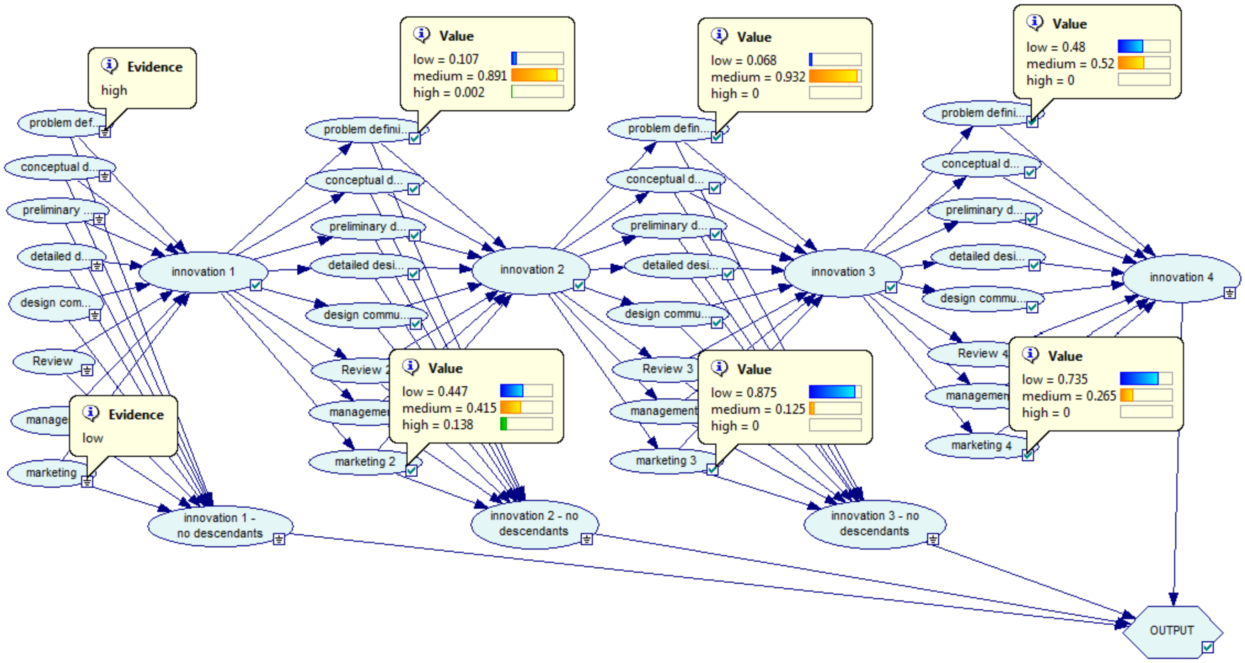


Figure 32. Design category utilization levels to get an innovative artifact with evidence

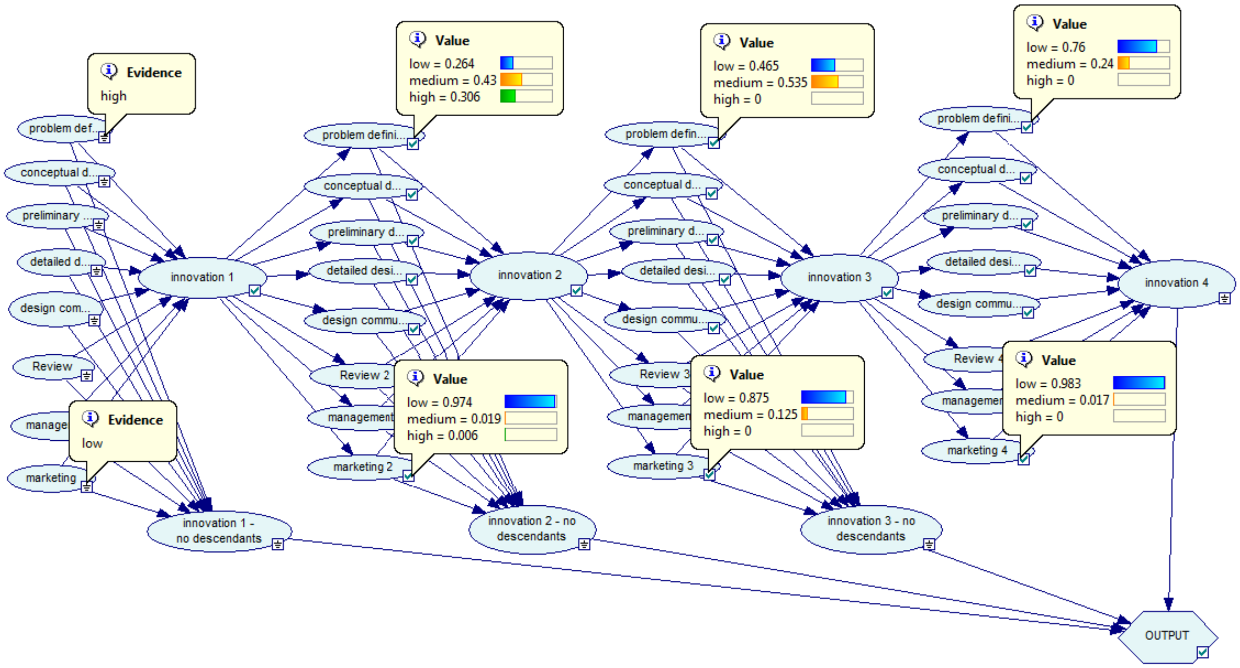


Figure 33. Design category utilization levels to get a non-innovative artifact with evidence

Note that this example provides only recommendations related to *problem definition* and *marketing*; but the model can easily provide suggestions for other activities as well. Faculty can continue to update and guide student teams as they traverse to the next epoch. In general, evidence is strongest at the prior epoch; hence, it is important to continually monitor team progress and update the model at each epoch to provide the best suggestions to the team.

7.0 SUMMARY AND CONTRIBUTIONS

7.1 SUMMARY

The goal of this research is to identify aspects of the design process and team attributes that contribute to the innovativeness of design artifacts. Research has been done on the design process, but little with the focused perspective on innovation of the artifact. Further, prior research has primarily investigated individuals, not teams. For this research, three separate studies are conducted using the same data set of near real-world design of senior capstone bioengineering projects that last between 23 and 24 weeks. Each investigation uses a different lense to uncover aspects that teams use to design innovative or non-innovative prototypes as rated by the instructors of the course. In the first and third studies, Dym's model is used as a framework for the investigation; and in all three studies, the timeline of the analyses is divided into three phases (early, middle and late) with two transition periods.

The first study investigates the activities used by the teams when matriculating through the design process. The differences between the two team types are investigated using both stepwise regression analysis as well as association mining that produced maps of how teams iterate between the different design categories. Each of these techniques are applied to the early, middle and late phases; and statistical analyses are conducted, and robustness tested, to determine if differences existed between innovative and non-innovative teams. Specifically, the type and timing of the activities are studied; and iteration of the teams through the design process is evaluated. Several significant results for the two methods indicate that innovative teams do, in fact, differ from their non-innovative counterparts in terms of what activities they engage in, how much they engage in the particular activities, and in what phase they conduct the activities.

The second study investigates the attitudes that individuals on teams express throughout their design process. These reflections form the basis of a rich qualitative database that includes students' open ended reflections and self-assessed "ah-ha" moments. Using grounded theory, the data is analyzed by marking key points, and those key points are then categorized into eleven main categories (with many sub-categories). Hypotheses are formulated about the characteristics of innovative teams, and these claims are tested by calculating the frequency of each category for both innovative and non-innovative teams for each time phase. As a result, characteristics of the innovative teams and when those characteristics become important are statistically identified and tested for robustness. Interestingly, these significant characteristics of innovative teams match several characteristics of high performing teams.

The first two studies are descriptive and empirical in nature. The third study uses the data to create a normative model, specifically a Bayesian network, which can be used as an intervention tool to support faculty teaching engineering design. Three separate dynamic models are built and validated for each time phase; and the tool considers the history of the team's activities. Based on the activities that teams engage in, the model allows instructors to predict the innovativeness of the team's final artifact. As example, if a team is doing "poorly" in terms of innovation, the instructor can make recommendations based on the current progress; and in some cases can advise the team to redirect their efforts.

Though the purpose of this work is to highlight aspects of innovative teams, a discussion about non-innovative teams is warranted. As noted in the first two studies, non-innovative teams utilize more *preliminary design* activities in both the early and late phases. It is believed that these teams are jumping to the *preliminary design* before properly engaging in *conceptual design* activities. Their iterations related to *conceptual design* is small further indicating that these teams did little in thinking about other design possibilities. In addition, from their reflections, non-innovative teams are not working sufficiently in the middle phase; however they seem to review their design often and obtain help from their instructors. As they matriculate to the late phase, they are <u>still</u> utilizing the *preliminary design* activities significantly more than their innovative counterparts. Re-doing design activities is also observed for non-innovative teams in this late time phase. In terms of iterations during the project, non-innovative teams do not have a smooth flow in the same way that innovative teams demonstrate; and throughout the design process, these teams reflect that they face certain problems; however they continue forward as they do not want to start over because of the sunk cost of time.

What is witnessed here is classical design fixation. Non-innovative teams start on one design and push through on this design regardless of the problems that are faced. We see that once they start to experience problems they continue to push forward as oppose to stopping and returning to the drawing board. As a result, they have a significant increase in iterations from other categories to *review*. Normally going to and from *review* would be a positive healthy iteration; however in this case, the teams are trying to find answers and “work-arounds” to their problems as opposed to obtaining verification and validation for their work. This is witnessed by the frustrating reflections of non-innovative teams’ expressions that they do not get help from anyone even when they ask for help. It is our impression that they likely are not hearing the answers they wish to hear.

7.2 CONTRIBUTIONS

Several contributions to the engineering design literature are derived from this research. These contributions are divided into three sections: those regarding the type of investigation that is conducted, empirical findings, as well as other advancements to engineering design literature.

7.2.1 Contributions of the type of study

The design process and its artifacts created by engineering students are studied both in engineering education and in the product realization literature. In general, past empirical studies include observations of teams or individuals designing for a particular artifact; and typically non-expert engineering students are studied. These observations are often for a fictitious non-real problem and the design process is conducted over a short non-realistic time period (e.g., three hours or less). Moreover, the emphasis of the research is on good technical design and how teams/individuals engage in the process. This research, however, provides very detailed longitudinal data collection of apprentice-like professionals (senior capstone students) addressing near-real engineering design projects in bioengineering, where most go on to full development. This is done through an on-line survey system where each individual from a team quickly evaluates what they are working on twice per week (capturing the design activities of their process); as well as capturing their attitudes throughout their design process through weekly self-reflections. Further, although others have researched the design process in terms of phases, this work adds transition periods between the phases to prevent loss of information by placing rigid borders on the data. Finally, and possibly most important, most research on the design process itself has been associated with how it relates to good technical design. The research presented here is one of the first studies that investigate how teams' design processes can actually influence the innovativeness of the artifact.

7.2.2 Empirical contributions to the literature

From the first two studies, several results are found that contribute to the design literature and specifically to the literature devoted to innovation in engineering design education.

As mentioned in the first study, the timing of design activities is investigated; more specifically, the activities that are done by the teams and when they are conducted are found to influence whether or not the final artifact is innovative. In terms of the use of activities, although the number of activities is quite small, we observe that teams designing innovative artifacts utilize significantly more *marketing* activities in the early phase. Moreover, *problem definition* and *conceptual design* activities, as well as *management* activities have key importance in the early phase. In the late phase, innovative teams engage in increased *design communication* activities, much more so than non-innovative teams; and they revisit *problem definition* activities. Engaging in all categories of the design process is important to develop an artifact. However, to develop an innovative artifact, it is important to recognize that certain activities may require more concentrated utilization at certain points in the design process. This research empirically defines those activities and where they occur in the design process.

In terms of iterations, this study shows that innovative teams iterate to and from *conceptual design* in the early phase; and the majority of movements to and from Dym's categories occur <u>at and before</u> the *preliminary design*. Further, and of particular importance to innovation, there are significant iterations involving *marketing*. Hence, innovative teams do, in fact, spend significant time and effort trying out different opportunities for design throughout the early phase before engaging in a particular design. As innovative teams move into the middle phase they actually iterate strongly around *detailed design*; and they iterate significantly more across all the categories than do non-innovative teams. Lastly, the innovative teams iterate <u>at and after</u> *preliminary design* in the late phase, continuing through the Dym's process. These results are what we would expect to see in a technically good design process. What this research contributes to the literature is specifically where these activities occur and the degree of iteration. Intuitively we know that iteration is important to the design process, but what types of iteration, where iterations should occur, and how much iteration is necessary has not been widely studied. This research provides empirical evidence to address these three questions in relationship to the innovativeness of the design artifact.

Further, we provide additional contributions to the literature though the qualitative investigation; specifically the attitudes and values of innovative team members regarding their particular design process. We find that members of the innovative teams act like problem solvers. Further, innovative teams know what they do not know, and know where to go for help. Moreover, the teams are cognizant of the time remaining and manage for this time when working as a group. In the literature, these attributes are resonant with high performing teams, but in the context of this research they are also critical for innovation. Hence, we conjecture that teams must also possess some aspects of high performing teams in order to be innovative. Finally, we find that the innovative teams do not recognize their innovativeness until the late phase indicating that their efforts are an epiphany even to the team members.

Overall, this research provides fundamental evidence about how design teams in engineering can become more innovative by applying certain types of activities at specific times within the design process, as well as provide knowledge regarding how teams should iterate through the process and what categories of the process they place emphasis on. Further, this research points out that it is not only what the team engages in, but how they function together and what they value as a team that further produces innovative artifacts. In close, the innovativeness of a design team is a function of both their chosen design activities as well as their attitudes.

7.2.3 Other contributions

In the engineering design literature, several researchers have investigated iterations. In this research, a novel approach to quantifying iterations is used. Specifically we have implemented a data mining technique, specifically association mining, to quantify how teams navigate and matriculate through the design process. To our knowledge, this approach has not been used in this realm of literature though it is common in healthcare and marketing research. From these analyses, we can empirically specify the strength of how teams enter and exit various categories of Dym’s model. As a result, this research provides a methodological contribution to the analysis of iterations in the engineering design process.

Second, intervention tools do exist to help facilitate and improve individual's/team's creativity in problem solving (most notably TRIZ). As a final contribution of this research an intervention tool, i.e., the Bayesian network model, is introduced to provide instructors and design managers assistance in tracking a team's design path providing feedback on how the actions of a team indicate whether or not they are moving towards a potentially innovative artifact. Such a tool can be used as an instructional aide in teaching innovative design, as well as helping students think about the overarching design process and the types of activities helpful to innovation.

8.0 LIMITATIONS AND FUTURE WORK

This final section discusses some limitations of the research as well as future work. Potential limitations of this work revolve around three primary areas: size of the data set, generalization of the results to all engineering fields, and the conundrum of innovative design versus "good design." A fourth, minor limitation involving methodological resources, is also offered. Also, the issues related to team work are provided. Each of these is discussed along with future directions. Further, a discussion on next steps in providing a working intervention model for engineering design education is provided.

8.1 DATA SET SIZE LIMITATIONS

The data in this research is from 26 bioengineering capstone teams collected from two different engineering schools. Further, of the 26 teams only 16 teams are actually used in the three studies (i.e., eight innovative teams and eight non-innovative teams). As such 16 records can be construed as a small data set; however, the studied data set constitutes 64 students that participated between 23 and 24 weeks (from initial conception to working prototype). Given that each individual spends approximately 12 hours per week on capstone design work, this data set involves approximately 17,600 hours of data. Hence, although the data set is small, it is rich in information. Notably even though the results of the three studies are checked for robustness and validity (as in the case of the third study), the addition of a new data set would allow for validation of the models created across the three studies. This can be added as future work.

8.2 GENERALIZABILITY

This research involves data from bioengineering. As a result, some researchers may feel that the results are not generalizable to all fields of engineering. We surmise that the results of this work can be generalizable to design processes that involve a physical artifact to be produced. With that said, some design processes result in a developed process or a service that can be delivered. For these types of design processes, a new study is warranted to determine if similar results can be found.

8.3 “INNOVATION” VS. “GOOD DESIGN”

A third potential and viable limitation of this research is deciphering whether or not our results are reflective of “innovation” versus what might constitute “good design,” as innovation may be confounded with good design practices. The rubric to measure the resulting artifacts in this research consists not only of “innovation”, but also other attributes that comprise a good design, specifically technical performance (TP), working prototype (WP), documentation (D), and overall impact on the customer (OI). For documentation, there is little variation among the artifacts produced (i.e., all teams have similar scores); and hence no further analyses are conducted with this attribute. Correlations among the other four outcome measures are calculated. As shown in Table 30, the innovation score has neither strong nor weak positive correlations with TP, WP and OI. Innovation is, at best, moderately correlated with elements of good design.

Table 30. Correlations between innovation and the other rating elements

	TP	**WP**	**OI**
Innovation	0.519	0.422	0.522
P-value	0.007	0.032	0.006

To further investigate if there are any similarities between innovation and the three measures of good design, investigation 1 analyses (i.e., stepwise regression and association mining) are repeated for the TP, WP and OI scores. Empirical models for each are developed, and the results are compared to the innovation scores, as provided in Table 31. A "+" or "–" sign indicates whether a design process category is positively or negatively significant for innovation, as well as if the same design process category is significant for TP, WP, or OI. For example, in the early phase, *conceptual design* is significant and positive for innovation and technical performance (TP). This means that both "innovative" teams and "high technical performance" teams utilize *conceptual design* activities significantly more than their counterparts. As noted in Table 31, there are four cells in which there are overlaps between "good design" attributes and innovation. In addition, association mining analyses are also conducted. Both sets of results are provided in Appendix I. These preliminary results help to support that "good design" does not necessarily mean "innovative design". Robustness of the quantitative investigation needs to be conducted to verify these initial results. Further, as part of future work, the qualitative investigation can be repeated for these elements of “good design.” Additionally, Bayesian network models can be developed for the TP, WP and OI scores.

Table 31. Significant variables of innovation “good design” elements

	Early	**Middle**	**Late**
Problem Definition	+		+
Conceptual Design	+ (TP)		
Preliminary Design	-		-
Detailed Design	+ (TP & OI)		
Design Communications			+ (TP)
Review			
Management	+		
Marketing	+ (TP)		-

8.4 CODING LIMITATIONS

As mentioned, there is a minor limitation introduced in the methodological approach involving the qualitative investigation. Given resource limitations, all reflections have been coded by a single researcher. To mitigate this limitation of potential coder bias, a coding instruction document is prepared to provide consistency. This limitation is further minimized in the research by having the data coded twice by the same researcher with a six month grace period between codings. Finally, any discrepancies are resolved through mediation with a second researcher knowledgeable on engineering design and team processes.

8.5 TEAM WORK

In this research, it is assumed that the students worked as a team on their projects. This is a fair assumption as the responses are honest in nature. In particular, innovative teams reflect about their team and state how different members have different skill sets. However, a more detailed analysis of teamwork is necessary to determine its impact on innovation. As a future research area, an investigation should be conducted to determine if the teams acted as groups of individuals doing different pieces of the project, or if they worked as a well functioning team. Further, an investigation is warranted to determine if innovative teams possessed an individual that served as the leader.

8.6 EXTENDING THE BAYESIAN NETWORK MODEL

The proposed Bayesian network model is designed to have one of two outcomes, either innovative or non-innovative. Our overall data set includes innovative and non-innovative artifacts, as well as ten artifacts that scored in the middle range (i.e., those designs with a score of three). These “in the middle” artifacts are not used the development of the model; however, they are used in model validation. Hence, there is opportunity to further develop the Bayesian model such that there are three outcome states. The Bayesian network model can also be improved by incorporating the results from the quantitative and qualitative investigations. Given the qualitative results, it is envisioned that additional nodes will be required for the model. Further, incorporating the quantitative results will require adjustments to the weights of various categories, as well as particular linkages between the epochs.

To make the network model more generalizable to other engineering disciplines, it is recommended incorporating engineering capstone design data from other fields; as well as consulting engineering design experts as to the face validity of the model. To do this, it is suggested that one-on-one interviews with experts using the model be conducted. Lastly, field testing the Bayesian network with engineering design educators monitoring student teams is a necessary future research direction, as the student interactions with the twice-per-week activity logs along with informed feedback from the model introduces two pedagogical interventions that potentially influence the innovativeness of the design.

APPENDIX A

STUDENT DESIGN PROJECTS DESCRIPTION AND EXAMPLES

Bioengineering students are introduced to biomedical product/process-based design methodologies and regulatory requirements and leverage them to a real-world bioengineering- or biotechnology-based project.

At the University of Pittsburgh, BioE 1160 - Senior Design I (fall term) is taught following by BioE 1161 – Senior Design II (spring term). In the first semester, facets of product development, particularly those unique to the design of medical devices, addressed include computer aided engineering, engineering analyses such as finite element analysis (FEA) and computational fluid dynamics (CFD), FDA regulatory requirements, and quality system regulation with a particular focus on design controls (21 CFR 820.30) At the conclusion of this course students present a project plan and a preliminary design history file for their candidate product/process design containing all essential documents. This project plan forms the road map from which student teams will execute their design project in the second semester. The design history articulates those criteria by which success of the team's projects will be evaluated in the second semester. Design projects are chosen to align with the strengths and interests of the group. Client-mentors serve as advisors to these student teams.

In the second semester, the course continues (BioE 1161) as student teams focus primarily on execution of their design projects under client-mentor supervision. In addition, various topics unique to the development of biomedical products are present by expert guest-lecturers such as representations from the FDA and Quality System managers from biomedical technology companies. At the end of this second semester, each student team is required to give an oral presentation at the senior design conference demonstrating whether their project work achieves those goals developed in the first semester (articulated in each team's design history file). Final grade is assigned based on evaluation of the presentation, completed project, and final design history file submission (based on the quality system inspection technique). Proceedings of all presentations are be assembled and include the abstracts, resumes, and other pertinent material for each term.

Similarly, at Rose Hulman Institute of Technology, three courses are used to implement their senior design project. It actually begins in the last quarter their junior year via BE 309 - Principles of Biomedical Engineering Design, followed by the first two quarters of their senior year BE 410 – Biomedical Engineering Design I and BE 420 Biomedical Engineering Design II. Content in the courses is similar to that of the University of Pittsburgh design courses.

Examples of projects include the following.

- OCT penlight
- Novel polyaxial vertebral hook
- Retractable oxygen tubing system
- Simplified Central Venous Catheterization
- A Specialized Anterior Cervical Corpectomy Fusion Plate
- Bone Screw System for Slipped Capital Femoral Epiphysis Applications

- Incubator for Albert Schweitzer Hospital in Haiti
- IVIS Intravenous Infusion Simulation
- Tampain
- Improved vaginal speculum

APPENDIX B

ELEMENTS/ACTIVITIES OF THE DESIGN PROCESS

The framework provided (i.e., stages and the list of elements) has been compiled from a thorough literature review as part of another study investigating the technology development process of corporate and academic inventors.

STAGE 1 – OPPORTUNITY IDENTIFICATION

Product Design Selection from Multiple Alternatives – If multiple alternatives are conceived, selection is made to undergo further development.

Create Product Description- Describing the intended product, its uses, features, functionalities, performance characteristics, as well as physical and technical characteristics.

Product Risk Assessment – Analyzing other ways in which the product could be used and ensuring that the user could not get hurt by the product.

Identify Primary Innovation – Establish the primary innovation of the idea or concept.

Customer Needs Analysis and Feedback – Once the target customer has been established, the customers' needs must be realized so the intended product will satisfy them and create a market for sales. Gathering customer feedback on the product, what additional features would they like, what they dislike, this can be done both during and after development.

Funding Considerations – How will the product be funded, internal, external, investors, angels, etc.

Define the Project Scope/Statement of Work – Defining the steps of the development process, what will be done, etc.

Schedule/Cost/Technical Performance Checks – Periodic examinations into whether the schedule, product cost and the product's technical performance are within desired specifications.

Create Communication Plan Among Team Members – Communication plan for the team so that all members are kept abreast of the product's design, features, etc.

Brainstorming- A technique in which a group of people think of ideas related to a particular topic, listing as many ideas as possible before critical evaluation of the ideas is performed.

Interaction With Outside Expertise – Meeting or interacting with external groups that could aid in the development or bring to mention items not previously considered.

Research Activities – consists of any of the following sub-activities:

- **Preliminary Research –** Initial research into possible technology areas, similar products, and issues related to the project.
- **Intellectual Property Awareness/Evaluation of Prior Art –** Discussions that what is being developed may contain intellectual property. Conduct an investigation to see if the technology or similar technologies have already been developed (or patented) by others.
- **Competitor Benchmarking –** Evaluating similar (fulfills same purpose) products from potential competitors.

Target Customer and Market Determination – consists of any of the following sub-activities:

- **Stakeholder Analysis** – Considering all persons involved (both directly and indirectly) in the resultant product.
- **Target Customer Determination** – Selecting the target customer for the product.
- **Define the Market and Its Growth Potential** – Who will this product be marketed to and how will this market grow? Considerations for market requirements.

Economic Analyses – consists of any of the following sub-activities:

- **Part/Product Cost Reduction** – Analyzing design to see if the product can be made for less money. This may include reducing piece thickness while maintaining the same performance characteristics.
- **Cost Estimate Projections/Financial Plan** – Costs are estimated for parts, personnel, facilities, etc. Financial analysis is conducted.
- **Determination of Product Cost** – This is the initial target cost whereby the design should meet or fall below this threshold.

Scheduling Considerations – consists of any of the following sub-activities:

- **Create a Schedule for the Product** – Adding the time element to the statement of work, the order in which things will be done, completion time, etc.
- **Develop a Work Breakdown Structure** – Dividing the development into subsections whereby individual team members get smaller pieces to work.
- **Resource Requirements** – Determining how many people, how much money, how much time are necessary to develop this product to its full requirements and specifications.

STAGE 2 – DESIGN AND DEVELOPMENT

Interaction With Outside Expertise – – Consultation with experts about product design choices/options.

Determining Part Sourcing – An element of supply chain management; this is the upstream end where product parts maybe outsourced instead of produced.

Software Development – Developing software for product or computer interface.

Produce 2-D and 3-D Drawings – Includes hand sketches up to un-scaled CAD drawings.

Prototype Development (computer model or physical mockup that is transferrable) – Creating computer based models or physical mockups of the product that can be transferred into a physical prototype via any prototyping technique (soft, hard, rapid).

Refine Tests and Models – Changing testing methods and models to incorporate new elements in the design.

Generate Multiple Product Alternatives – Based on customer needs, various product alternatives can be generated fulfilling the needs in different manners.

Design Modifications – Design changes occurring throughout the design process.

Technical Problems Arising During Development – Unforeseen technical problems that arose during development that caused a delay.

Schedule / Cost / Technical Performance Checks – Periodic examinations into whether the schedule, product cost and the product's technical performance are within desired specifications.

Finalization of Technical and Physical Requirements – Set "in stone" all of the requirements (technical and physical) that the final product must adhere to.

Regulatory Certification / Compliance / Government Mandates and Requirements - If the product being developed has certain impacts on humans, certification or governmental compliance may be necessary.

Design Review(s) – Design reviews are formal technical reviews conducted during the development of a product to assure that the requirements, concept, product or process satisfies the requirements of that stage of development, the design is sound, the issues are understood, and the risks are being managed. Typical design reviews include: requirements review, concept/preliminary design review, final design review, and a production readiness/launch review.

Documentation of Design Work – Formally documenting design work, testing, etc. in written communication to other members of the development team.

Patent Consideration – Discussion and work involved applying and obtaining the patent.

Design within Constraints– consists of any of the following sub-activities:

- **Design For Assembly –** Refers to the principles of designing assemblies so that they are more manufacturable. DFA principles address general part size and geometry for handling and orientation features to facilitate insertion, assembly orientation for part insertion and fastening, fastening principles, etc. The objective of DFA is to reduce manufacturing effort and cost related to assembly processes.

- **Design For Automation –** Incorporating into the design, considerations so that the product could produced, assembled, packaged, etc via an automated process using machines instead of people.

- **Design for Environment (Is Product Recyclable, Reusable, Reducible, Disposable?) –** Process for the systematic consideration during design of issues associated with environmental safety and health over the entire product life cycle. DFE can be thought of as the migration of traditional pollution prevention concepts upstream into the development phase of products before production and use.

- **Design For Manufacturability –** Optimizing a product's design to make its parts more manufacturable (fabrication). DFM includes: understanding the organization's process capabilities, obtaining early manufacturing involvement, using formalized DFM guidelines, using DFM analysis tools, and addressing DFM as part of formal design reviews.

Customer Feedback Evalution– consists of any of the following sub-activities:

- **Customer Feedback Evaluation –** Gathering customer feedback on the product, what additional features would they like, what they dislike, this can be done both during and after development.

- **Determine Changing Customer Needs / Market Requirements –** Considerations for existing products to be updated and developed based on changing customer needs and market requirements and how in the future changing needs will impact the sales of the product.

Product Marketing– consists of any of the following sub-activities:

- **Product Marketing 3 C’s, 4 P’s –** The process of planning and executing the conception, pricing, promotion, and distribution of ideas, goods, services, organizations, and events to create and maintain relationships that will satisfy individual and organizational objectives, Product, Place, Promotion, Price and Cost, Convenience, Communication and Customer Satisfaction.

- **Determination of Product Positioning / Segmentation –** How will this product be positioned against its competitors, does it fulfill any additional needs. Is it segmented from the existing competitors/market?

Design for Usability– consists of any of the following sub-activities:

- **Ergonomic Evaluation –** Considering if the product is ergonomically appropriate for the targeted customer in their application.

- **Incorporate Available Technologies to Improve Functionality, Safety, Etc**. **–** Using computer based software packages to improve design, rapid prototyping, etc.

Modeling, Simulation, and Optimization of Design (computer model or experimental study of situations) – consists of any of the following sub-activities:

- **Optimization of Design** – Ensuring all features of conceptual design are theoretically optimized for performance and cost.

- **Modeling and Simulation to Study Design –** Computer based modeling or experimental studies to study various situations the product might encounter, e.g., stress, strain, fatigue, pressure.

STAGE 3 – TESTING AND PREPRODUCTION

Continual Customer Feedback– Gathering customer feedback on the product, what additional features would they like, what they dislike, this can be done both during and after development. Considerations for whether the product being developed actually meets the customers’ needs.

Product Use / Knowledge Dissemination – If the product is new or unfamiliar, how will the product be introduced to the customer, e.g. tradeshow, word of mouth, demonstrations, etc.

Beta Testing – A more extensive test than the Alpha, performed by real users and potential customers. The purpose of Beta testing is to determine how the product performs in an actual user environment.

Analysis, Evaluation and Reporting of Test Data – Physical testing of the product by any of the various testers (alpha, beta, gamma), analyzing the results of the test, evaluating, reporting to the designers and then making appropriate changes to design if necessary.

Design Manuals Written – Documentation for the design, how it works, with what parts, etc.

Product Bill of Materials – A hierarchical list of subassemblies, components and/or raw materials that make up a higher-level component, assembly, product or system. An engineering BOM represents the assembly structure implied by the parts lists on drawings and drawing tree structure. A manufacturing BOM represents the assembly build-up the way a product is manufactured.

Develop a Product Manufacturing Plan – Development of the theoretical process by which the product could be produced in full scale production.

Schedule / Cost / Technical Performance Checks – Periodic examinations into whether the schedule, product cost and the product's technical performance are within desired specifications.

Design/Prototype Review(s) – Design reviews are formal technical reviews conducted during the development of a product to assure that the requirements, concept, product or process satisfies the requirements of that stage of development, the design is sound, the issues are understood, and the risks are being managed. Typical design reviews include: requirements review, concept/preliminary design review, final design review, and a production readiness/launch review.

Documentation of Design Work – Formally documenting design work, testing, etc. in written communication to other members of the development team.

Final Design Approval – The point where the final design has been decided and pilot and full scale production considerations can begin.

Alpha/In-House Testing– consists of any of the following sub-activities:

- **Prototype Testing –** Preliminary testing to see if the product works.
- **Reliability Testing, Test to Failure, Limit Testing –** Testing that includes trying to make the product fail, making sure the product doesn't fail upon x number of uses, and that the product functions safely under all possible operating conditions.
- **Alpha/In-house Testing –** A crucial "first look" at the initial design, done in-house. The results of the Alpha test either confirm that the product performs according to its specifications or uncovers areas where the product is deficient.
- **Pilot Scale Operational Testing and Evaluation –** Testing to see how small scale production of the product works, identifying and ensuring that full scale production would be possible.
- **Technical Problems Arising During Testing –** Unforeseen technical problems that arose during testing that caused a delay.
- **Test Method Definition –** Defining the test that will be used to evaluate whether the product performs to desired requirements.

STAGE 4 – PRODUCT INTRODUCTION AND PREPRODUCTION FOR MARKET

Continual Customer Feedback– Gathering customer feedback on the product, what additional features would they like, what they dislike, this can be done both during and after development. Considerations for existing products to be updated and developed based on changing customer needs and market requirements and how in the future changing needs will impact the sales of the product.

Actual Versus Planned Cost Evaluation – Financial considerations comparing the planned cost of the product versus the actual cost of the product.

Design Modifications – Design changes occurring throughout the design process.

Schedule / Cost / Technical Performance Checks – Periodic examinations into whether the schedule, product cost and the product’s technical performance are within desired specifications.

Design Review(s) – Design reviews are formal technical reviews conducted during the development of a product to assure that the requirements, concept, product or process satisfies the requirements of that stage of development, the design is sound, the issues are understood, and the risks are being managed. Typical design reviews include: requirements review, concept/preliminary design review, final design review, and a production readiness/launch review.

Documentation of Lessons Learned in Development – Refers to specific lessons that are experienced, learned, and captured or knowledge that is gained during the execution of a project or activity. Lessons learned are captured and documented for others in the organization to learn from, use to improve their performance on a project, and avoid repeating with negative consequences.

Documentation of Design Work – Formally documenting design work, testing, etc. in written communication to other members of the development team.

APPENDIX C

AN EXAMPLE OF THE QUANTITATIVE DATA

In Figure 34, each column corresponds to a day and each row corresponds to a design activity in a particular stage. Different colors represent team members. The table on the right hand side of the figure belongs to an innovative team progress, and the other one displays a non-innovative team progress. Those tables present an overall view of the design processes of two particular teams.

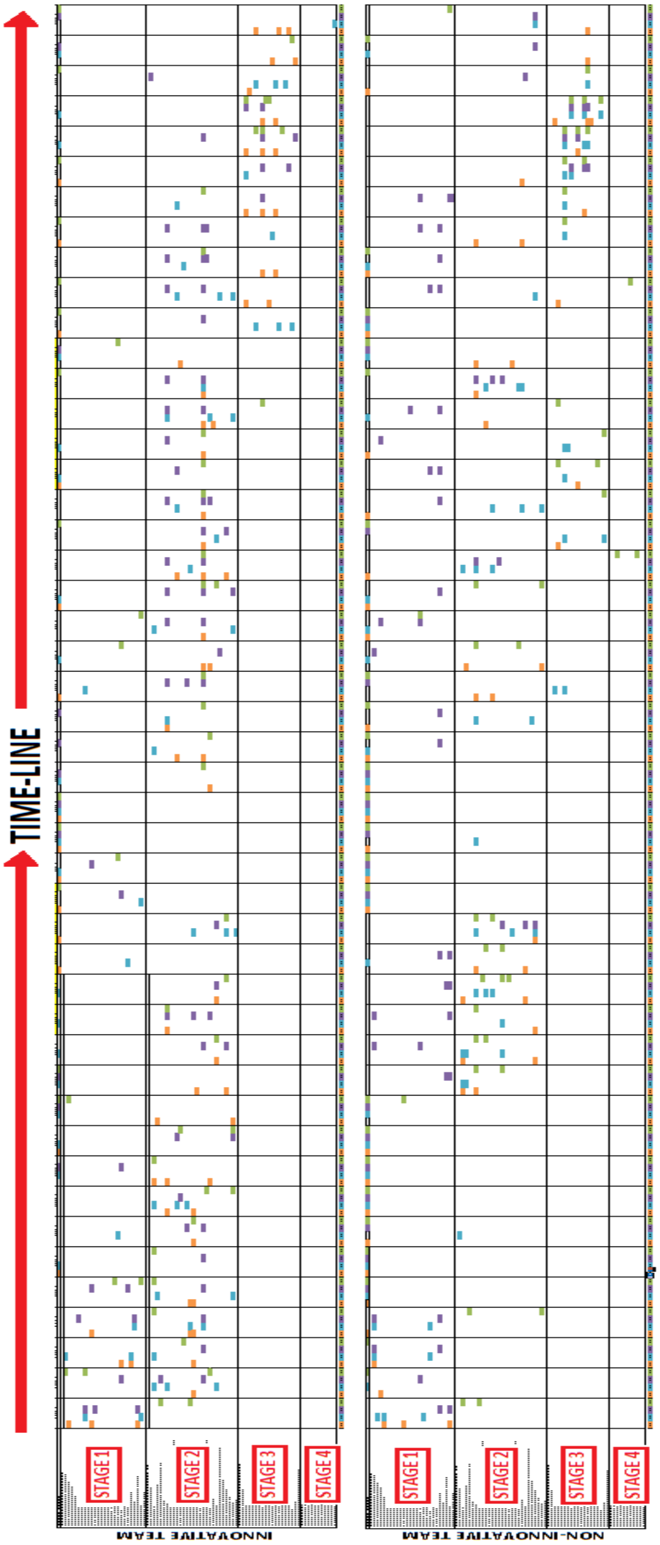


Figure 34. Tuesday and Friday survey data overview

APPENDIX D

THE STEPWISE REGRESSION AND VALIDATION RESULTS

Each time phase is divided into three sub-phases. The Table 32 reports the regression analysis results for all sub-phases.

Table 32. The stepwise regression results with p-values and R^2 values

	PARTS	EQUATION	P	R-Sq(adj)
EARLY PHASE	First	No variables entered or removed		
	Second	innovation score = 0.119 + 0.432 Conceptual Design + 1.18 Marketing	0.003	0.53
	Third	innovation score = - 0.561 + 1.69 Detailed Design + 0.370 Problem Definition	0.000	0.74
Transition 1		innovation score = 0.278 + 0.797 Management - 0.183 Preliminary Design	0.001	0.61
MID-PHASE	First	innovation score = 0.579 + 0.440 Detailed Design - 0.172 Review	0.032	0.32
	Second	innovation score = 0.185 + 0.252 Design Communication + 0.316 Conceptual Design	0.054	0.26
	Third	No variables entered or removed		
Transition 2		No variables entered or removed		
LATE PHASE	First	innovation score = 0.080 + 0.321 Design Communication + 2.99 Problem Definition	0.001	0.60
	Second	innovation score = 0.398 + 0.401 Design Communication - 0.297 Preliminary Design	0.005	0.48
	Third	innovation score = 0.391 - 1.67 Marketing + 0.170 Design Communication	0.090	0.20

Table 33 shows the significant variables in the validation of regression analysis. The stepwise regression is run by excluding one innovative team and one non-innovative team leaving only 14 data records. All possible 64 combinations are exhausted. The abbreviations of design categories are used in Table 33 (i.e., Problem definition = PD, conceptual design = CD, preliminary design = PrD, detailed design = DD, design communication = DC, review = R, Management = MG and marketing = MR). The first two columns of Table 33 show the numbers of “excluded teams” (one innovative and one non-innovative team). For example, when Team 2 and Team 9 are excluded, and the regression analysis is done for the remaining 14 teams, there is no significant variable in the first part of the early phase (i.e., T1-1). Conceptual design (CD) and marketing (MR) categories are significant in the second part of the early phase (i.e., T1-2), and conceptual design (CD) category is again significant in the third part of middle phase (i.e., T2-3).

Table 33. Significant variables in the validation step for regression analysis

Excluded Teams		**Early**				**Middle**				**Late**		
		T1-1	T1-2	T1-3	TR1	T2-1	T2-2	T2-3	TR2	T3-1	T3-2	T3-3
Team 2	Team 9		CD MR	DD PD	MG PrD	DD R	MG	CD		DC PD	PrD DC	MR DC
Team 2	Team 4		CD MR	DD PD	MG PrD	DD R	MG R			DC PD	DC PrD	MR DC
Team 2	Team 10		CD MR	DD PD	MG PrD DD	DD MG	MG DC	CD		DC PD	DC PrD	
Team 2	Team 16	R PrD	CD MR	DD PD CD	MG PrD	DD R	MG DC	CD DC	DC R	DC PD	PrD DC	MR
Team 2	Team 1		CD MR	DD PD	MG PrD	DD CD	MG DC			DC PD	PrD DC PD	MR
Team 2	Team 8		CD MR	DD PD	MG PD	DD R	DC	CD PrD DC		DC PD	DC PrD	
Team 2	team 7		DC	DD PD	MG PrD	DD R	MG			DC PD	DC PrD	
Team 2	Team 11		CD MR	DD PD	MG PrD	DD R	DC MG	R CD		DC PD	PrD DC	
Team 3	Team 9		CD MR	DD PD	MG PrD	DD R CD	MG			DC PD DD	PrD DC	MR DC

Table 33 (continued).

Team 3	Team 4		CD MR	DD PD	MG PrD	DD R CD	MG R		DC PrD	DC PD	DC PrD	MR DC
Team 3	Team 10		CD MR	DD PD	MG PrD DD	DD PD CD	MG DC CD		DC	DC PD DD	DC PrD	PD R
Team 3	Team 16	R PrD PD	CD MR	DD PD CD PrD MG	MG PrD CD MR	DD R CD	MG DC CD	DC	DC R MG	DC PD	PrD DC	MR
Team 3	Team 1		CD MR	DD PD	MG PrD	DD DC	MG MR DC		DC PrD	DC PD DD	PrD DC PD	MR DC
Team 3	Team 8		CD MR	DD PD	MG PD MR	DD R CD	DC CD MG	DD PD		DC PD	DC PrD	
Team 3	team 7		CD MR	DD PD R MG MR	MG PrD	DD DC	MG CD DC		DC	DC PD	DC PrD R MG	
Team 3	Team 11		CD MR	DD PD	MG PrD	DD R CD	DC CD MG	R		DC PD	PrD DC	
Team 5	Team 9		CD MR	DD PD	MG PrD	DD CD	DC CD	R		DC PD CD	DC PrD PD	PrD
Team 5	Team 4		CD MR	DD PD	MG PrD	MG DD	MG R		DC PrD MR	DC PD	DC PrD PD	PrD
Team 5	Team 10	PD	CD MR	DD PD	MG PrD DD	DD MG	DC CD		DC PrD MR	DC PD	DC PrD PD	PrD PD
Team 5	Team 16	R	CD MR	DD PD CD	MG PrD CD	DD MG	DC CD		DC PrD	DC PD	PrD DC	PrD
Team 5	Team 1		CD MR	DD PD	MG PrD	DD CD PrD	DC MR		DC PrD MR	DC PD	PrD DC PD	PrD
Team 5	Team 8		CD MR	DD PD	MG PD	DD CD	DC CD	DD PD		DC PD	DC PrD	PrD

Table 33 (continued).

Team 5	team 7	PD	CD MR	DD PD	MG PrD	DD MG	DC CD MG		DC PrD MR	DC PrD MR -	DC PrD R MG DD PD	PrD
Team 5	Team 11		CD MR	DD PD	MG PrD	DD CD	DC CD	R	R MR DC PD	DC PD	DC PrD PD	PrD
Team 6	Team 9		CD MR	DD PD	MG PrD	DD	DC CD	R		DC PD	DC PrD	MR DC
Team 6	Team 4		CD MR	DD PD	MG PrD	DD R -	MG R			DC PD	DC PrD	MR DC
Team 6	Team 10		CD MR	DD PD	MG PrD DD	DD MG	DC CD			DC PD	DC PrD	PD R
Team 6	Team 16	R PrD PD	CD MR	DD PD CD	MG PrD	DD	DC CD		DC PrD MR	DC PD	PrD DC	MR DC
Team 6	Team 1		CD MR	DD PD	MG PrD	DD DC	DC CD			DC PD	PrD DC DD	MR DC
Team 6	Team 8		CD MR	DD PD	MG R	DD DC	DC CD	DD		DC PD	DC PrD	
Team 6	team 7		CD MR	DD PD	MG PrD	DD	DC CD MR MG			DC PD	DC PrD DD	DC MR
Team 6	Team 11	PrD PD MG CD	CD MR	DD PD	MG PrD - DD	MR	DC CD	R		DC PD	DC PrD	
Team 12	Team 9		CD MR	DD PD	MG PrD	R DD CD	R DC CD	R		DC PD	PrD DC	MR DC
Team 12	Team 4		CD MR	DD PD	MG PrD	MR	R DC CD MR	R DD	DC PrD	DC PD	DC PrD	R DC MR

Table 33 (continued).

Team 12	Team 10		CD MR	DD PD	MG PrD DD R MR	DD MG	R DC		PrD DC	DC PD	DC PrD	
Team 12	Team 16	R PrD	CD MR	DD PD	MG PrD DD R MR	MR PD PrD	R DC CD	DC	DC R	DC PD	PrD DC	R
Team 12	Team 1		CD MR	DD PD	MG PrD DD R MR	MR	DC CD MG		DC PrD	DC PD	PrD DC	R
Team 12	Team 8		CD MR	DD PD	MG PrD DD R MR	MR PrD PD	DC CD R			DC PD	DC PrD	R
Team 12	team 7		DC MR CD	DD PD	MG PrD R DD MR	MR	DC CD R		DC PrD	DC PD	DC PrD	
Team 12	Team 11	PrD	PrD MR CD	DD PD	MG PrD R DD MR CD	MR	R DC CD	R	R MR DC PD	DC PD	DC PrD	R
Team 13	Team 9		MR CD	DD PD	MG PrD	MG	R DC CD			DC PD	PrD DC MG R	MR DC
Team 13	Team 4		CD MR	DD PD	MG PrD	MG	MG R			DC PD	DC MG PrD DD	MR DC
Team 13	Team 10		CD MR	DD PD	MG PrD DD	MG PD PrD				DC PD	MG DD DC	

Table 33 (continued).

Team 13	Team 16		MR CD	DD PD DC	MG PrD	MG			R DC	DC PD	PrD MG R DC	MR
Team 13	Team 1		MR CD	DD PD	MG PrD	MG	CD DC			DC PD PrD DD CD	PrD DC PD	MR
Team 13	Team 8		MR CD	DD PD	MG R	MG				DC PD	MG DC MR	
Team 13	team 7		MR CD	DD CD	MG PrD	MG	DC CD MG			DC PD	DC PrD	
Team 13	Team 11		MR CD	DD PD	MG PrD	MG		R	R MR DC PD	DC PD	MG DC PD	
Team 14	Team 9		CD MR	DD PD	MG PrD	DD R		R		DC PD	PrD DC	MR DD
Team 14	Team 4		MR CD	DD PD	MG PrD	MG	MG R			DC PD	DC PrD	MR
Team 14	Team 10		CD MR	DD PD	MG PrD	DD MG PD				DC PD	DC PrD	MR
Team 14	Team 16		MR CD	DD PD CD	MG PrD	DD R CD			R DC PD	DC PD	PrD DC	MR
Team 14	Team 1		MR CD	DD PD	MG PrD	MR DD	MR DC			DC PD	PrD DC PD	MR
Team 14	Team 8		CD MR	DD PD	MG PD MR	MR PrD				DC PD	DC PrD	MR
Team 14	team 7		MR CD	DD PD	MG PrD	DD DC	CD DC MG			DC PrD	DC PrD R MG	MR

Table 33 (continued).

Team 14	Team 11	PrD PD	CD MR	DD PD	MG PrD	MR PrD		R	R MR DC PD MG	DC PD	PrD DC	MR
Team 15	Team 9		MR CD	DD PD DC	MG PrD	R DD		R	PrD DC PD MR	DC PD	PrD DC	MR DC
Team 15	Team 4		MR CD	DD PD	MG PrD	R DD	MG R CD MR		PrD DC PD MR	DC PD	PrD DC	MG
Team 15	Team 10		MR CD	DD PD DC	MG PrD	DD MG			PrD DC PD MR	DC PD	DC PrD	PD
Team 15	Team 16		MR CD	DD PD	MG PrD	DD R CD			R DC	DC PD	PrD DC	MG
Team 15	Team 1		MR CD	DD PD	MG PrD	MR DD	CD DC MG		PrD DC	DC PD	PrD DC PD	MG
Team 15	Team 8		MR CD	DD PD	MG R	MR DD			PrD DC	DC PD	DC PrD	MG
Team 15	team 7		MR CD	DD PD DC	MG PrD DC	DD DC	CD MG			DC PD	DC PrD	MG
Team 15	Team 11	PrD PD	MR CD	DD PD	MG PrD	MR		R	R MR DC PD MG	DC PD	PrD DC	

APPENDIX E

THE LIST OF THE SUB-CATEGORIES USED IN QUALITATIVE ANALYSIS

The categories and their sub-categories used in the qualitative data analysis, specifically in the coding process, and related examples are provided in Table 34. The code-handbook prepared for the qualitative investigation is also available. If you wish to receive the code-handbook, please contact the researcher.

Table 34. The list of sub-categories used in qualitative analysis

Category	Sub-category	Example (Quotations from students' reflections)
Timing	Behind-worry	We are seriously behind on all aspects of the design process
	Conscious	We are all dedicating time to getting the requirements in on time
	Positive	I feel we have enough time to complete the ideas set forth at the beginning of the project.
	Urgency	We should hopefully have our project finalized ASAP!

Table 34 (continued).

Team Dynamics	Communication Bad	No communication between group members
	Complain	No one wants to take charge and put forth any ideas. We went to a meeting with our group members and three group members did not contribute anything. They didn`t say a single word beyond hello. It really pissed me off.
	Difficulty to meet	Our schedules have been such that we have not met as a whole group in weeks.
	Unmotivated	Sometimes my partner is unmotivated to do work and that puts more stress on me.
	Managerial	We email back and forth to keep everyone updated with the design process.
	Motivated	Our team dynamic is strong and our group members are all willingly contributing to the design process.
	Need to work	we need to start working harder, faster, smarter
	Negative	Also, another big thing is responsibility. If a team member says that they will do something, they should.
	Neutral	We still haven`t had any issues with team dynamics or really gotten into the technical design
	Positive	I feel we have established great team dynamics.
	Refresh	Our team dynamic seems to be almost fully repaired, with our problem member being very enthusiastic about making up for lost time.
	Separately	Our work was more individual this week.
	Working well	So far our team has been working really well

Table 34 (continued).

Skill	Consider	We currently have 3 different proposal ideas, all of which may be beyond our ability for design. (however we understand that we underevaluate our abilities and these mentors would assist)
	Negative	However, we do not necessarily have all of the programming and electrical skills necessary to work towards the simulation projects and might be getting in too deep.
	Positive	we all have our strength that others don`t. some member are more organize and delegate better while others are more technical and create designs better.
Progress	Almost done	We`re almost done; everything is coming together.
	Brainstorming	So far, our team has been brainstorming potential project ideas.
	Decide	We finally picked a project! That`s a huge step, in my opinion...
	Documentation	Wrote first draft of design brief.
	Done with the design-prototype	We`ve finally developed a working prototype of our design,
	Done with the project	We finished our project.
	Evaluation	I think one of my biggest concerns is that we choose a project that`s going to be feasible within our experience and knowledge base. I don`t want to take on something we can`t handle, so right now my main focus is gaining more information about our potential projects to better be able to choose which one will suit us best.

Table 34 (continued).

Progress	Feasibility	We are also considering the technical feasibility again of the WISER center project.
	Idea	We have a clear idea of what we want to do.
	Make changes	However, we are running into many technical problems as we begin to assemble the completed pieces and have had to make several design changes along the way.
	Meet	We meet on tuesday night to look at the assignment and then split up the work from there.
	Modification-Revise	In this stage we refined our design to only include a fraction of the system we had originally thought of.
	Moving ahead	Our project is moving along very well.
	Need to do	Our group needs to do significant research before we all meet together and decide how we`re going to tackle the assignments.
	Neutral	We finally found where we could order some of the components for our design.
	No physical	But no physical work has been done.
	No progress	There has been no progress.
	Order	we are beginning to order raw materials for our first prototype.
	Positive	We have accomplished the items we have set out to do and we are moving right along with the process.
	Presentation	We worked on our presentation
	Re-do	We redesigned one of our subsystems for our simulation device.
	Research	This week we considered several designs and did more research on current designs available.

Table 34 (continued).

Progress	Review	We are reviewing multiple prototypes
	Revise Documents	Modified previous documentation (really productive)
	Simplify	During our client meeting, I realized the project was not as complex as I had thought; we are simplifying some aspects.
	Slow	This week was slow
	Strategy	We have decided on our final design concept and have broken it into subsystems.
	Testing	we tested our materials and neoprene was the best choice
	Waiting	We are currently waiting for our mentor`s advice on how to proceed.
	Well	Our team is progressing well.
	Work hard	Ok we are putting in some late stressfull nights dealing with sensor mounting and saudering and presentation working.
	Quickly	We are progressing very rapidly in build our model.
Problem	Could not solve	We have made multiple modifications to our solenoid, but none has produced enough voltage to successfully power our otoscope.
	Not apply the solution	Ideally, we would remake another prototype with professional stitching and retest it, but we dont` have the time to do so before the end of the semester
	General	When we tested our product, the material that we were using for the skin wasn`t as conductive as we had hoped.
	Generate solutions	Met with our adviser and came up with some good solutions to problems in our design.

Table 34 (continued).

Problem	Identify	After a meeting with the design professors, we believe that the excess air in the tubing may be causing a great amount of extra stress on the motor.
	Issue	We have some ideas, but are still struggling with how everything will fit together.
	Solve	We wound a new solenoid this week and are now achieving enough voltage to power the LED in the otoscope.
Plan	Divide work	We split up the documentation that needs to be completed and set a schedule.
	Progress	This week, we compiled a number of risk analysis documents and made a more detailed plan for our design.
	Schedule	We order supplies this week and were able to get a clear schedule of what needs to be completed at certain times.
	Short term	drawing up the final design in the next week.
Knowledge	Experience	We went to UPMC to learn how the current device works and to get our hands on what we need to accomplish in adding to the device
	Learn	we learned to put a counterbore into a square piece of poly that we had in order to sink the screw inside
	Realization-Figuring out	We came to the realization that a crank dynamo would provide a more reliable power source, but sacrifice ease of use.
Getting help in	Availability Negative	We had a hard time getting hold of our mentor so that slowed us down.

Table 34 (continued).

Getting help in	Expertise	this week we have met with two experts. Dr. X who showed us a vascular injection on the Blue Phantom simulator and Y who does all of the machine work in Benedum.
	Financial	our mentor has stated that money is not an issue and he will work with us as much as possible.
	Meeting	We have met with outside expertise, such as clinicians, nurses, etc.,
	Motivation	After talking to X, we got a lot of encouragement and positive feedback on our design so far
	Review	We also received feedback from a doctor who works with health care in developing countries, the proposed market for our device.
Getting help from	Clinician	I met with the doctor and viewed a couple of colonoscopies to discuss the trouble doctors have with endoscopes.
	Customer	we have spoken to our mentors and the customer about the project, but have not yet begun the actual design.
	Experts	We have already spoken to an OT and an engineer about the feasibility and usefulness of the project.
	Instructor	The documents have come together pretty well and have had positive initial reviews from our instructor.
	Mentor	We also met with our mentor to brainstorm project ideas and decided our the specific project we want to do.

Table 34 (continued).

Getting help from	Negative	However, as I have mentioned in the past, the lack of support from our professor and his lack of understanding out project along with how advanced we are, hinders our self-esteem as a group greatly.
Emotional assessment	Positive-Optimistic	In general it is easy for us to stay on task and efficiently complete work at our weekly meetings
	Negative	This will be extremely difficult
	Worry	His concern about the feasibility of our device scares me
Extra	DID NOT WORK	I have been on vacation since Thursday of last week, and have not worked on the project.
	Communicating with the customers in “Problem definition” phase	So, this week we sat down with the customer to try and better define the objectives and design specifications of the two other projects.
	Considering source limitations	Since our budget is small, we cannot spend frivolously, but we must spend some money so that we can get moving
	Have a mentor	this week we found a mentor
	Hope	Hopefully this weekend something will break for us.
DID NOT TAKE THE SURVEY		

APPENDIX F

BAYESIAN NETWORK MODELS OF THE MIDDLE AND LATE PHASES

This section provides the models create for the middle and late phases. The middle phase is provided first, followed by the late phase, as shown in Figures 35 and 36.

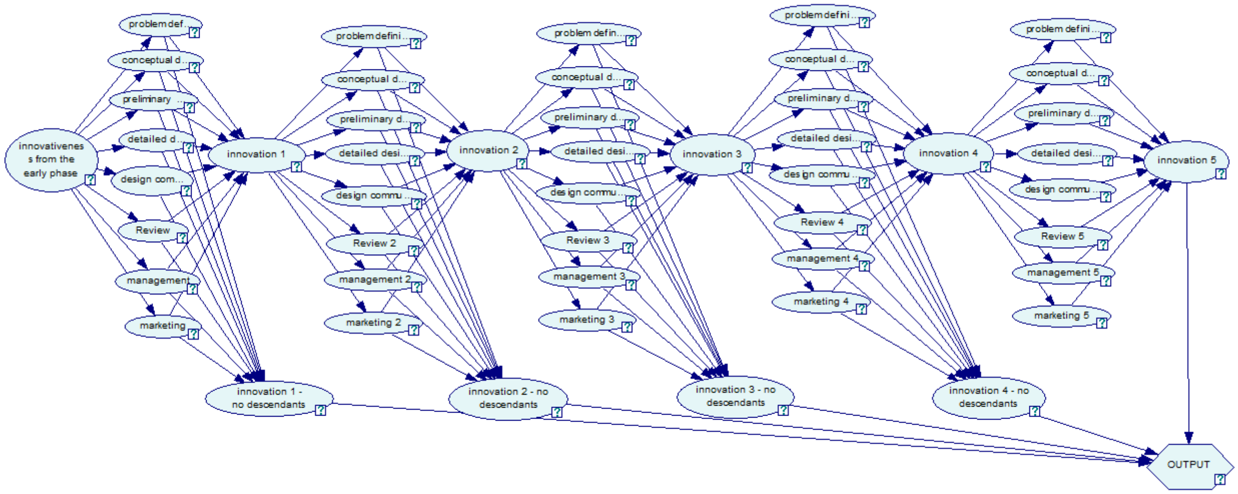


Figure 35. Bayesian network model for middle phase which has five time epochs

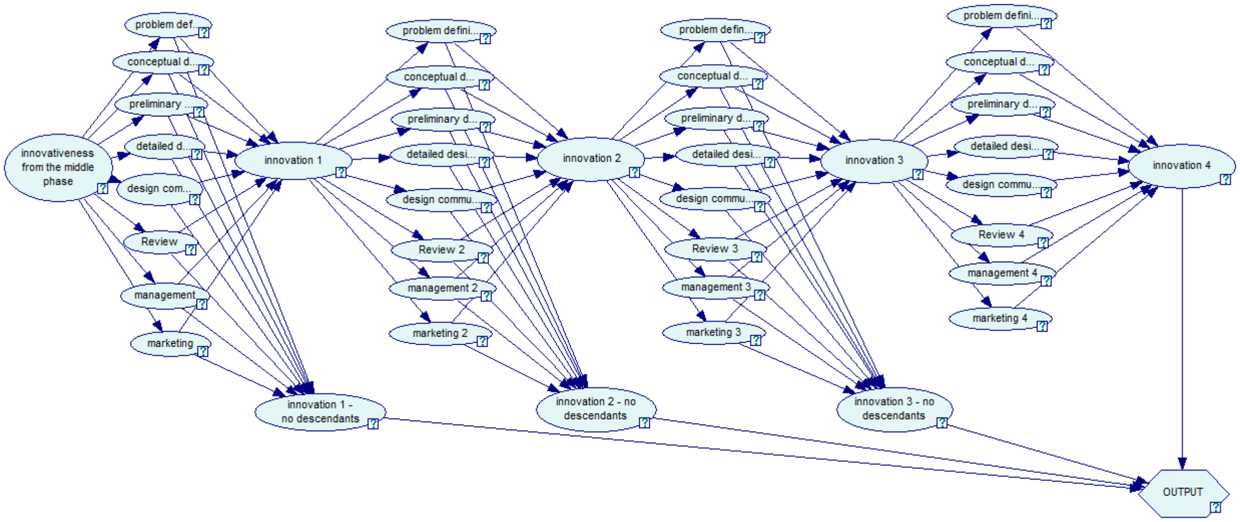


Figure 36. Bayesian network model for late phase which has four time epochs

Middle and late phase Bayesian network models have nodes which carry information from the previous phase (i.e., "innovativeness from the early phase" and "innovativeness from the middle phase"). These nodes have two states: innovative and non-innovative.

APPENDIX G

CLUSTERING RESULTS FOR EACH CATEGORY

The utilization levels of each category are clustered; and Tables 35 through 41 show the clustering results for each design category.

Table 35. Two-step clustering results for conceptual design

Number of conceptual design activities	Cluster	Quality
0-1	Low	0.798
2-5	Medium	
6-up	High	

Table 36. Two-step clustering results for preliminary design

Number of preliminary design activities	Cluster	Quality
0-2	Low	0.674
3-7	Medium	
8-up	High	

Table 37. Two-step clustering results for detailed design

Number of detailed design activities	Cluster	Quality
0-5	Low	0.767
6-13	Medium	
14-up	High	

Table 38. Two-step clustering results for design communication

Number of design communication activities	Cluster	Quality
0-2	Low	0.706
3-8	Medium	
9-up	High	

Table 39. Two-step clustering results for review

Number of review activities	Cluster	Quality
0-6	Low	0.702
7-17	Medium	
18-up	High	

Table 40. Two-step clustering results for management

Number of management activities	Cluster	Quality
0-2	Low	0.723
3-6	Medium	
7-up	High	

Table 41. Two-step clustering results for marketing

Number of marketing activities	Cluster	Quality
0	Low	0.986
1	Medium	
2-3	High	

APPENDIX H

SENSITIVITY ANALYSIS FOR MIDDLE AND LATE PHASES

The sensitivity analysis results for middle and late phases are provided in Figures 37 to 40. The horizontal axis shows the six different teams (i.e., “1” shows Team 6, “2” shows Team 12, “3” shows Team 3, “4” shows Team 9, “5” shows Team 1 and “6” shows Team 16). The red diamond represents the probability obtained by the original clustering. Cases 1, 2, 3 and 4 (explained in Table 29) are represented by the light blue, green, purple and dark blue diamonds, respectively. As a reminder, Teams 3, 6 and 12 are innovative and Teams 1, 9 and 16 are non-innovative teams.

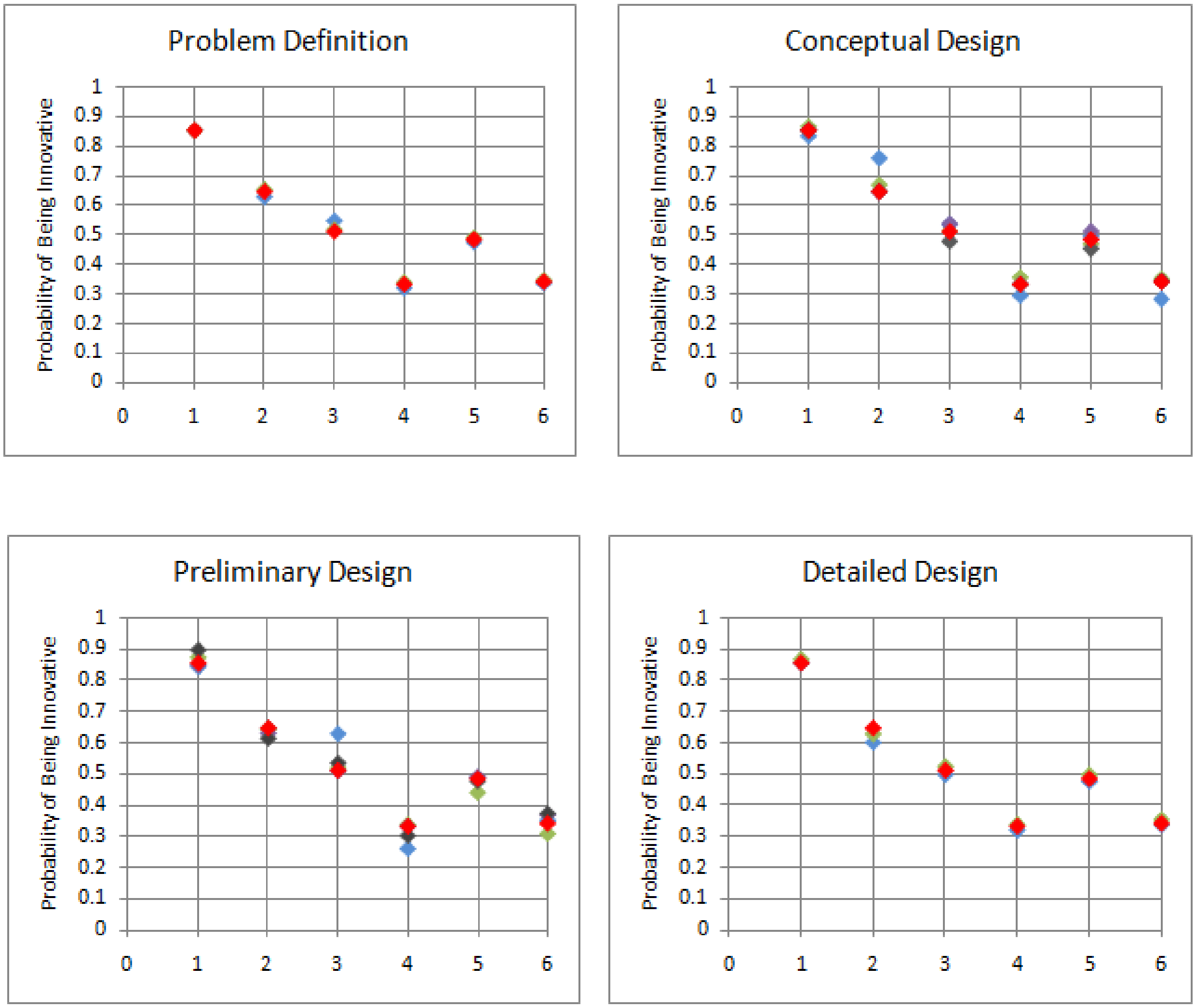


Figure 37. Middle phase sensitivity analysis results for all design categories in all cases - 1

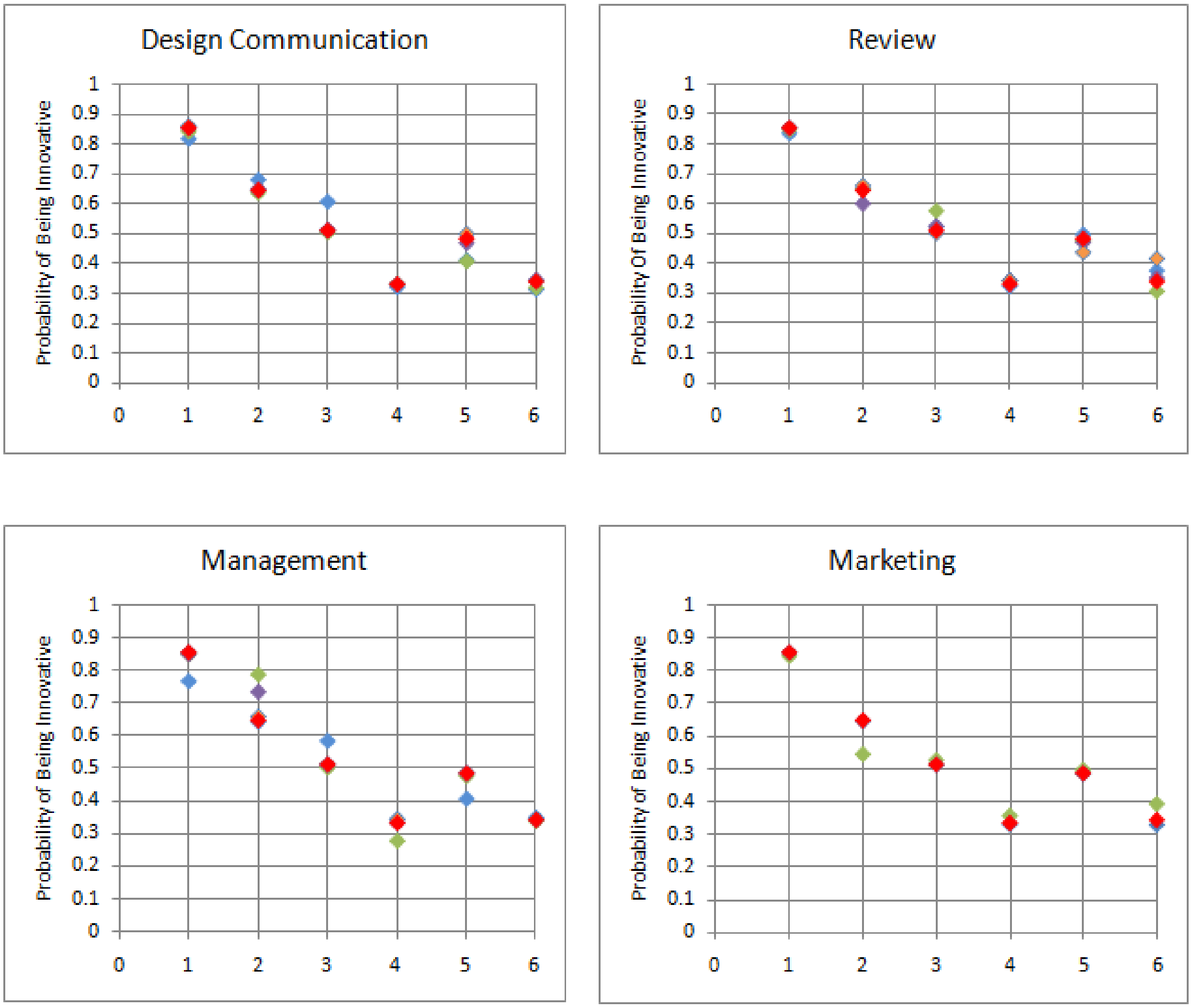


Figure 38. Middle phase sensitivity analysis results for all design categories for all cases - 2

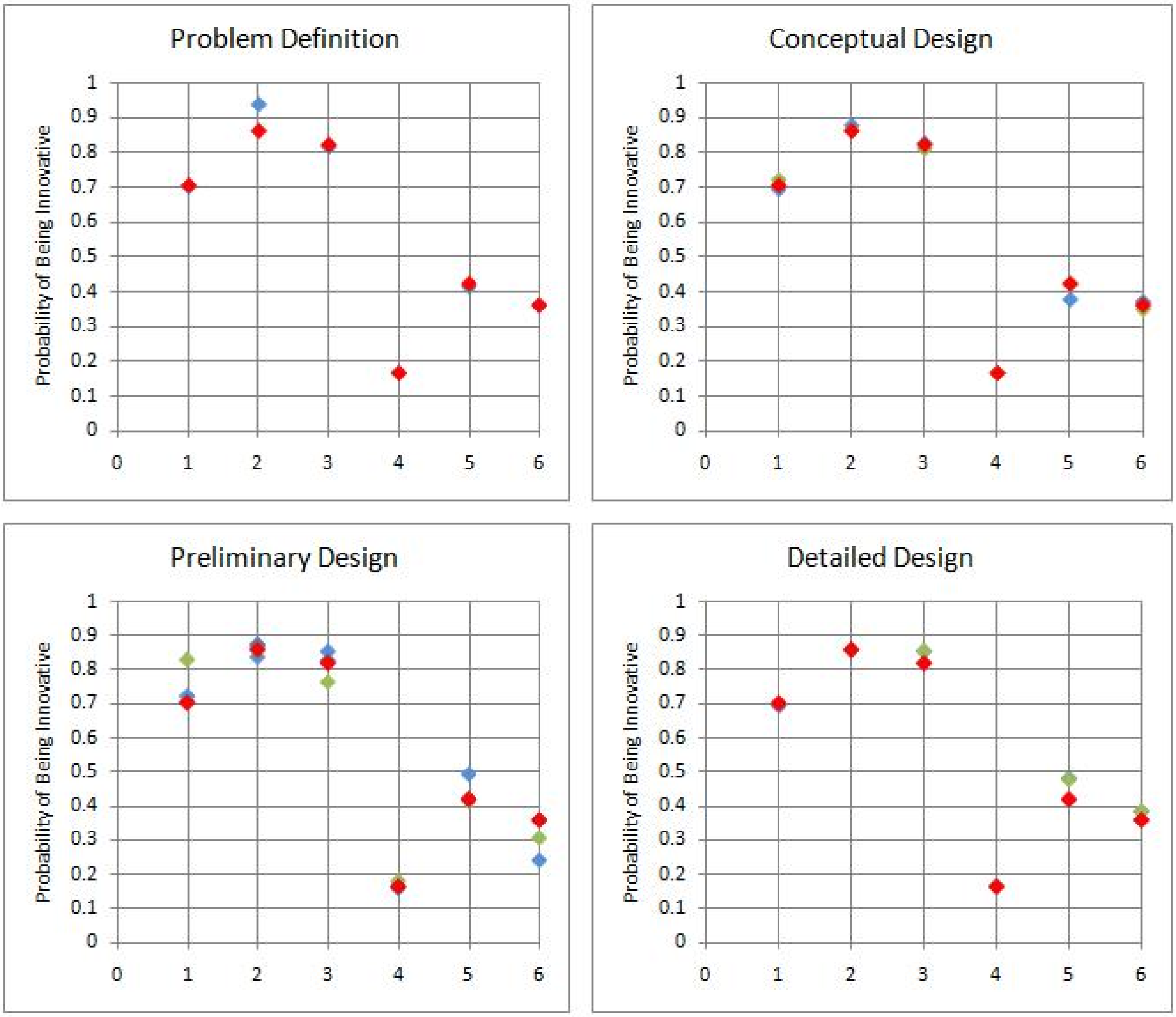


Figure 39. Late phase sensitivity analysis results for all design categories for all cases - 1

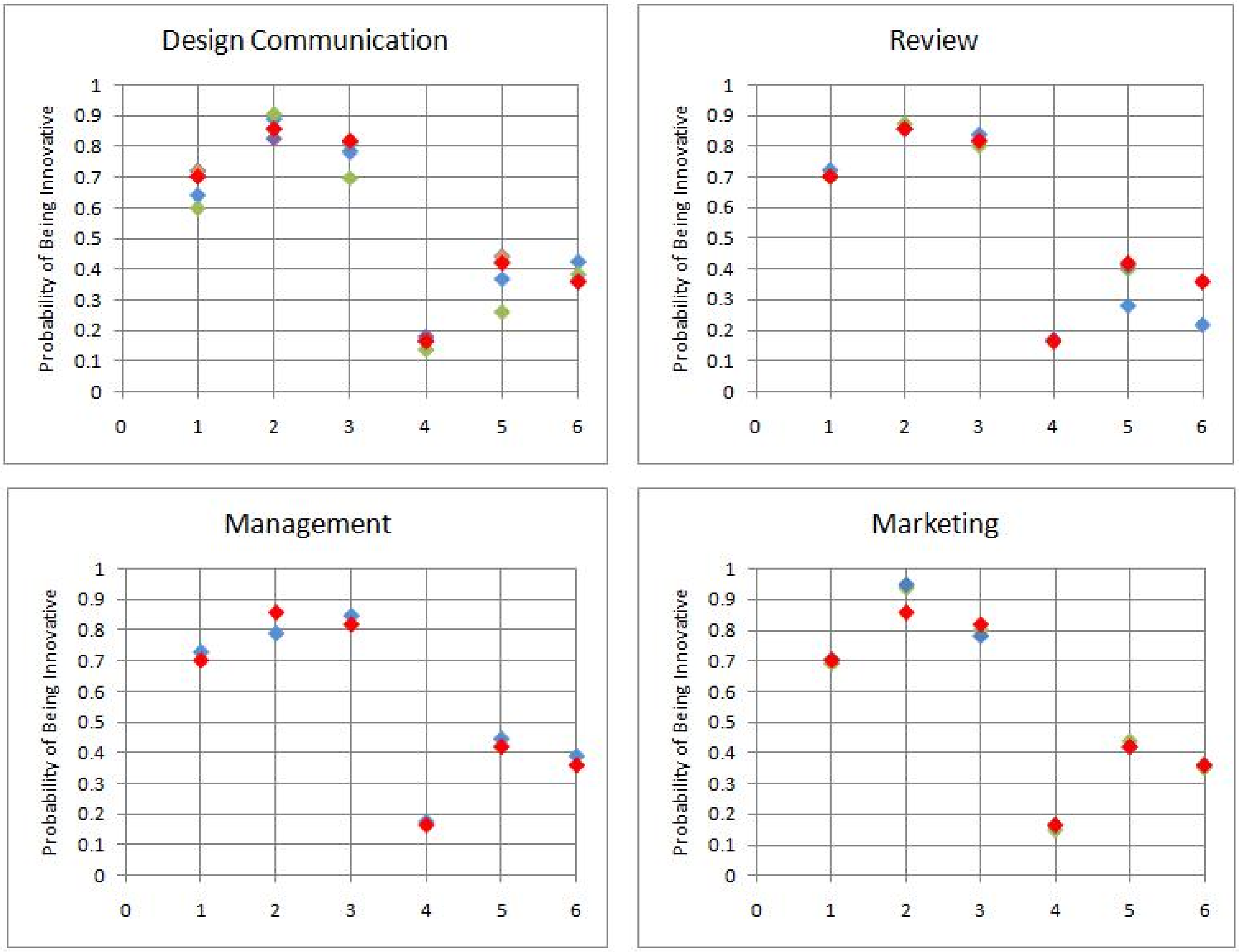


Figure 40. Late phase sensitivity analysis results for all design categories for all cases - 2

APPENDIX I

REGRESSION RESULTS AND ASSOCITION LEVELS FOR OTHER RATING ELEMENTS: TECHNICAL PERFORMANCE, WORKING PROTOTYPE AND OVERALL IMPACT

Each time phase is divided into three sub-phases. Tables 42, 43 and 44 report the regression analysis results (i.e., the results of technical performance, working prototype and overall impact) for all sub-phases. Table 31 (Comparison of the significant variables of innovation and the significant variables of "Good Design") is developed based on the overlaps in particular sub-phases. The overlaps with p and R^2 values are highlighted in bold.

Table 42. Regression results for technical performance

TIME		EQUATION	P	R-Sq(adj)
EARLY	time1-1	No variables entered or removed		
	time1-2	TP = 0.031 + 0.355 ***conceptual design*** + 0.555 detailed design + 0.107 management + 1.37 ***marketing***	0.005	77.10%
	time1-3	TP = - 0.318 + 1.25 ***detailed design*** + 0.634 preliminary design - 0.442 design communication	0.026	54.10%
Transition1		TP = 0.167 + 0.351 detailed design + 0.630 problem definition	0.088	28.80%
MIDDLE	time2-1	No variables entered or removed		
	time2-2	TP = 0.234 + 0.782 Management	0.05	26.40%
	time2-3	TP = 1.43 - 0.310 Review - 0.862 conceptual design	0.017	50.80%
Transition2		No variables entered or removed		
LATE	time3-1	TP = 0.278 + 0.182 detailed design	0.13	13.50%
	time3-2	TP = - 0.165 + 0.673 ***design communication*** + 0.687 preliminary design	0.006	60.50%
	time3-3	No variables entered or removed		

Table 43. Regression results for working prototype

	TIME	EQUATION	P	R-Sq(adj)
EARLY	time1-1	No variables entered or removed		
	time1-2	WP = 0.334 + 0.455 design communication - 0.161 REVIEW	0.072	29.20%
	time1-3	No variables entered or removed		
Transition1		No variables entered or removed		
MIDDLE	time2-1	WP = 0.723 - 0.271 review	0.077	18.90%
	time2-2	WP = - 0.053 + 1.05 management	0.003	51.70%
	time2-3	No variables entered or removed		
Transition2		WP = 0.011 + 0.782 detailed design - 0.254 review	0.011	51.30%
LATE	time3-1	WP = - 0.153 + 0.221 detailed design	0.023	33.20%
	time3-2	WP = 0.268 + 1.03 conceptual design	0.092	16.70%
	time3-3	No variables entered or removed		

Table 44. Regression results for overall impact on customers

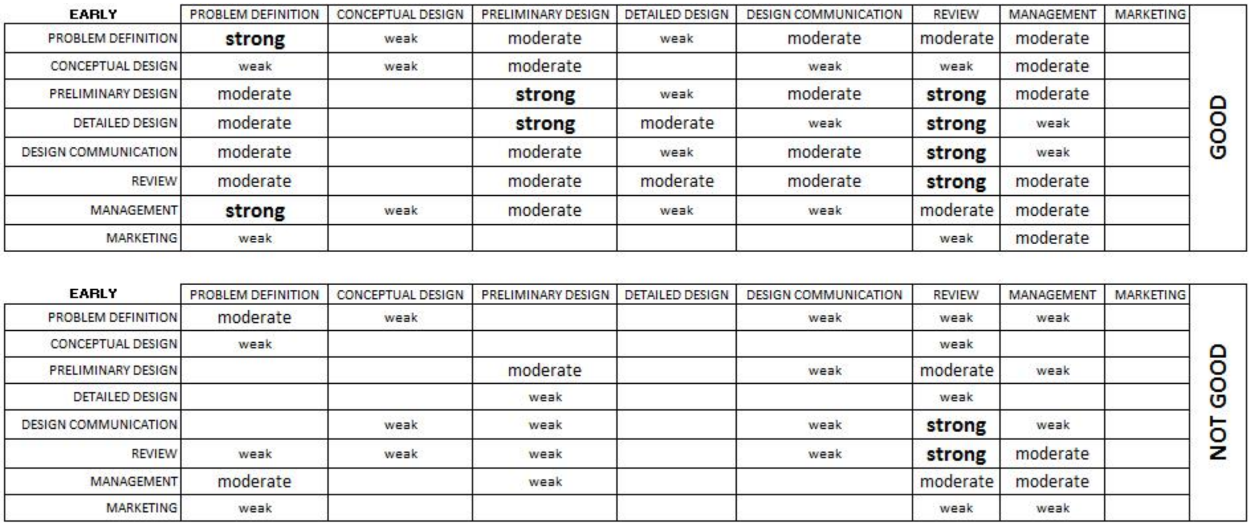
	TIME	EQUATION	P	R-Sq(adj)
EARLY	time1-1	OI = 0.829 - 1.33 conceptual design - 0.954 marketing	0.038	32.30%
	time1-2	OI = 0.253 + 0.300 review	0.068	17.50%
	time1-3	OI = 0.718 + 0.836 ***detailed design*** - 0.392 Review + 0.474 conceptual design	0.020	46.00%
Transition1		OI = 1.20 - 0.268 Review + 0.375 detailed design	0.03	35.10%
MIDDLE	time2-1	OI = 0.316 + 0.328 preliminary design	0.11	12.20%
	time2-2	No variables entered or removed		
	time2-3	OI = 0.691 + 1.35 problem definition - 0.576 design communication	0.022	38.10%
Transition2		OI = 0.997 + 0.546 detailed design - 0.716 preliminary design	0.001	62.90%
LATE	time3-1	OI = - 0.054 - 0.276 review + 0.526 preliminary design + 0.364 detailed design	0.003	63.10%
	time3-2	OI = 0.645 - 2.84 management + 0.243 detailed design - 0.208 review	0.015	49.10%
	time3-3	OI = 0.477 + 0.946 problem definition	0.117	11.50%

Tables 45 to 53 report the association levels for particular rating elements in particular time phases (the explanations are given as caption names).

Each table has two parts representing the association levels for “good” and “not good” teams for that particular rating element. For example, in Table 45, “good” means “having high score in technical performance”, and “not good” means “having low score in technical performance.

The row provides the starting point and the column provides the ending point a particular association. For instance, in Table 45, the association from *problem definition* to *management* is moderate. The association from *management* to *problem definition* is strong.

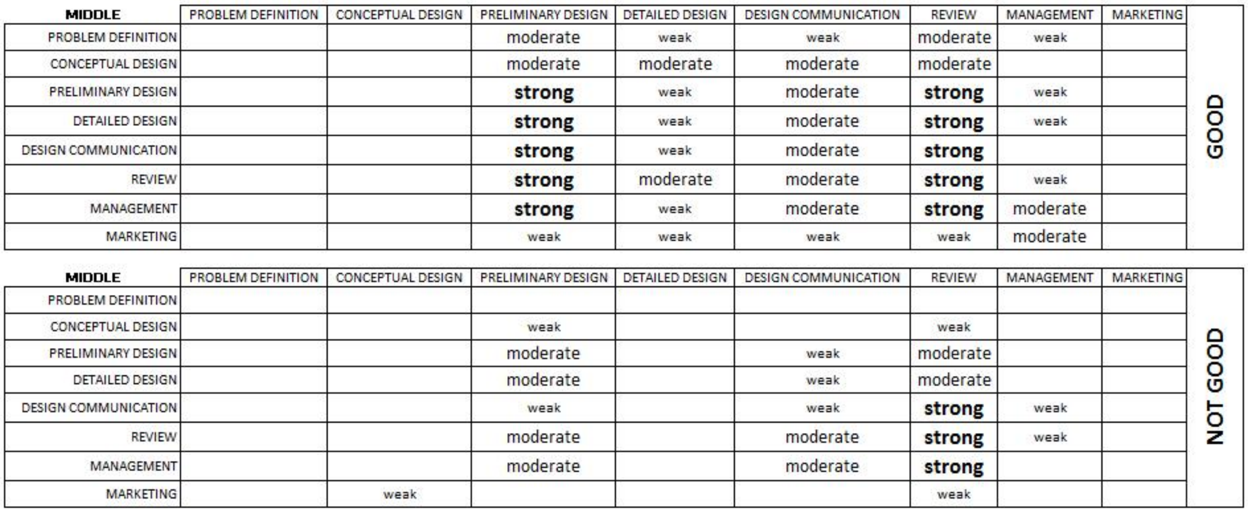
Table 45. Association levels for technical performance in the early phase



EARLY	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION	**strong**	weak	moderate	weak	moderate	moderate	moderate		GOOD
CONCEPTUAL DESIGN	weak	weak	moderate		weak	weak	moderate		
PRELIMINARY DESIGN	moderate		**strong**	weak	moderate	**strong**	moderate		
DETAILED DESIGN	moderate		**strong**	moderate	weak	**strong**	weak		
DESIGN COMMUNICATION	moderate		moderate	weak	moderate	**strong**	weak		
REVIEW	moderate		moderate	moderate	moderate	**strong**	moderate		
MANAGEMENT	**strong**	weak	moderate	weak	weak	moderate	moderate		
MARKETING	weak					weak	moderate		

EARLY	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION	moderate	weak			weak	weak	weak		NOT GOOD
CONCEPTUAL DESIGN	weak					weak			
PRELIMINARY DESIGN			moderate		weak	moderate	weak		
DETAILED DESIGN			weak			weak			
DESIGN COMMUNICATION		weak	weak		weak	**strong**	weak		
REVIEW	weak	weak	weak		weak	**strong**	moderate		
MANAGEMENT	moderate		weak			moderate	moderate		
MARKETING	weak					weak	weak		

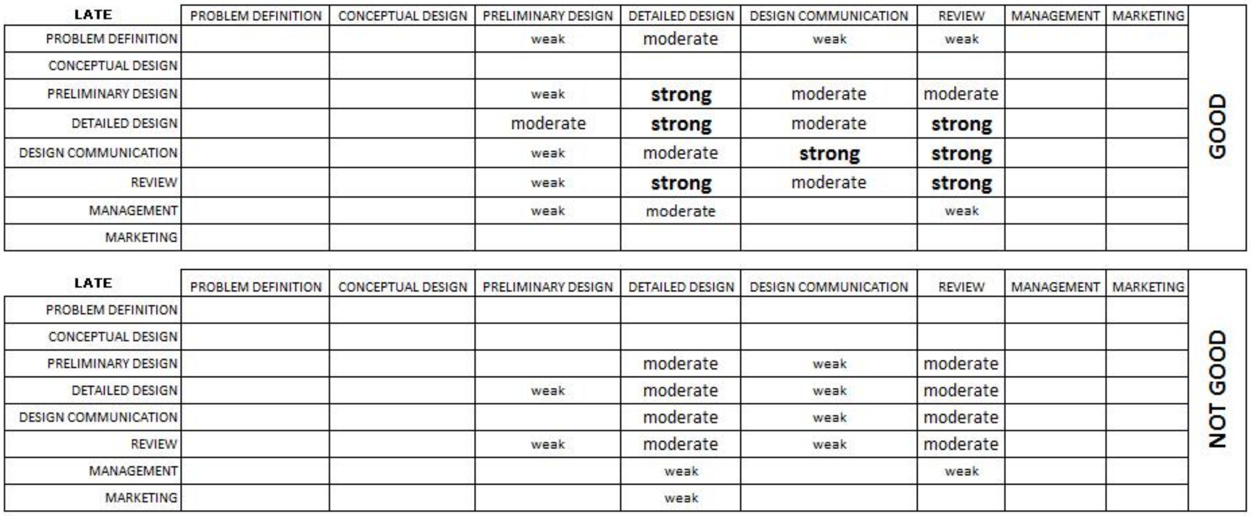
Table 46. Association levels for technical performance in the middle phase



MIDDLE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION			moderate	weak	weak	moderate	weak		GOOD
CONCEPTUAL DESIGN			moderate	moderate	moderate	moderate			
PRELIMINARY DESIGN			**strong**	weak	moderate	**strong**	weak		
DETAILED DESIGN			**strong**	weak	moderate	**strong**	weak		
DESIGN COMMUNICATION			**strong**	weak	moderate	**strong**			
REVIEW			**strong**	moderate	moderate	**strong**	weak		
MANAGEMENT			**strong**	weak	moderate	**strong**	moderate		
MARKETING			weak	weak	weak	weak	moderate		

MIDDLE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION									NOT GOOD
CONCEPTUAL DESIGN			weak			weak			
PRELIMINARY DESIGN			moderate		weak	moderate			
DETAILED DESIGN			moderate		weak	moderate			
DESIGN COMMUNICATION			weak		weak	**strong**	weak		
REVIEW			moderate		moderate	**strong**	weak		
MANAGEMENT			moderate		moderate	**strong**			
MARKETING		weak				weak			

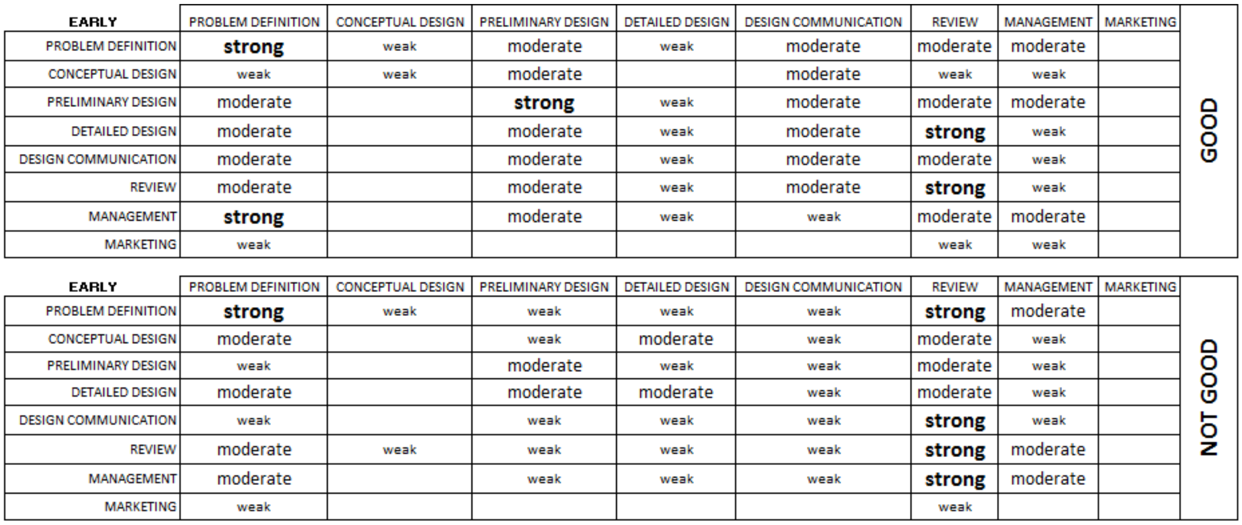
Table 47. Association levels for technical performance in the late phase



LATE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION			weak	moderate	weak	weak			GOOD
CONCEPTUAL DESIGN									
PRELIMINARY DESIGN			weak	**strong**	moderate	moderate			
DETAILED DESIGN			moderate	**strong**	moderate	**strong**			
DESIGN COMMUNICATION			weak	moderate	**strong**	**strong**			
REVIEW			weak	**strong**	moderate	**strong**			
MANAGEMENT			weak	moderate		weak			
MARKETING									

LATE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION									NOT GOOD
CONCEPTUAL DESIGN									
PRELIMINARY DESIGN				moderate	weak	moderate			
DETAILED DESIGN			weak	moderate	weak	moderate			
DESIGN COMMUNICATION				moderate	weak	moderate			
REVIEW			weak	moderate	weak	moderate			
MANAGEMENT				weak		weak			
MARKETING				weak					

Table 48. Association levels for working prototype in the early phase



EARLY	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION	**strong**	weak	moderate	weak	moderate	moderate	moderate		GOOD
CONCEPTUAL DESIGN	weak	weak	moderate		moderate	weak	weak		
PRELIMINARY DESIGN	moderate		**strong**	weak	moderate	moderate	moderate		
DETAILED DESIGN	moderate		moderate	weak	moderate	**strong**	weak		
DESIGN COMMUNICATION	moderate		moderate	weak	moderate	moderate	weak		
REVIEW	moderate		moderate	weak	moderate	**strong**	weak		
MANAGEMENT	**strong**		moderate	weak	weak	moderate	moderate		
MARKETING	weak					weak	weak		

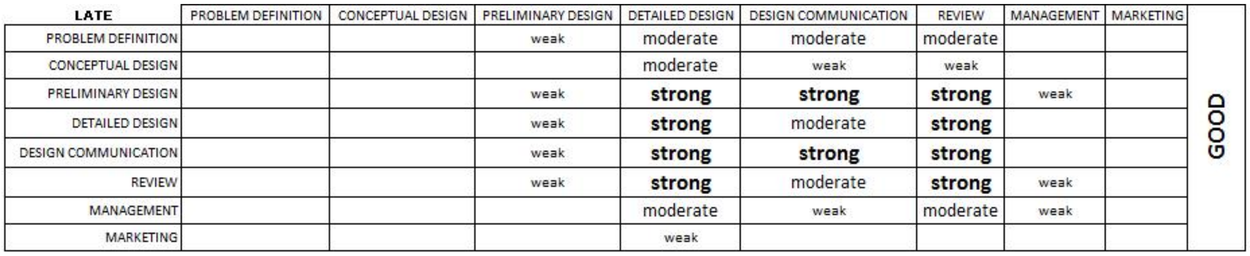
EARLY	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION	**strong**	weak	weak	weak	weak	**strong**	moderate		NOT GOOD
CONCEPTUAL DESIGN	moderate		weak	moderate	weak	moderate	weak		
PRELIMINARY DESIGN	weak		moderate	weak	weak	moderate	weak		
DETAILED DESIGN	moderate		moderate	moderate	weak	moderate	weak		
DESIGN COMMUNICATION	weak		weak	weak	weak	**strong**	weak		
REVIEW	moderate	weak	weak	weak	weak	**strong**	moderate		
MANAGEMENT	moderate		weak	weak	weak	**strong**	moderate		
MARKETING	weak					weak			

Table 49. Association levels for working prototype in the middle phase

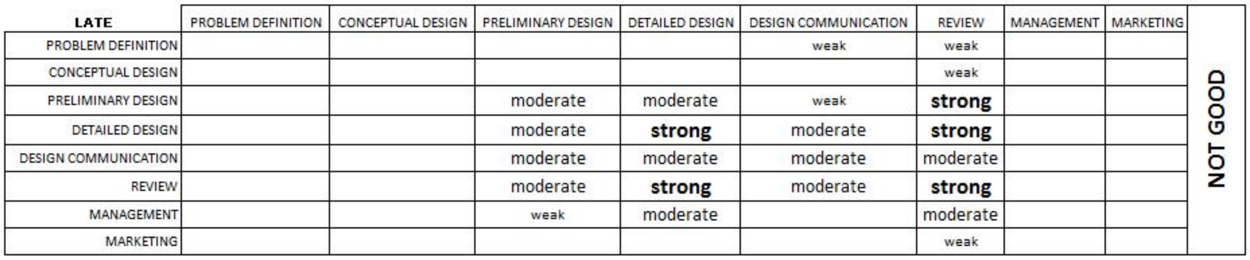
MIDDLE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION		weak	moderate	weak	moderate	moderate	weak		GOOD
CONCEPTUAL DESIGN		weak	**strong**	moderate	moderate	moderate	weak		
PRELIMINARY DESIGN		weak	**strong**	weak	moderate	**strong**	weak		
DETAILED DESIGN		weak	**strong**	weak	moderate	**strong**	weak		
DESIGN COMMUNICATION			**strong**		moderate	moderate	weak		
REVIEW			**strong**	weak	moderate	**strong**	weak		
MANAGEMENT			moderate	weak	moderate	moderate	moderate		
MARKETING			weak			weak	weak		

MIDDLE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION			weak		weak	moderate			NOT GOOD
CONCEPTUAL DESIGN		weak	moderate			moderate			
PRELIMINARY DESIGN		weak	**strong**	weak	weak	**strong**	weak		
DETAILED DESIGN			moderate	weak	weak	moderate			
DESIGN COMMUNICATION			moderate	weak	weak	**strong**			
REVIEW		weak	**strong**	weak	weak	**strong**	weak		
MANAGEMENT			**strong**		weak	**strong**	weak		
MARKETING			weak			moderate			

Table 50. Association levels for working prototype in the late phase



LATE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION			weak	moderate	moderate	moderate			GOOD
CONCEPTUAL DESIGN				moderate	weak	weak			
PRELIMINARY DESIGN			weak	**strong**	**strong**	**strong**	weak		
DETAILED DESIGN			weak	**strong**	moderate	**strong**			
DESIGN COMMUNICATION			weak	**strong**	**strong**	**strong**			
REVIEW			weak	**strong**	moderate	**strong**	weak		
MANAGEMENT				moderate	weak	moderate	weak		
MARKETING				weak					



LATE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION					weak	weak			NOT GOOD
CONCEPTUAL DESIGN						weak			
PRELIMINARY DESIGN			moderate	moderate	weak	**strong**			
DETAILED DESIGN			moderate	**strong**	moderate	**strong**			
DESIGN COMMUNICATION			moderate	moderate	moderate	moderate			
REVIEW			moderate	**strong**	moderate	**strong**			
MANAGEMENT			weak	moderate		moderate			
MARKETING						weak			

Table 51. Association levels for overall impact in the early phase

EARLY	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION	**strong**		moderate	weak	weak	moderate	moderate		**GOOD**
CONCEPTUAL DESIGN	weak		moderate		weak	moderate	moderate		
PRELIMINARY DESIGN	moderate		**strong**	weak	weak	**strong**	moderate		
DETAILED DESIGN	moderate		moderate	weak	weak	**strong**	weak		
DESIGN COMMUNICATION	moderate		weak	weak	weak	**strong**	weak		
REVIEW	moderate		moderate	weak	weak	**strong**	moderate		
MANAGEMENT	**strong**		moderate	weak	weak	moderate	moderate		
MARKETING	weak					weak	weak		

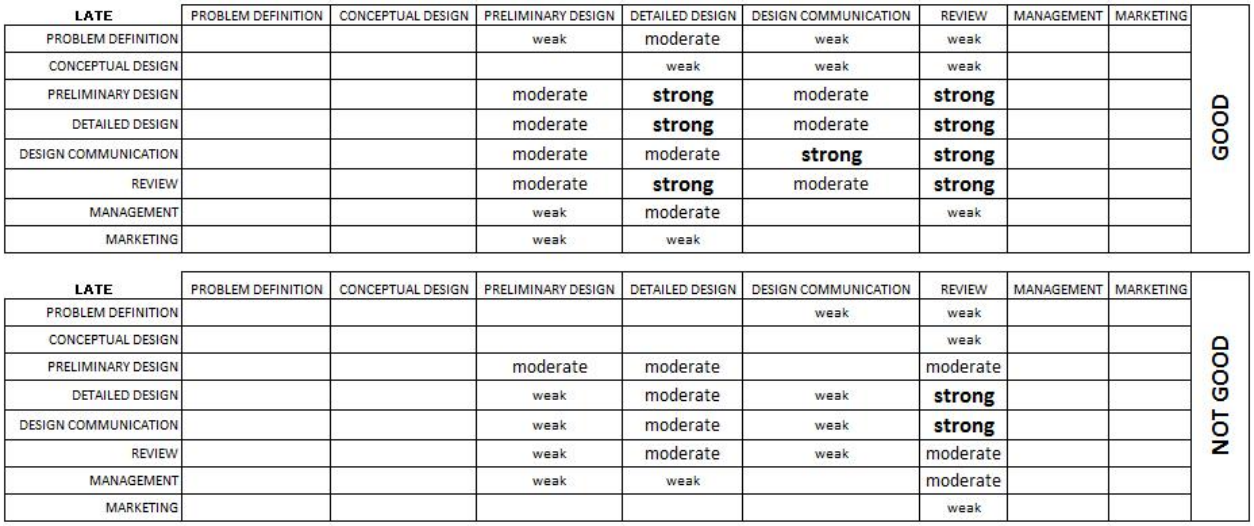
EARLY	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION	**strong**	weak	weak	weak	weak	moderate	moderate		**NOT GOOD**
CONCEPTUAL DESIGN	moderate		weak	weak	weak	moderate	weak		
PRELIMINARY DESIGN	weak		moderate		weak	**strong**	weak		
DETAILED DESIGN	moderate		moderate	moderate	weak	moderate	weak		
DESIGN COMMUNICATION	weak	weak	weak	moderate	weak	**strong**	weak		
REVIEW	moderate		moderate	weak	weak	**strong**	moderate		
MANAGEMENT	**strong**		moderate		weak	**strong**	moderate		
MARKETING									

Table 52. Association levels for overall impact in the middle phase

MIDDLE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION			moderate	weak		moderate	weak		**GOOD**
CONCEPTUAL DESIGN			moderate	moderate	weak	moderate	weak		
PRELIMINARY DESIGN			**strong**	weak	weak	**strong**	weak		
DETAILED DESIGN			**strong**	weak	weak	moderate	weak		
DESIGN COMMUNICATION			moderate	weak	weak	moderate			
REVIEW			**strong**	weak	weak	**strong**	weak		
MANAGEMENT			moderate	weak		**strong**	moderate		
MARKETING									

MIDDLE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION						weak			**NOT GOOD**
CONCEPTUAL DESIGN			moderate			moderate			
PRELIMINARY DESIGN		weak	**strong**		moderate	**strong**	weak		
DETAILED DESIGN			moderate		weak	moderate			
DESIGN COMMUNICATION			moderate		weak	moderate			
REVIEW			**strong**		weak	**strong**	weak		
MANAGEMENT			**strong**		weak	**strong**	weak		
MARKETING			weak			weak			

Table 53. Association levels for overall impact in the late phase



LATE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION			weak	moderate	weak	weak			**GOOD**
CONCEPTUAL DESIGN				weak	weak	weak			
PRELIMINARY DESIGN			moderate	**strong**	moderate	**strong**			
DETAILED DESIGN			moderate	**strong**	moderate	**strong**			
DESIGN COMMUNICATION			moderate	moderate	**strong**	**strong**			
REVIEW			moderate	**strong**	moderate	**strong**			
MANAGEMENT			weak	moderate		weak			
MARKETING			weak	weak					

LATE	PROBLEM DEFINITION	CONCEPTUAL DESIGN	PRELIMINARY DESIGN	DETAILED DESIGN	DESIGN COMMUNICATION	REVIEW	MANAGEMENT	MARKETING	
PROBLEM DEFINITION					weak	weak			**NOT GOOD**
CONCEPTUAL DESIGN						weak			
PRELIMINARY DESIGN			moderate	moderate		moderate			
DETAILED DESIGN			weak	moderate	weak	**strong**			
DESIGN COMMUNICATION			weak	moderate	weak	**strong**			
REVIEW			weak	moderate	weak	moderate			
MANAGEMENT			weak	weak		moderate			
MARKETING						weak			

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