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Divergent prototyping effect on the final design solution: the role of "Dark Horse" prototype in innovation projects

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Abstract

Product development processes require prototypes to materialise ideas and share concepts. Prototypes' nature can be classified as convergent or divergent. Converging prototypes represent an evolution of a concept, while diverging ones seek to cover different solution paths. The diverging group includes the "Dark Horse" prototype, which calls for the exploration of other, high-risk high-return ideas. This paper examines the "Dark Horse" influence on final design concepts. Fifty-nine projects developed by multi-disciplinary student teams following a Design Thinking approach were studied. Comparison criteria and statistical analysis were implemented to understand the effects of the "Dark Horse" on the final solution. In particular the influence of the "Dark Horse" characteristics and its level of radical innovation on the quality and nature of the final solution of the project were examined.

Keywords: Innovation; Prototyping; Design Thinking; Dark Horse.

1. Introduction

New product development (NPD) is a critical business process to companies' innovation. Various approaches can be applied to manage the NPD process, ranging from highly structured stage-gates [1] to the user-centric Design Thinking [2].

The top-down structure provided by former design paradigms provides high efficiency and is well suited for projects in which design requirements can be explicitly determined in advance. However, in applications where design requirements are hard to specify without significant user-testing and feedback, more flexible, bottom-up approaches seem to be more appropriate. One such approach, known as Design Thinking (DT), emphasises proximity to the user, to understand their needs early and deeply, and fast prototyping that speeds up learning cycles and supports innovative solutions [3].

Although focusing on different aspects of the NPD process [2], both approaches share the use of prototyping cycles. A prototype provides a testable representation of a product, which can be experienced and validated by users, and allows the exploration of new ideas. It can have a diverging nature, to open up the problem space, or a converging nature, to explore the solution space [4].

Usually, early prototypes have a diverging nature, to generate concepts for problem solution. As the development process progresses, prototypes acquire a converging nature to refine the proposed solutions and to test them with final users [4]. The "Dark Horse" prototype has been proposed to provide a diverging prototyping cycle in the NPD process; it explicitly calls for the exploration of different ideas that would not be explored in that stage of the development process [5,6].

Bushnell et al. [7] assess the impact of the "Dark Horse" prototype on the final solution in a qualitative way. Thus there is still need for more quantitative analyses. The goal of this

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paper is to analyse the role of the “Dark Horse” divergent prototype on the final design solution and on the design process, specifically how the level of radical innovation influences the quality and nature of the project output.

The paper is structured in six sections. Section 2 provides a state-of-the-art literature review. In Section 3, the research approach is presented. Sections 4 and 5 present the data analysis and the results discussion. The conclusion and an outlook on further research needs are discussed in Section 6.

2. Literature review

2.1. New product development

Design is the process of creation in which specific tools are applied to invent artefacts and institutions, and as society and its demands evolve, so does the ability to employ design [8]. Enhanced manufacturing capabilities must be paired with better product development performance [2,9] creating more efficient processes [2].

Over the years, a wide range of design methods have emerged, some mainly following structured processes, including stage-gate [10] and concurrent engineering [11,12]. The stage-gate process ensures a disciplined approach to product development and provides a roadmap for controlling the design activity [10]. Stage-gates are based on structured processes [2,13–15], and on concepts from business process management [16] and lean manufacturing [17]. Concurrent engineering considers the parallel product and manufacturing process development, as development activities are executed simultaneously in teams [2,11,18,19].

More flexible, user-centric approaches have also been proposed, such as Design Thinking [2], which requires designers to examine the problem from different perspectives [2,3,20]. DT processes suggest that teams go through iterative cycles of empathy generation, problem definition, idea generation, prototyping, and user testing to develop a solution [21]. Solution-finding is based on divergent and convergent thinking, related to finding an answer to a question. Its intent is to uncover new possibilities and to open new pathways to exploration of the problem [22].

Many authors consider that prototypes offer a way to work with converging and diverging thinking [20,23,24]. They also provide the means to share the concepts with users. However, the influence (and how to measure the influence) of different prototypes on the final design result has not been thoroughly examined in the literature.

2.2. Prototyping types

Different kinds of prototypes may be considered, depending on the purpose, the focus, and the project phase [25–27]. The focus of the prototyping activity may cover a range of aspects including functionality, integration, assembly, and appearance [28,29].

A prototype may be classified into different categories. Considering the nature of the product and the prototype, it can be physical or virtual [30,31]. Considering the intended objective of the prototype, it can focus on the explicit purpose of the prototype (learning, evaluation, communication) or the users [32,33]. Considering the prototypes fidelity, it can fully represent the product function and appearance, or it may only examine a subset of the final idea [28]. Also, considering the stage in the development process, a prototype may represent the output from a diverging or converging design activity [4,6].

Considering the stage of development, the diverging phase includes the prototypes responsible for exploring the problem space, gathering requirements from the users and translating it into product requirements. Examples of divergent prototyping include “Design space exploration”, which explores the experiences from the users and designers regarding the problem [4].

On the other hand, the converging phase contains the prototypes for exploring the solution space providing relevant insights for the solution design and perfecting the functions until the final solution [4]. Examples of convergent prototyping include “Funky prototype” and “Part X prototype”. “Funky prototype” provides clear impacts on the functions to be developed albeit in a “funky” or rough-hewn way. “Part X prototype” focuses on a discrete component or subsystem within the overall solution concept and manufactures that to fully functional level, suitable for incorporation in the final completed prototype.

Therefore, there is a clear connection between the different stages of prototype development which ultimately lead to the final design solution. The diverging stages help generate ideas that are later refined and perfected during the converging stages. However, in between the diverging and converging phases, it has been hypothesized that it might be beneficial for teams to investigate “previously unexplored and potentially risky” concepts [2,7], an activity which has been termed the “Dark Horse” prototyping stage. The title of this prototype is borrowed from the world of horse racing. Conventionally, a “Dark Horse” refers to a contender who is little known and believed to be unlikely to succeed. However, if such a contender has an unexpectedly good performance, the payoff will be relatively huge [4,6,34]. The concept and term was initially formulated in 1999 by Stanford Professor Mark Cutkosky and later became part of the Stanford ME310 design engineering program [34].

2.3. Evolution of SUGAR and Dark Horse prototype (DH)

SUGAR is a global network of higher education institutions which run design innovation programs. Those institutions have graduate courses based on year-long Product Development projects typically comprising one-third to one half of the credits for a Master’s degree. Students enrolled in SUGAR projects work in interdisciplinary teams comprising participants from two international partner universities on complex engineering product design briefs, proposed and funded by a sponsoring company. SUGAR courses are based on pedagogy and innovation processes developed and applied in the ME310 design course at Stanford University.

In SUGAR projects, all student teams follow the same DT process (Figure 1) from defining design requirements to constructing functional prototypes that are ready for user testing and technical evaluation [35].

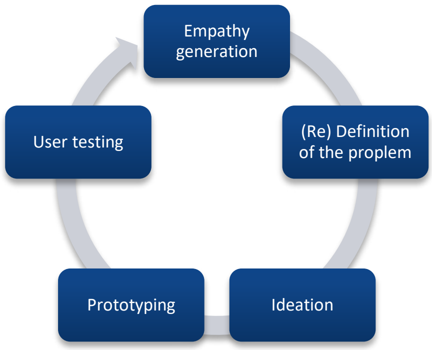


Figure 1: DT process [36]

Over the course of the program, a number of prototypes, including the "Dark Horse", are developed [34]. During the "Dark Horse" phase, teams are encouraged to revisit previous ideas that may have been rejected for not being feasible, or too high-risk. In so doing, the activity encourages radical innovation and gives designers the permission to think bigger and more creatively [6]. Therefore, the "Dark Horse" phase consistently results in the generation of interesting and innovative concepts, evaluated through physical prototyping and user testing. However, at present, the benefits of the "Dark Horse" phase have not been extensively analysed. While Bushnell et al. [4] propose an initial discussion about the reasons why this type of prototype positively impacts design innovation, this aspect of the design cycle has not yet been studied in a quantifiable way.

3. Methodology

3.1. Data gathering

This study investigated the role of the "Dark Horse" prototyping phase in 59 design projects, undertaken over a period of six years, through the SUGAR design program, as well as in a local capstone design course that follows the same project approach and phases as SUGAR projects.

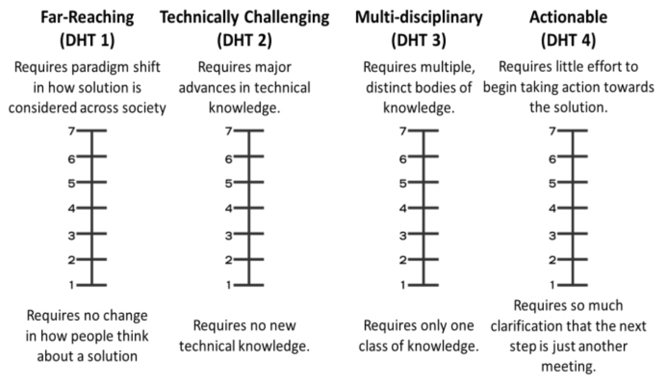
Among the 59 projects, 43 were developed in Brazil and 16 were developed in Ireland. In total, 13 projects were developed in global environments and 46 were developed in local (country - level) environments. All cases involved engagement with an industrial sponsor that assigned the project prompt and regularly liaised with the team throughout the module. Each team was typically made up of between 4-8 team members, with global teams generally having 3-4 students per partner university team.

Several classifications were made based on the type of the project, observed engagement of industrial sponsor, final prototype grade and the degree to which the "Dark Horse" was perceived to influence the final direction of the project. The employed categories are shown in Table 1.

Table 1: Collected parameters from the projects

	Collected parameters	Possible answer
1.	**Nature of the team**	Local/Global
2.	**Sponsor engagement**	(1-3) {poor/good/excellent}
3.	**Cohesion with global partners**	(1-3) {poor/good/excellent}
4.	**Overall prototype grade**	(1-100)
5.	**How "Dark Horse" effected final prototype**	(1-3) {not at all/ a little/ a lot}

The DARPA Hard Test (DHT) was used to determine an innovative score for each "Dark Horse" prototype. The DHT was a test used at DARPA to evaluate the breakthrough potential of a technology and has since been adopted as an innovation tool for team-based projects [37]. The DHT is



composed of four ordinal measurement scales (1-7), each one corresponding to a different dimension of innovation (Figure 2).

Figure 2: DARPA Hard Test scales of innovation [37]

3.2. Research Questions

The primary aim of the research was to investigate if there is evidence that innovative "Dark Horse" prototypes lead to tangible changes in project direction and/or a better overall final concept. The following two research questions were posed to explore these hypotheses:

1. *"Do projects that involve radically innovative DH prototypes result in better overall final concepts?"*
2. *"Are radically innovative DH prototypes more likely to result in significant changes to the final solution?"*

It was also hypothesized that due to challenges in communication associated with remote collaboration, global project teams may produce less innovative "Dark Horse" prototypes and may also be less likely to carry findings from "Dark Horse" through to the final solution. In response, the following two research questions were posed:

3. *"Does international collaboration influence how radical the DH solutions are?"*

4. *"Does international collaboration influence the probability of DH representation in the final prototype?"*

Finally, it was postulated that company liaisons might be more resistive to radical changes in the project direction, resulting in less innovative "Dark Horse" prototypes among teams where company engagement was high. The following research question was posed:

5. *"Does intense company engagement influence the degree of radical innovation in the DH prototype?"*

4. Results

First, the degree to which the "Dark Horse" prototype influenced the project direction was examined. This involved comparing the working concept before the "Dark Horse" phase, as described in formal documentation submitted as part of the module, with the final concept, as described in another formal document. Also, for each of the projects examined, the DARPA Hard Test (DHT) was applied to determine an innovative score (4 levels) for each "Dark Horse" prototype. To ensure consistency of assessment across all projects considered, all scores were determined by consensus involving the same two researchers who were involved in this activity. The researchers chosen collectively possessed first-hand prior experience of all projects that were examined. The degree to which the project changed direction was classified into three levels ("no effect", "significant effect", "major effect"). It was found that the "Dark Horse" led to a measurable change in project direction for 67% of the projects tested. A bar chart showing the effect of the "Dark Horse" prototype on the direction of the projects is presented in Figure 3.

A Fishers exact test was performed to investigate if the make-up of teams (local or global) significantly affected the adoption of factors from the "Dark Horse" into the final design solution (two levels: no effect, significant or major effect). This analysis showed significance at ($p<0.01$), indicating that international collaboration has an effect on the utilisation of findings from the "Dark Horse" phase.

A Chi-square test with Yeates' continuity correction was performed to investigate if there was a significant effect between the change in project direction (as a result of the "Dark Horse" prototype) and the engagement of the sponsor company. There was no significance found at the $p<0.05$ level between the three conditions.

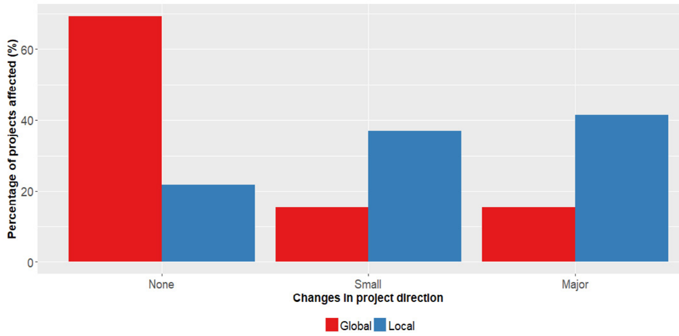


Figure 3: Changes in project direction after "Dark Horse" prototyping phase

Considering the DARPA Hard Test parameters, it was possible to infer that 58% of the projects presented high level actionable prototypes, and 25% high level technically challenging ideas. However, only 10% of the ideas were highly multidisciplinary and 13% represented a paradigm shifting. Boxplots summarizing the outputs of this test are given in figure 4.

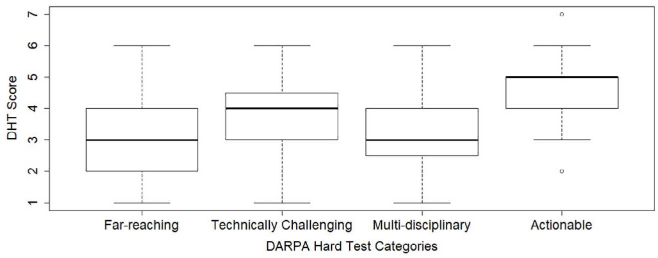


Figure 4: Boxplots indicating the results of applying the DARPA Hard Test

An ordinal logistic regression analysis was performed to investigate if there was a correlation between changes in project direction after the "Dark Horse" period and the innovative level of "Dark Horse" prototypes (for each of the DHT dimensions) or the make-up of teams (local/global). The dependent variable was the observed effect that the "Dark Horse" had on project direction measured across three ordinal levels ("no observed effect", "significant effect", "major effect"). The predictors were scores in the DHT (low/high) and the type of team (local/global). In this analysis, the data from Brazilian and Irish projects was pooled to provide the greatest possible sample size.

There was a significant effect of DARPA Hard Test #2 ('technically challenging') and change in project direction at the 95% confidence interval ($p=0.042$). Post-hoc examination of the data indicated that the proportional odds assumption was valid. This finding suggests that for a one unit increase in DHT #2 (i.e. moving from low to high innovation index) the odds of observing either a "significant" or "major" effect versus "no effect" are 20% greater ($OR=0.2$), given that all the other variables in the model are held constant. There was no significant effect between scores in DARPA Hard Test dimensions #1/#3/#4 and changes in project direction. Similarly, there was no significant effect between changes in project direction and team make-up.

For each dimension of the DHT, an independent-samples t-test was conducted to compare final overall grades in low and high "Dark Horse" innovation level conditions. To best account for differences in variances and sample sizes, the Welch two sample t-tests were used. The "Dark Horse" innovation level was considered 'low' if the DHT score was between 1-4 and high if it was between 5 and 7. Since the grading criteria for the final prototypes were slightly different for Brazilian and Irish projects, the analysis was performed separately on the data from both sets of projects. Boxplots summarizing the grades from Dark Horse prototypes in Brazil and Ireland are given in Figure 5 and Figure 6 respectively.

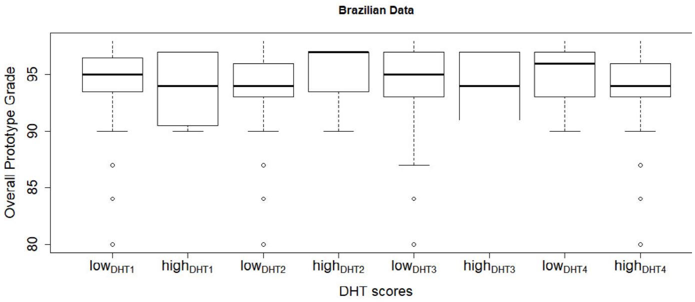


Figure 5: Boxplot DH grades in Brazil

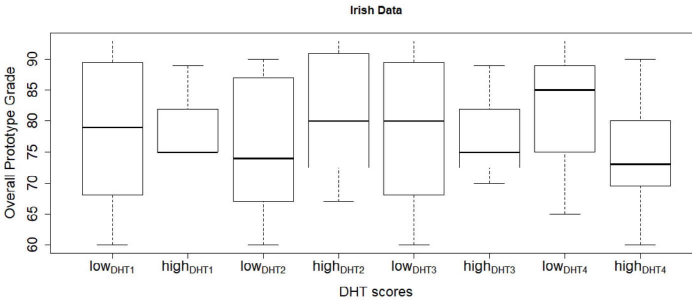


Figure 6: Boxplot DH grades in Ireland

For all tests performed using data from the Brazilian projects, there was not a significant effect of "Dark Horse" innovation level and overall grade at the $p<0.05$ level for the two conditions. Similarly, for all tests performed using data from the Irish projects, there was not a significant effect of "Dark Horse" innovation level and overall grade at the $p<0.05$ level for the two conditions. The results of this analysis are presented in table 2.

Table 2: Results from t-tests performed to investigate the relationship between the innovation level of the "Dark Horse" prototype (low/high) and final prototype grade (0-100).

	DARPA Hard Test Score			
	Low	**High**	**t**	**df**
DHT 1 (Brazil)	93.87 (4.04)	93.75 (3.77)	0.059	3.947
DHT 2 (Brazil)	93.57 (4.14)	95.00 (3.10)	-1.011	12.004
DHT 3 (Brazil)	93.84 (4.01)	94.00 (4.24)	-0.049	1.111
DHT 4 (Brazil)	94.91 (2.678478)	93.30 (4.44598)	1.336	32.144
DHT 1 (Ire)	78.25 (12.04)	78.50 (7)	0.050	9.359
DHT 2 (Ire)	75.75 (11.229)	80.87 (10.39832)	-0.947	13.919
DHT 3 (Ire)	78.66 (11.81)	77.250 (8.18)	0.265	7.621
DHT 4 (Ire)	81.22 (10.92)	74.57 (10.11)	1.259	13.498

Note. * = $p < .05$, *** = $p < .001$. Standard Deviations appear in parentheses below means.

5. Discussion

5.1. Does the "Dark Horse" phase lead to tangible changes in project direction and/or a better overall final concept?

Based on the assessed data, there is no correlation between how innovative DH prototypes are and the grades of the final prototype (either in Brazil or in Ireland).

There is not a statistically significant link between how far-reaching, actionable, multi-disciplinary a DH prototype is and the likelihood of carrying it thorough to final concept stage.

There is a statistically significant link between how technically innovative a DH prototype is and the likelihood of carrying it thorough to final concept stage. As an example, a particular project presented a challenge to "imagine the future of human-robot communication". A key requirement identified was that the robot should be capable of representing internal states through the expression of emotions. The dark horse prototype explored the use of advanced holographic displays. The final prototype used two independent LCD screens mounted in a plastic 'head' – the upper screen being used for the eyes and the lower for the mouth. The dark horse prototype was graded as 6/7 for technical challenge, and the concept was represented to a moderate degree in the final prototype – while holograms were not used, the emotions were represented in a similar visual manner using the LCD screens.

5.2. Does team make-up influence the value of the "Dark Horse" phase?

There seems to be a strong correlation between the likelihood of using findings from DH and the team make-up. It would seem that global teams are significantly less likely to use findings from DH phase than local teams. That might be related to communication issues. While local teams typically have weekly face-to-face meetings, global teams usually have only two in - person, week - long working sessions, relying mostly on online meetings during the project.

There is not a statistically significant link between team make-up and any of the DHT dimensions.

5.3. Does sponsor engagement affect the likelihood of adopting findings from "Dark Horse" phase?

There does not seem to be an effect of how engaged the sponsor is and how likely a team will be to carry forward findings from DH prototype.

"Dark Horse" prototypes lead to tangible changes in project direction and/or a better overall final concept.

The radical level of the "Dark Horse" prototype does not affect the final results of the project - whether the DH concept is represented in the final concept or not. This situation pertains in both Ireland and Brazil. Further work must include an analysis in the final grades methodology of the capstone design courses. For that, it is recommended to analyse the final results according to the DARPA Hard Test and compare the evolution of the results.

Second, the technically challenging level is likely to result in changes on the final solution ($p<0.05$) while the nature of the team, the far-reaching level, the multidisciplinary level, and the actionable level do not affect the final result. As both Brazilian and Irish institutions are engineering schools, these results might represent a bias towards technically challenging prototypes over far-reaching or multidisciplinary ones. Therefore, it is recommended to study the implications of the DH in different types of institutions.

6. Conclusion and further research

This paper analyses the "Dark Horse" prototype impact on the final design project based on data gathered from 59 design projects developed in Brazil and Ireland.

Results suggest that technically challenging "Dark Horse" prototypes are more likely to influence the final project solution. Additionally, results indicate that global projects generate more radical DH prototypes, and that sponsor engagement and cohesion with the global partner do not have statistical significance for the innovation level of the DH. Another important result is that the grades of the final project are not related with the innovation level of the DH, This might be related with the conduction of the project and the grading methodology adopted by the partners.

By focusing on quantitative analyses, this paper presents an additional research step related to the adoption of the "Dark Horse" prototype concept in development projects. However, the analysis has several limitations. The data analysed was based on a limited set of projects from only two institutions. Moreover, the projects analysed cover a range of six years, during which the institutions' design know-how has evolved. Even considering those limitations, the paper offers a first quantitative discussion on the impact of the DH prototypes.

As future research opportunities, the authors suggest an analysis of the radical innovation level of the final prototype – through DARPA Hart Test. Moreover, there is an opportunity to extend this study for different institutions. Finally, the quantitative approach could be complemented by qualitative data to explore the impact of the "Dark Horse" on team dynamics.

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