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Innovative Design within the Context of Virtual Internships: How Can It Be Defined and How is It Related to the Student Design Process?

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Innovative Design within the Context of an Epistemic Game: How Can it be Defined and How is it Related to the Student Design Process?

Abstract

Definitions of "innovative design" vary among authors and fields of study. This presents a difficulty for those seeking to identify innovation when it occurs in a novel context, such as within the epistemic game Nephrotex. Nephrotex encourages players, who assume the role of virtual interns within the game, to explore a constrained design space with the goal of producing an optimized dialysis membrane as the end product. We have taken as a starting point the definition of Baregheh, Rowley, and Sambrook[1], which defines the process leading to an innovative design as "a process that not only leads to unique physical or technical product attributes but also adds value beyond existing designs on the market." To evaluate whether a device within Nephrotex adds "value," quality can be assessed based on the work of Arastoopour and colleagues[2], and takes technical and economic performance into consideration. Uniqueness of the design can then be determined by employing decision trees to understand at which points in the design process teams make innovative choices that lead to unique, high-quality designs. Higher branches within the decision trees are weighted more heavily in terms of uniqueness.

This research was performed with sophomore chemical engineering students in the Spring 2014 and Spring 2015 semesters. A total of 50 teams of approximately 4-5 students each were studied. Half of the teams participated in a focus group as described by Markovetz and colleagues[3]. Student design processes were evaluated based on design performance as well as weekly design journal entries wherein students reported the three activities they spent the most time on, which were categorized according to the framework of Dym[4].

We found that participation in a focus group has a medium effect in terms of odds ratio (1.8) in increasing innovation in student designs. From student surveys we found that there were no significant differences between innovative and non-innovative teams in terms of the occurrences of the design activities (grouped by Dym's categories) they spent the most time on (t and Mann-Whitney tests), though our sample size was small. However, the category with the largest effect size (d=0.68) was management, for which improvements have been shown to increase innovation by Ozaltin[5]. In terms of design attributes that contribute to generating innovative final products, we observed that teams with lower innovation scores may deprioritize cost while also reviewing prior information more than innovative teams. This is useful in that it provides a map for design decisions that could possibly lead to more innovative designs within the context of constrained design spaces such as Nephrotex.

Introduction

The term “innovative design” has a number of meanings that are specific to the field of practice. Despite this diversity, innovation is widely considered essential to the growth and survival of enterprises[6–8]. Due to the myriad definitions of innovative design, what may be innovative in the eyes of a marketing executive or architect may have no bearing on what a process engineer considers innovative when designing a plant for a new product. However, each of these practitioners value innovation as part of their respective epistemology[1]. Furthermore, organizational innovation requires the reorganization of physical, intellectual, and human resources, in addition to the integration of innovative ideas, to allow for the successful diffusion and application of a new product or process[9].

The benefits, and even necessity, of innovation in the marketplace underscore the importance of improving the process by which engineering students are educated about the research, development, and implementation phases of product design in practice[7,10]. Follet[11] put forth the notion that implementing innovation in organizations can be accomplished by domination, compromise, or integration and that integration wherein “a design which will satisfy both the engineers’ requirements and the customers’ demand,” is the best means to do so. However, providing practical context for students to learn about innovative design in a traditional classroom environment is not easily accomplished. This lack of context poses a challenge for the educator intent on teaching students the principles of design.

Game-based learning in the form of epistemic games seeks to remedy the practical shortcomings of traditional design pedagogy by immersing the player (student) in a simulated field of practice. Epistemic games account for the unique language, skills, values, and identities of differing fields of practice in accordance with epistemic frame theory [12]. Specifically, Shaffer and colleagues have developed the epistemic game Nephrotex to simulate an engineering design internship focused on the development of a dialysis membrane for the virtual company Nephrotex[13]. Through the process of playing the game, students are given technical and economic design performance criteria from stakeholders within the company and tasked with integrating the requirements into their final design by varying the following design components: material, surfactant, polymerization process, and % carbon nanotube (%CNT) used.

We have yet to define what is meant by the phrase “innovative design” for the specific study of engineering product design within an epistemic game environment. Therefore, in this work we adopt the following definition of innovation - based largely on that of Baregheh, Rowley, and Sambrook[1]- as “a design process that not only leads to unique physical product attributes but also adds value beyond existing designs on the market.” In the context of Nephrotex the definition was used to select student designs that were “unique” in comparison to other student teams while achieving a high quality score (quality metrics are used to determine the ability of the design to integrate the internal stakeholder requirements provided to students). Uniqueness was determined based on designs that were made from different surfactants than other students or designs that utilized the same surfactant as other students but selected a different manufacturing process from all other students, with increasing quality requirements at each level of design. This allowed for the characterization of early deviations in design that led to higher quality outcomes.

Research Question

How does the student design process differ for a team that generates an innovative vs. non-innovative design within an epistemic game environment?

- Do "innovative" teams report more frequently that they spend the most time on specific design activities (as grouped by Dym's category) versus non-innovative teams?
- Do "innovative" teams make their final design justification on the basis of different design factors versus their non-innovative counterparts?

Methodology

Sophomore chemical engineering students at the University of Pittsburgh were studied in the Spring 2014 and Spring 2015 semesters. A total of 50 teams of approximately 4-5 students each were studied across the two years combined, with each year split into class sections separated temporally; one section from each year played through Nephrotex with a focus group while the other did not[3].

Teams were first sorted according to choice of final design material, then further sorted based on choice of surfactant, then choice of process, and %CNT if necessary. This sorting follows from the chronological exposure these students received to material relating to each design component. This sorting strategy is graphically represented in Figure 1 as a hierarchical tree diagram, with one section presented as an example. Design quality scores were calculated according to the framework given by Arastoopour and colleagues[2] for Nephrotex designs. Teams were then classified as either innovative or non-innovative according to the following thresholds for innovative design performance:

1. Unique in terms of material selection with quality greater than section average OR
2. The highest scoring non-unique material, but unique in process, design OR
3. Achieved a "perfect" quality score of 18.

Students were also provided with weekly design journal questionnaires and asked to list the three activities that they spent the most time on during each week of the epistemic game. Statistical analyses (i.e., t and Mann-Whitney tests) were employed to determine if any differences existed in the reports of the design activities that innovative versus non-innovative teams spent the most time on. The count of design activities within each Dym's[4] design category for each team was normalized by the number of surveys submitted by the team members, thereby accounting for differences in team size. Dym's engineering design model was selected for its wide recognition as a successful framework for describing the design process and stages within constrained design space.

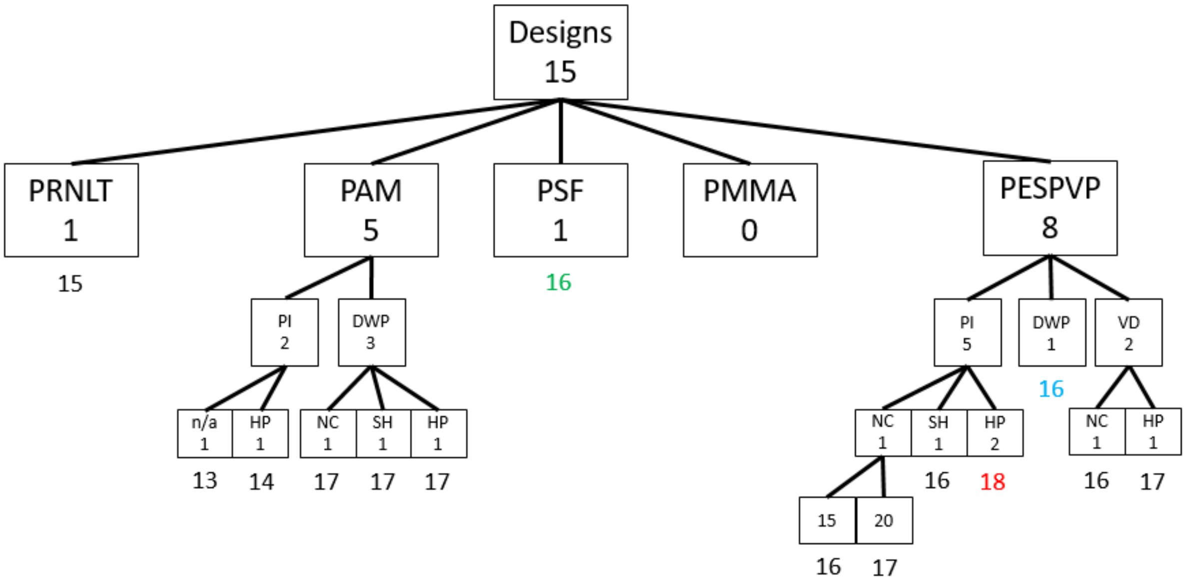

Figure 1. Tree diagram representing final design composition for one section of Nephrotex. Shorter branches represent more unique designs. Numbers within nodes indicate number of designs in that lineage. Numbers below branches represent the quality score of the design with the best unique (rule 1) design in green, a high-quality, unique-process (rule 2) design in blue, and a perfect quality (rule 3) design in red. The first branch-level represents dialyzer material selection given choices of either polyrenalate (PRNLT), polyamide (PAM), polysulfone (PSF), polymethylmethacrylate (PMMA), or polyethersulfone-polyvinylpyrrolidone (PESPVP). The second level gives polymerization process: phase inversion (PI), Dry-Wet Jet Printing (DWP), or vapor deposition (VD). The third level gives surfactant selection: hydrophilic (HP), negative charge (NC), or steric hindrance (SH). The final level is carbon nanotube percentage.

Students also submitted activity journal entries as part of their epistemic game experience. The final design justification journal entries were analyzed for general themes using a grounded framework (without separation being made between the students on innovative vs. non-innovative teams). This coding framework was designed to incorporate similar themes as those given in Dym's methodology as well as important concepts specific to membrane design in Nephrotex but was not predetermined prior to student notebook analysis. The framework is given below in Table 1.

Table 1. Grounded theory framework used for assessing final design justification responses

Category	Subcategory	Explanation
Problem Definition	Defined	Student identified or defined the problem to solve
Detailed Design	Related	Related an attribute to an output
	Flux (high or low)	Identified flux as more important (high) or less important (low) in the final design
	Blood Cell Reactivity (BCR) (high or low)	Identified BCR as more important (high) or less important (low) in the final design
	Reliability (high or low)	Identified reliability as more important (high) or less important (low) in the final design
	Cost (high or low)	Mentioned cost of final design as more important (high) or less important (low)
Design Communication	Team	Mentioned intra-group communication
	Internal	Mentioned communication with internal consultants
	External	Mentioned communication with external consultants (i.e. customers)
Review	Reviewed	Referred to knowledge gained from past designs
Management	Decision	Explained how a design decision was made
	Tasks	Distributed or mentioned tasks (to be) accomplished
Marketing	Marketability (high or low)	Mentioned marketability of final design as more important (high) or less important (low)

Training was performed using 20 student entries, and the resulting dataset for analysis contained 211 individual responses. Themes in the data were recorded by two individuals who separately coded the responses. Inter-rater reliability (IRR) between coders was assessed using Cohen's κ. Upon completion of the analysis, entries were then sorted into their respective teams.

Results and Discussion

Using the innovation schematic given in the Methodology section and Figure 1, we determined there were 8 total teams in the 2014 and 2015 implementations of Nephrotex that were innovative. The quality scores of these groups are highlighted in Figure 2, which contains the innovation diagrams for all four sophomore class sections that played Nephrotex in 2014 and 2015.

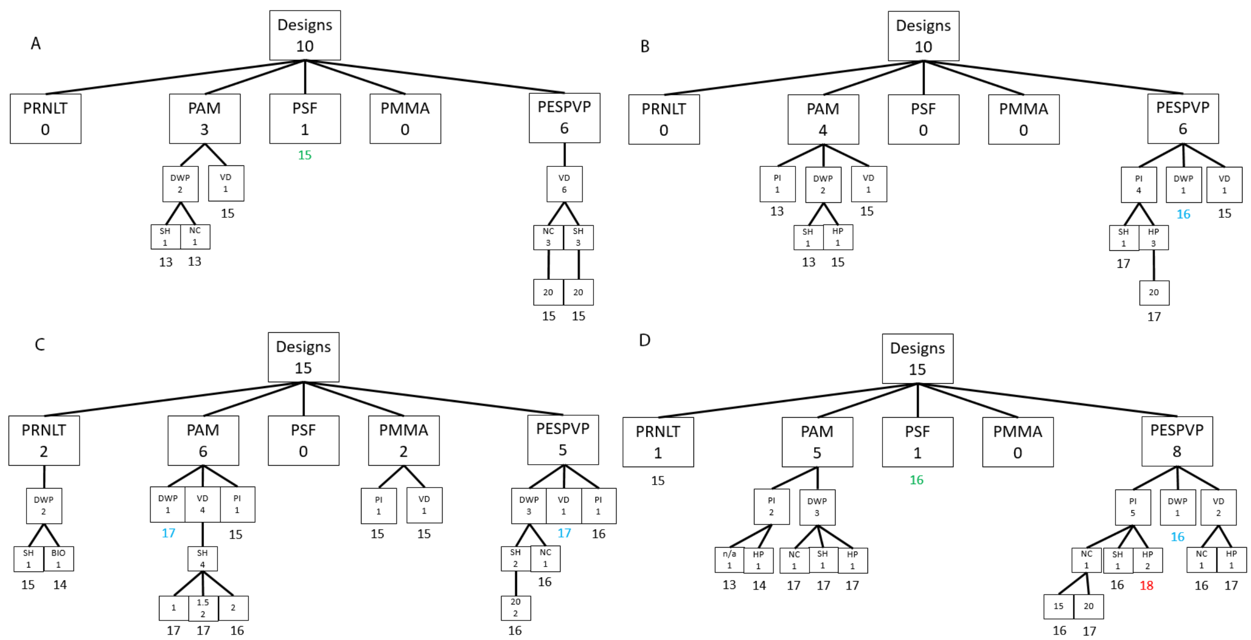

Figure 2. Tree diagrams for all student teams in Nephrotex: A) 2014 section without focus group B) 2014 section with focus group C) 2015 section without focus group D) 2015 section with focus group. Quality scores for innovative teams are highlighted in green (1), blue (2), and red (3).

Two teams met rule 1 for being innovative; four teams met rule 2; two teams, both in the same section, met rule 3 for having a maximum quality design. The sections with focus groups in both years had higher overall quality scores wherein they were exposed to stakeholders external to Nephrotex; the relationship between those elements is discussed in detail in Markovetz et al.[3]. The number of innovative teams in focus group sections was also increased (5 with focus groups vs. 3 without) yielding an odds ratio of 1.8 in favor of focus group-exposed teams producing innovative designs, which is a medium effect size[14]. The increased number of innovative designs in the sections with focus groups may also indicate that direct exposure to external stakeholders may increase the ability of designers to meet customer demands, which is an essential component of our definition of innovation.

Using the responses generated from the questionnaire based on Dym's framework, we sought to answer *whether innovative teams have more frequent reports of specific design activities (as grouped by Dym's category) they spent the most time on, versus non-innovative teams?*

The reported frequencies are given in Table 2, and statistical analyses were performed on the relative frequency of responses that occurred in each category.

Table 1. Normalized frequency of survey responses stating that a student's group spent the most time on the categories described by Dym[4].

	Normalized Count of Design Activities (by Dym's Category) (Most Time Spent)						t test	Mann-Whitney U test	Cohen's Effect Size
	Teams w/ Innovative Designs			Teams w/ Non-Innovative Designs					
Dym's Design Category	**Mean**	***sd***	**n**	**Mean**	***sd***	**n**	***p***		***d***
Problem Definition	0.013	0.023	7	0.035	0.061	43	0.38	0.58	0.38
Preliminary Design	0.012	0.021	7	0.025	0.036	43	0.36	0.43	0.38
Detailed Design	0.481	0.153	7	0.469	0.116	43	0.82	0.60	0.10
Design Communication	0.439	0.199	7	0.507	0.110	43	0.41	0.27	0.55
Review	1.153	0.154	7	1.258	0.198	43	0.19	0.13	0.54
Management	0.008	0.020	7	0.001	0.008	43	0.44	0.62	0.68
Marketing	0.000	0.000	7	0.006	0.022	43	0.48	0.78	0.29

We found there were no significant differences between innovative and non-innovative teams in terms of the normalized counts of the Dym-categorized activities they spent the most time on and the absolute counts of the activities. Analysis was based on both a t-test and a Mann-Whitney test. However, our sample size was very small for the innovative teams.

We also evaluated whether any of the components of Dym's framework had an important effect on yielding innovative design as measured by Cohen's d. The effect sizes were either small or medium. The largest effect size was for *Management* at d=0.68, with innovative teams reporting more frequently (than non-innovative teams) that they spent the most time on Management activities. This is of note since work done by Ozaltin et *al.*[5] demonstrated that innovative teams working on an open ended biomedical engineering project spent significantly more time on management related activities than non-innovative teams. While the Nephrotex design environment is not open ended, the moderate effect that arises in this study would indicate that Management is an important area of focus in engineering design in general. Furthermore, it is possible that with a larger sample size that we may be able to show statistical significance based on the magnitude of effect reported here.

In order to address the second component or our research question: *Do innovative teams make their final design justification on the basis of different design factors versus their non-innovative counterparts?*

We analyzed the individual justifications given for the final design selected by the students' teams according to the framework given in Table 1. There were 42 responses from innovative teams and 169 from non-innovative teams. Inter-rater reliability was very high ($\kappa=0.87$). Agreement was then reached on responses that were coded differently between the readers, and the number of responses in each category was counted. Proportions of students from both innovative and non-innovative teams who used each category from the grounded framework are given in Table 3. No results were statistically significant ($p>0.05$, all categories). Three categories did, however, approach significant diminution ($p<0.10$) for innovative teams versus non-innovative teams: devaluation of cost ($p=0.075$), high valuation of flux ($p=0.095$) and reviewing of information ($p=0.061$). The specific coding categories of "Flux High" and "Reviewed" both had medium effect sizes according to their respective odds ratios (OR) of 2.3 and 2.0 in favor of selection by non-innovative groups. The OR for Cost Low was incalculable as not one innovative student of 42 made a comment devaluing device affordability as a design element, however the OR for Cost High was 1.6 in favor of innovative teams, which indicates that there is at least a small effect of valuing cost in order to create innovative designs.

Table 2. Relative frequencies at which students gave responses mentioning one or more of the themes from the grounded framework in Table 1.

	Non-innovative	**Innovative**	**z-score**	**P**
Defined	0.030	0.048	-0.584	0.280
Related	0.959	0.952	0.178	0.429
Flux High	0.148	0.071	1.308	**0.095**
Flux Low	0.012	0.000	0.708	0.239
Blood Cell Reactivity (BCR) High	0.024	0.000	1.007	0.157
BCR Low	0.000	0.000	-	-
Reliability High	0.000	0.000	-	-
Reliability Low	0.006	0.000	0.500	0.309
Cost High	0.112	0.167	-0.957	0.169
Cost Low	0.047	0.000	1.438	**0.075**
Team	0.166	0.190	-0.382	0.351
Internal	0.929	0.952	-0.545	0.293
External	0.112	0.071	0.778	0.218
Reviewed	0.284	0.167	1.551	**0.061**
Decision	0.876	0.857	0.323	0.373
Tasks	0.000	0.000	-	-

	Non-innovative	Innovative	z-score	P
Marketability High	0.077	0.095	-0.390	0.348
Marketability Low	0.000	0.000	-	-

Teams who focused more on improving flux and reviewing prior information were found to be less innovative in terms of final design procedure. The emphasis on review in non-innovative teams may imply that these teams were unwilling to modify older designs in an attempt to improve the final product, thus diminishing the opportunities to diversify their design space or increase product quality, ultimately reducing innovativeness. Regardless of the reason, however, these agree with the results in Table 2, that review is favored by non-innovative teams, and has a medium effect on the design process or outcome.

In the case of flux, the effect may have been due to an excess of attention directed toward technical performance. Markovetz and colleagues[3] have reported that it is important for design quality to account for both technical and economic concerns of all stakeholders as opposed to one or the other. As an extension of their argument, customers are very concerned about cost, and by devaluing the importance of low cost to external stakeholders a non-innovative design would not be an unexpected outcome. The potential to sort out whether a student or student group is able to identify both internal and external market demands based on the innovative design criteria used in our framework is evident from these findings, and can be furthered with additional improvements to make the framework more robust.

Conclusion

Innovative design is critical to the viability of any enterprise in all matters, including engineering. Despite this, the definition of innovation remains somewhat ambiguous. In this work we have taken the definition of innovation in product design to be, "a design process that not only leads to unique physical product attributes but also adds value beyond existing designs on the market." We then constructed a set of rules that establish a design as innovative and applied it to the dialysis membrane designs developed in Nephrotex.

We found that this set of rules may have been able to discriminate between innovative and non-innovative designs based on the emphasis the student design team places on cost of the design. This result agrees with our previous work regarding the effect of external stakeholder input on the engineering design process leading to lower cost designs. Students with more innovative designs were also more likely to be students that were exposed to external stakeholders in a focus group setting, making a stronger case for emphasizing the importance of customer voice in the engineering curriculum. We also report that management tasks were more frequently the activities that innovative teams spent more time on compared to non-innovative teams, which aligns with the findings of Ozaltin and colleagues[5]. We suggest that the results related to the amount of review students perform according to both that framework and a grounded theory framework developed by the authors for this study agree that increased review may be related to less innovative design. And from our framework, we also suggest that non-innovative teams may focus too much on technical performance like flux rate at the expense of affordability, which is a desirable trait for customers.

By further refining our innovative design framework developed in this work, better discriminatory power may be achieved in determining what elements of the design process can be manipulated to best allow for innovation. At present, however, these results suggest that by increasing engineering student awareness about the needs of external stakeholders in terms of both technical performance and economic constraints, more innovative design is immediately achievable.

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