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Technology and Tactics as Dimensions of Design: Explicit Representation of User Actions in the Product Design Space

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ABSTRACT

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The initial phases of the design process – including interactions with stakeholders, ideation of concept candidates, and the selection of the best candidates — have a large impact on the success of a project as a whole. Much of the value generated during these phases comes from the designers' exploration of the design space as they create concepts for the final solution. Unfortunately, an entire dimension of the design space is often ignored during the initial phases of the design process – the tactics dimension. Engineers tend to emphasize the design of technology in their work, while paying less attention to how that technology is used. By adding tactics to technology as two dimensions of the design space and creating the Tech/Tac plot as a means for visualizing those dimensions, the designer's ability to visualize, understand, and explore an expanded design space is improved. In this paper, we introduce a deliberate design-space structure that can help teams generate and evaluate integrated Tech/Tac concepts. The structure improves concept exploration during the early phases of the design process by harnessing the information provided by a two-dimensional, structured design space. This design space is represented here as a vector space with a basis of technology and tactics. Also presented are definitions and principles that facilitate the use of the technology-tactics framework to represent the design space in various useful ways. Six tests were carried out during this research to develop and evaluate the structure. The final instantiation of the concepts presented in this paper has been shown to be meaningful to design teams during ideation.

Keywords: design space exploration, ideation effectiveness, technology, tactics, Technology-tactics plot, bi-objective

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NOMENCLATURE

n	The number of dimensions of the concept-performance space
d	The number of design variables considered for the concept-performance space
p	The number of performance objectives considered for the concept-performance space
S_0	The existing solution, or the solution that the user will continue to employ if the design team does nothing
$\Delta Tech$	The magnitude of change, at a conceptual level, between S_0 and a concept in the set in terms of technology
ΔTac	The magnitude of change, at a conceptual level, between S_0 and a concept in the set in terms of tactics
M_{Tech}	The maximum tech, or the upper bound on the $\Delta Tech$ axis, which is defined as the point where the change in the technology has become so great that the team doesn't have the capability to develop it
M_{Tac}	The maximum tac, or the upper bound on the ΔTac axis, which is defined as the value where the tactics have changed so much that the user wouldn't consider adopting the solution
l	The concept index
j	The index for elements in level k
k	The level number, where the lowest (most detailed) level is k=1 and levels increase. In this paper, detail-level is $k = 1$, embodiment level is $k = 2$ and principle is $k = 3$.
k_{max}	The maximum level number
$\vec{A}_l$	The vector describing concept l
x_l	The absolute x coordinate of concept l
y_l	The absolute y coordinate of concept l
x_0	The absolute x coordinate of S_0
y_0	The absolute y coordinate of S_0
x_{up}	The upper bound on the x-axis
y_{up}	The upper bound on the y-axis
N	The total novelty score of a concept set
N_l	The novelty score of concept l
N_{kl}	The novelty score of the element in level k that belongs to concept l
E_{kj}	Element number j at level k of the tree. Element ordering at a given level is arbitrary.
B_{kj}	The branch variety score for E_{kj}
$w_{V,k}$	The novelty weighting of level k
S_{kj}	The sibling variety score for E_{kj}
D_{kj}	The descendant variety score for E_{kj}
C_{kj}	The set of element indices for all children of the parent of E_{kj}
$n(C_{kj})$	the size of the set C_{kj}; the number of children of the parent of element E_{kj}
β	A constant that ensures the sibling variety converges for large values of $n(C_{kj})$. In this paper, $\beta = 0.7$.
c_{kj}	The set of element indices for all children of element E_{kj}
$n(c_{kj})$	the size of the set c_{kj}; the number of children of element E_{kj}
A_{kj}	The allocated variety score for E_{kj}
P_{kj}	The parent variety score for E_{kj}
p_{kj}	The index j for the parent element of E_{kj}

V	The total variety score of a concept set
Q	The total quantity of a concept set

CHAPTER 1. INTRODUCTION

Many product concepts involve both technology (the physical equipment, device or software utilized to achieve an outcome) and tactics (the sequence of steps that employ technology to achieve an outcome as executed by a user, system or machine). In these concepts, there is significant room for creative design in both the technology or tactics of the product. However, when generating concepts, engineers tend to emphasize the development of technology over the development of tactics, while designers in other fields may emphasize the tactics over the technology. Emphasizing one aspect of the product can limit opportunities for further concept exploration and cause teams to end their ideation with large portions of the design space unexplored.

Tech/Tac (Technology and Tactics) is a theory designed to better enable designers to consider a wider design space during the design process. By enabling designers to consider these two aspects of their design in tandem, we may be able to increase the value of concept sets produced during ideation, improve problem solving during design, and enable greater understanding of users and their approach to solving problems. This thesis emphasizes the value of Tech/Tac during the ideation phases of the design process as well as presenting a Tech/Tac tool to assist designers in their application of Tech/Tac in their work.

This research is built on the following premises:

- Good ideation results in better final products
- It is desirable to increase the Novelty, Variety and Quantity of a set of concepts
- It is desirable to create design tools that make using the Tech/Tac framework accessible and valuable to designers.

The purpose of this research is to develop a framework that enables designers to develop tactics alongside technology during the ideation phase of the design process. The framework is based upon existing product design methodology, and is made useful to design teams by way of the

Tech/Tac plot, a tool that enables design teams to visualize and explore the design space in terms of technology and tactics. The second chapter of this thesis is the published paper "Technology and Tactics as Dimensions of Design: Explicit Representation of User Actions in the Product Design Space". The paper introduces the Tech/Tac framework and plot in sections 2.1 through 2.3, and investigates the impact of the plot in terms of the novelty, variety and quantity of the concept sets resulting from ideation, as well as feedback from teams using the tool in section 2.4.

Though this paper emphasizes the use of Tech/Tac during ideation, the paper also serves as the foundation for using Tech/Tac throughout the entire design process, and continuing research into further applications should be pursued. Chapter 3 of this thesis is a discussion of the limitations of this work and recommendations for future research, as well as a collection of Tech/Tac plots produced by the design teams and other relevant data from the experiments performed.

CHAPTER 2. TECHNOLOGY AND TACTICS PAPER

This chapter presents the theory and empirical findings that resulted from this research. The content of this chapter was submitted, as it is written here, to the ASME Journal of Mechanical Design. A prior paper on the same topic was published as part of the IDETC conference proceedings in 2019 as ”The Technology/Tactics (TEC/TAC) Plot: Explicit Representation of User Actions in the Product Design Space.”

2.1 Introduction

An early step in the design process is ideation. Its goal is to produce a set of candidate concepts from which a final concept will be chosen and developed into a final product. Because the selected concept will be chosen from the set of concepts generated during ideation, ideation effectiveness is of high importance during the design process [1].

Many concepts involve both technology and tactics. Technology is defined as the physical equipment, device or software utilized to achieve an outcome, while tactics are the sequence of steps that employ technology to achieve an outcome as executed by a user, system or machine. In generating concepts, engineers tend to emphasize the development of technology over the development of tactics. This can limit opportunities for further concept exploration and cause teams to end their ideation with large portions of the design space unexplored. *Examining the aspects of technology and tactics in tandem* (Tech/Tac) during ideation may combat this tendency as designers take advantage of an expanded design space.

When seeking to improve ideation effectiveness, two significant evaluations often occur: 1) The evaluation of the concept set, and 2) the evaluation of individual concepts within the set. Shah [2] presented a widely-cited method for evaluating the effectiveness of the ideation phase by examining the quantity, variety, novelty, and quality of a resultant concept set within a design space. A design space is defined as the set of all possible concepts that feasibly meet the objectives and constraints of the project, and ideation can be thought of as exploring the design space by identifying diverse concepts that lie within it. Improving the resulting concept set in terms of the measures identified by Shah is a major goal of this research. We will specifically show that the addition of tactics to the design space was useful in increasing the quantity, variety and novelty of several initial concept sets in an experiment. The quality of the concepts within the set is not evaluated in this paper.

It is worth noting that the concept set that results from ideation is a subset of the design space, as the design space contains all possible solutions. Also, the design space is commonly represented only theoretically or amorphously in most ideation methods, since the actual limits of the design space are not known precisely in the early phases of the design process. When the design space is represented graphically, concepts in the concept set are often represented as points in the design space. If the point locations are specifically defined by measurable aspects of each concept, the design space can be structured as a vector space. As such, the quantity of points represents the quantity of concepts in the set, and the distribution of point locations within the design space represents variety within the concept set. Importantly, such a structured design space, coupled with metrics for evaluating a concept set, can guide the design team during ideation to deliberately pursue greater quantity or variety in sparsely populated regions of the design space.

While the amorphous design space can be so structured by any pertinent coordinate system, such as orthogonal axes of cost versus mass, some coordinate systems may positively influence the ideation process more than others. In this paper, we present a particular two-dimensional vector space called the Technology/Tactics Space that can be represented by a *Tech/Tac plot*, that has been found useful in exploring the design space during the ideation process, resulting in greater quantity, novelty and variety in the final concept set.

As shown in this paper, at least 9 different design space plots involving technology and tactics can be used to guide and evaluate ideation. These different plots consider various perspectives such as differentiation in technology versus differentiation in tactics relative to a current solution, technology development cost versus tactics development cost, development team skill to develop new technology versus new tactics, and more.

To be clear, this paper combines two well-accepted philosophies into one approach that can enhance design space exploration. Specifically, we combine (i) the philosophy of characterizing ideation effectiveness graphically with a design space and by using metrics such as quantity, variety, novelty, and quality [2] with (ii) the philosophy that there is innovation potential in both the product itself and in how it is used [3]. Set in the early phases of the design process, this combination of philosophies encourages teams to plot the concept set on two orthogonal axes; the technology differentiation axis and the tactics differentiation axis. Importantly, we find that this approach helps teams explicitly ideate on user tactics at the same time they are ideating on the technology. Such an approach recognizes the existence of both technology and tactics, and promotes their co-development while helping prevent their conflation.

2.1.1 Literature Survey

The addition of tactics as a second dimension of the design space can be deemed as valuable if it enables the design team to pursue certain principles identified in literature. An overview of those principles is provided in this section.

Evaluation of Concept Sets

Many researchers work to better understand the outcome of ideation [2,4,5] as opposed to the process of ideation [2]. These researchers have produced many indicators that can be used to evaluate the desirability of an entire concept set, as well as to guide the design team as they create the set. Some of the most used evaluation metrics are quantity of concepts in the set and variety of concepts across the set [2,6]. Other metrics include *solution density*, describing the number of concepts considered within the design space [7] and *expansion*, which describes the degree to which the team expanded the feasible design space by considering concepts that are perceived to be impossible or infeasible [2]. Generally, the desired state is that all of these indicators be maximized, though there currently exists no measure to quantitatively determine if any of these indicators are sufficiently maximized.

Evaluation of Individual Concepts

When considering how individual concepts can be evaluated, some of the metrics used to evaluate the concept set do not apply, and other metrics are needed. Shah proposed *novelty* to evaluate how unusual or unexpected an idea is when compared to other ideas already in existence and *quality* to evaluate how well an idea is expected to meet the needs of the user [2]. Many researchers proposed evaluating the creativity of individual candidates with dimensions of creativity including *workability* and *relevance* to distinguish candidates [8, 9]. Others described creativity in terms of *usefulness* and *rarity* [10–13].

While concept creativity is not the focus of this paper, it is considered by many researchers and practitioners to be a characteristic of optimal solutions [14,15]. Therefore, in this paper, *novelty* will be used to evaluate the presence of creative solutions in the candidate set as one indication that ideation has been effective.

Some researchers have proposed a graphical method to examine individual concepts, similar to the graphical representation of the design space used to evaluate concept sets – a *concept performance space.* Mahdavi, for instance, proposed an n-dimensional concept-performance space, where the size of the space is $n = d + p$, and d is the number of design variables that define a concept, while p is the number of performance objectives that concept is designed to meet [16]. Romer proposed a number of performance objectives for use in the field of wireless sensor design including *mobility* and *deployment* [17]. Such performance objectives can be considered sub-dimensions of the quality metric for the concept set, and while they are frequently used for convergent purposes, they are also useful for determining if further ideation is necessary.

From the literature, we see various measures associated with evaluating design teams or concept sets during the ideation phase of the design process [18]. The current paper examines the *variety, novelty* and *quantity* of the concept sets to evaluate ideation effectiveness. *Quality*, though an important measure, is not examined in this paper. The principles presented in this paper are designed to improve the concept set in each of these areas by encouraging teams to explore and expand the design space as well as increasing the density of concepts within the feasible design space.

The remainder of this paper is laid out as follows: Section 2.2 presents theoretical developments of Tech/Tac analysis, followed by recommended process for building and analyzing Tech/Tac plots in Section 2.3. Empirical findings from six experiments used to test the feasibility and usefulness of Tech/Tac plots during ideation are presented in Section 2.4. Conclusions are presented in Section 2.5.

2.2 Theoretical Developments

In this section, we consider tactics as a useful dimension for design and introduce the Tech/Tac plot as a means of developing technology and tactics in tandem.

2.2.1 Tactics as a Dimension of Design

Tactics are the sequence of steps followed to use a product and achieve an outcome. This paper is concerned with designs that have a significant interaction of technology and tactics. This includes the vast majority of all products humans interact with (e.g. vehicles, furniture, computers, tools, machinery, robots, etc). While both tactics and technology evolve throughout the design process through various stages of detail, only technology has traditionally evolved as an artifact of design, progressing from a vague idea to annotated sketches, 3D models and, at the end of the project, a design package [19]. It is important to note, however, that tactics exist in every case, if only implied. These tactics drive, to a large extent, the design of the technology as well as its success in achieving design outcomes.

The explicit examination of tactics results in many opportunities to create new concepts and improve the concept set [20, 21]. For example, new technologies could be found that better enable the tactic, or new tactics might be found that require new technologies. Additionally, several different tactics can produce different outcomes using a given technology, and vice-versa. A desired outcome may be achieved by using an existing technology in a new way, or a concept with a feasible technology may be found to use an infeasible or undesirable tactic. If the technology is found to be undesirable or infeasible, new tactics could be generated to make the concept a reasonable option. This also creates the opportunity for tactics to be ideated first, and the technology enabling the tactic added second. When design teams focus only on the technology in the solution concept, they are unknowingly creating tactics they will not perceive, thus restricting their ability to explore the design space in a meaningful way.

2.2.2 Distinguishing Between Technology and Tactics

To examine technology and tactics effectively, the team must be able to distinguish between a concept's technology and its tactics. To assist teams with this we propose the use of control

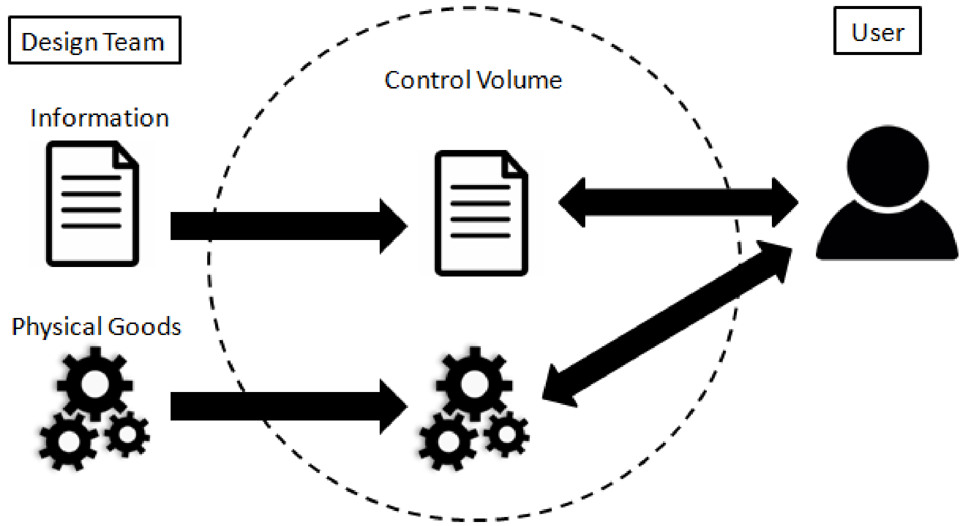

Figure 2.1: Control Volumes in Solution Delivery: all aspects of a given solution must be passed through the boundary by the design team (at a cost) to become accessible by the user (also at a cost)

volumes, which are generally used in thermodynamics and elsewhere to simplify the evaluation of complex systems [22].

We define the control volume to contain everything the design team sends to the user at the end of the design process. For example, the control volume for an engineered product may contain some equipment (Technology) and, whether explicit or not, the actions required to use the equipment (Tactics). Relative to the control volume, this means that the design team works to transition information and physical goods across the control volume boundary, while the user crosses the boundary to acquire or access what the team delivered. This idea is illustrated in Fig. 2.1, where the dashed line represents the control volume boundary.

One reason why control volumes are meaningful to Tech/Tac is that they clarify how a concept is different from what the user is already using or doing. Specifically, changes in the contents of the control volume indicate whether a concept has just a technology difference, just a tactics difference, or both. Establishing what is different (technology and/or tactics) is essential in building the Tech/Tac plot described later in this paper. When a team wishes to place a concept on the Tech/Tac plot, the team should ask:

- Does new technology need to be delivered to the user for them to implement this concept? In other words, does this concept require the user to have technology they don't currently have? If so, new technology crosses the control volume boundary.

- Do new tactics need to be delivered to the user for them to implement this solution? In other words, does the user have to follow a different process with respect to existing or new technology to accomplish the desired task? If so, new tactics cross the control volume boundary.

In this paper, the control volume is defined by what is delivered to the end user – not what is delivered to management or the manufacturer (i.e. the contents of the control volume will be different than the deliverables of the design project). This is helpful in clearing up confusion about what information or physical goods are crossing the boundary.

Importantly, there is a cost associated with crossing the boundary of the control volume. To develop a concept into a solution and make it available to the user, the design team must pay the cost of developing, testing, and shipping the product, which in the context of control volumes means a cost (in terms of time, money, and skill) to transition technology across the control volume boundary. The user will also pay a cost to cross the boundary and access the designed solution, or a cost (in terms of time, money, and skill) to acquire and learn to use the new technology within the control volume. This cost associated with crossing the boundary is an essential basis for the variations of the Tech/Tac plot described later in this paper.

2.2.3 The Technology-Tactics Plot

The Technology/Tactics plot (Tech/Tac plot) provides a view of the design space from the perspective of technology and tactics aspects found in each concept in the space. An example of a Tech/Tac plot is shown in Fig. 2.2. In the plot, each point represents a concept, and is plotted based on the magnitude of the differentiation each concept represents, in terms of tactics (ΔTac) and technology ($\Delta Tech$), from the existing solution (S_0). Also represented on the plot is the *feasible design space*, or the portion of the full design space that contains feasible solutions. Note that in this paper, "*feasible*" refers to whether the design team and user will be able to implement the design given their resources. Technical feasibility is included under these terms. The feasible

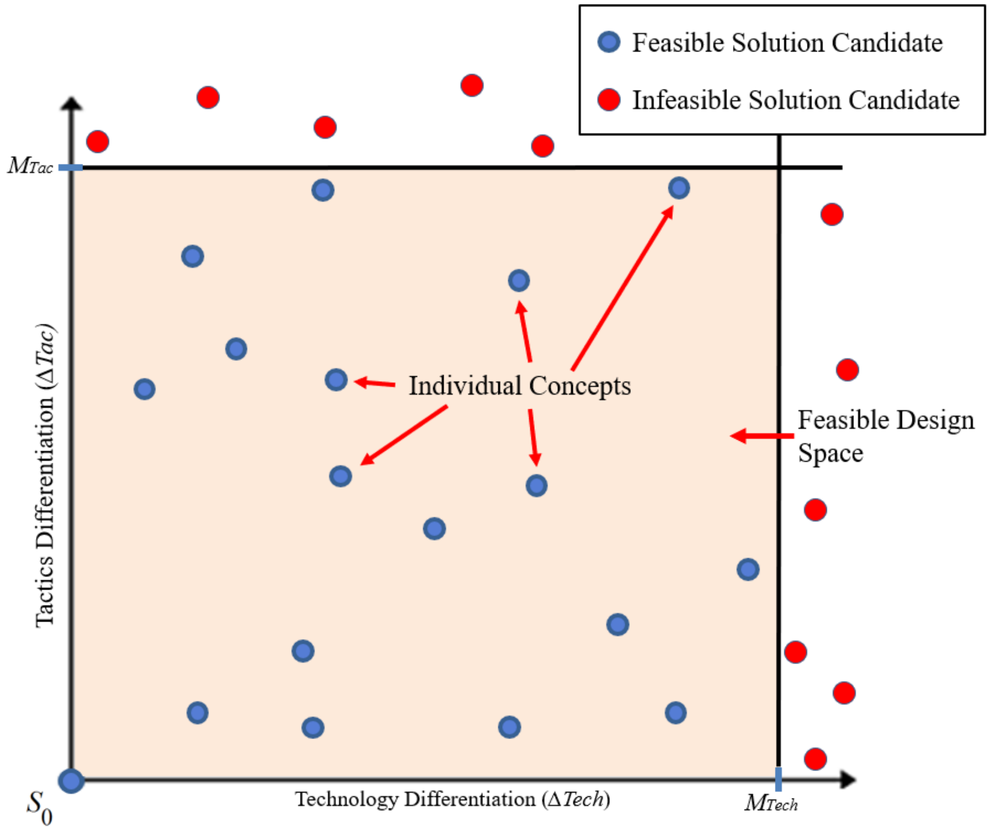

Figure 2.2: The Tech/Tac plot

design space is bounded by the *x* and *y* axes, as any "difference" is represented as a positive value, and an upper bound on both ΔTac and $\Delta Tech$. The upper bound on $\Delta Tech$ represents the point at which greater differences in technology aren't feasible given the design team's resources. The upper bound on ΔTac represents the point at which the user can no longer be expected to adopt greater differences in the tactics of the solution. Several other variations of the plot axes, which depending on the goals of the design team may be more useful visualizations, are considered later in this paper.

The significant elements of a Tech/Tac plot can be summarized as:

- S_0: The Existing Solution, or the solution the user will continue to employ if the design team does nothing
- $\Delta Tech$: The magnitude of differentiation, at a conceptual level, between S_0 and a concept in the set in terms of technology

Figure 2.3: The Design Space represented by Technology differentiation only

- ΔTac: The magnitude of differentiation, at a conceptual level, between S_0 and a concept in the set in terms of tactics
- M_{Tech}: The Maximum Tech, or the upper bound on the $\Delta Tech$ axis, which is defined as the point where the differentiation in the technology has become so great that the team doesn't have the capability to develop it
- M_{Tac}: The Maximum Tac, or the upper bound on the ΔTac axis, which is defined as the point where the tactics are so different that the user wouldn't consider adopting the solution

An example of building the Tech/Tac plot demonstrates the added visibility granted by considering tactics together with technology as two dimensions of design. If we imagine a design team that is viewing each of their ideas in terms of technology only, we can represent their concept set by plotting each concept as a point within their space. In this case, each would be plotted in terms of a difference in the technology from an existing solution ($\Delta Tech$). This is shown in Fig. 2.3. Using this representation of the design space, we see that the team has been following the objectives of coverage, exploration, and expansion noted previously. Using this visualization, however, it is difficult to identify portions of the design space with opportunity for deeper exploration, and a team using this view might end the ideation phase at this point. However, each of the concepts shown in Fig. 2.3 will have a tactics aspect, even if it isn't represented on the plot.

If we add "differentiation in tactics" as a second dimension on the plot, the result is the plot shown in Fig. 2.4, where each point in Fig. 2.3 was, in fact, a projection of a point from this 2-dimensional (2D) space onto the x axis. The 2D plot increases the level of detail the design team is able to see in the design space. In this case, it reveals that the concept set has not yet reached the upper limit of the tactics axis. It also shows significant differences between two points that are near each other in Fig. 2.3.

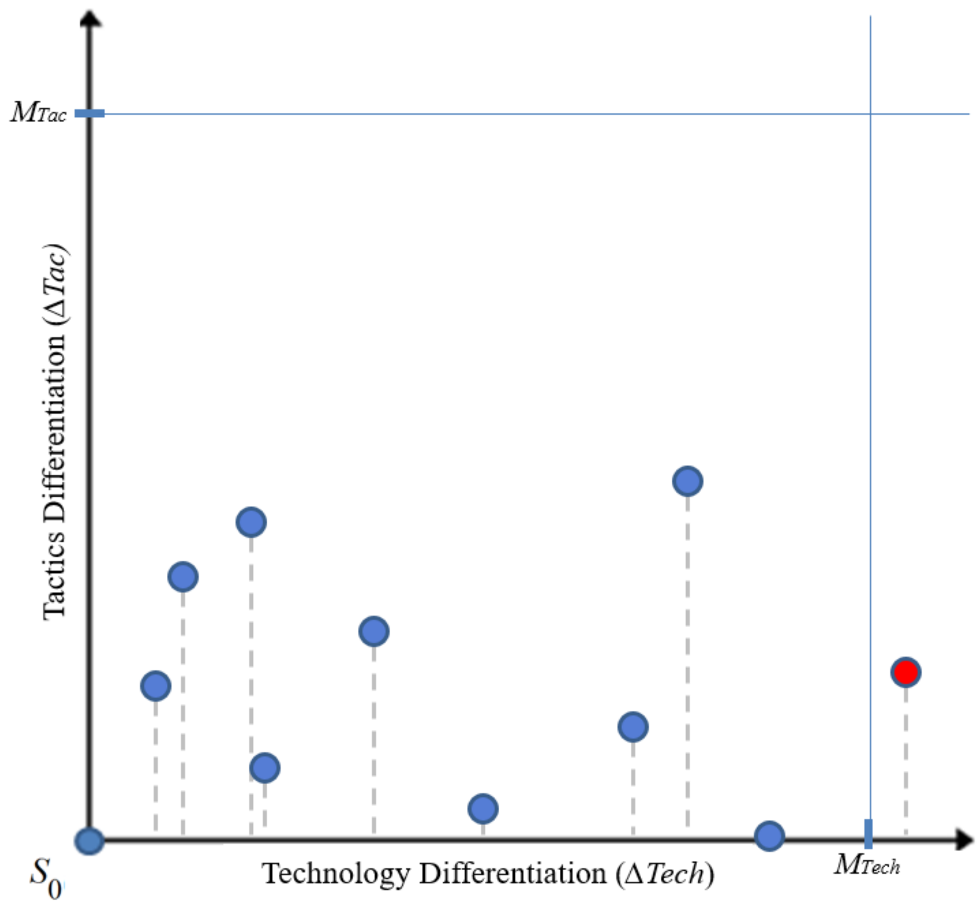

Figure 2.4: The Design Space represented by Technology and Tactics differentiation

Once the concept set has been represented in the Tech/Tac plot, the Tech/Tac plot will show where in the design space sufficient ideation has occurred and where more ideation is desirable. The team can also determine if their concept set has expanded out to the limits of the design space or if there is opportunity for further expansion. This guides the team to locations in the design space needing more detailed exploration.

The Tech/Tac Plot as the Full Design Space

The Tech/Tac plot can represent the full feasible design space when it is modeled as a vector space with the following characteristic: each unique concept has a unique location in the design space, which is located by a vector beginning at the origin. When modeled in this way, it follows that a vector basis would exist for this design space, requiring one or more measurable qualities that can be attributed to each of the concepts in the set. The number of unique qualities chosen for the basis establishes the geometric dimension of the vector space.

For this paper, differentiation in technology and differentiation in tactics are suitable qualities for a vector basis, as they can be reasonably established for each of the concepts in the set, and are meaningful during ideation. In fact, we believe that these two vectors span the entire design space. To justify this, we adopt the philosophy of "Jobs to be Done" [20]. Under this philosophy, the design process starts with a problem to solve (termed: job to be done). To accomplish the job to be done, there are two areas of potential focus: (i) improve the tools/product/hardware to do the job (technology), and (ii) improve the way people use the technology to do the job (tactics). No third option is immediately apparent. We can summarize the proposition in this way:

- Principle 1: Any difference in the actions of the user with regard to the job to be done constitutes a tactics differentiation.
- Principle 2: Any difference in the equipment utilized by the user with regard to the job to be done constitutes a technology differentiation.
- Principle 3: If the actions of the user with regard to the job to be done are held perfectly constant, the only option for differentiation with regard to the job to be done must be a technology differentiation, and vice-versa.

When these three principles are true, any difference with regard to the job to be done will be a tactics differentiation, a technology differentiation, or a combination of both.

Generalization of the Origin

The Tech/Tac plot requires the establishment of an origin. Up to this point, we have considered the origin to be the existing solution (S_0), located at (0,0). But this can be stated more generally as being located at (x_0 , y_0), which may or may not be at $x_0 = 0$ and $y_0 = 0$.

Whether stated generally or not, the origin establishes a baseline for characterizing the differentiation in technology and differentiation in tactics that define the Tech/Tac plot. As such, any point on the Tech/Tac plot is defined by the vector A_i, where

$$\vec{A_i} = (x_i - x_0) + (y_i - y_0) \;\; \forall \;\; x_0 \leq x_i \leq x_{up}, y_0 \leq y_i \leq y_{up} \tag{2.1}$$

where i represents the i-th concept, and x_{up} and y_{up} are the upper limits of x and y, respectively.

2.2.4 Three Different Perspectives on Tech/Tac Plots

We have so far considered the Tech/Tac plot from the perspective of differentiation in technology ($\Delta Tech$) and differentiation in tactics (ΔTac) beyond an existing solution. We can refer to that perspective as the "Relative Difference Perspective." This is the general perspective from which the Tech/Tac plot is created.

There are, however, at least two other perspectives that from which Tech/Tac plots can be used in a meaningful way during the design process; using them (i) to characterize the anticipated development costs or benefits for each concept, and (ii) to characterize the anticipated costs or benefits for users to acquire and learn to use the concept under consideration. In brief, three different perspectives are considered in this paper:

1. Relative Difference Plots
2. Design Team-Centric Plots
3. User-Centric Plots

By considering team- and user-centric Tech/Tac plots, the design team can benefit in two ways. First, the team can evaluate the quantity and variety of the concepts in the set. Second, the team can impose meaningful upper limits on the space in terms of maximum development costs or maximum development times, for example. Such limits capture what the design team can accomplish based on the resources they and/or the user are willing to invest. Any solution candidates that fall beyond this upper resource limit can be discarded.

Relative Difference Plot (General Tech/Tac Plot)

The value of the general Tech/Tac plot (Fig. 2.5) is its simplicity. The plot can be used generically and relatively, without defining a specific calculation for differentiation in technology and differentiation in tactics. This lends itself to divergent thinking early in the design process, because very little needs to be known about a concept in order to place it on a relative difference plot. Concepts can be added to the plot easily, and the meaning of each concept's location within

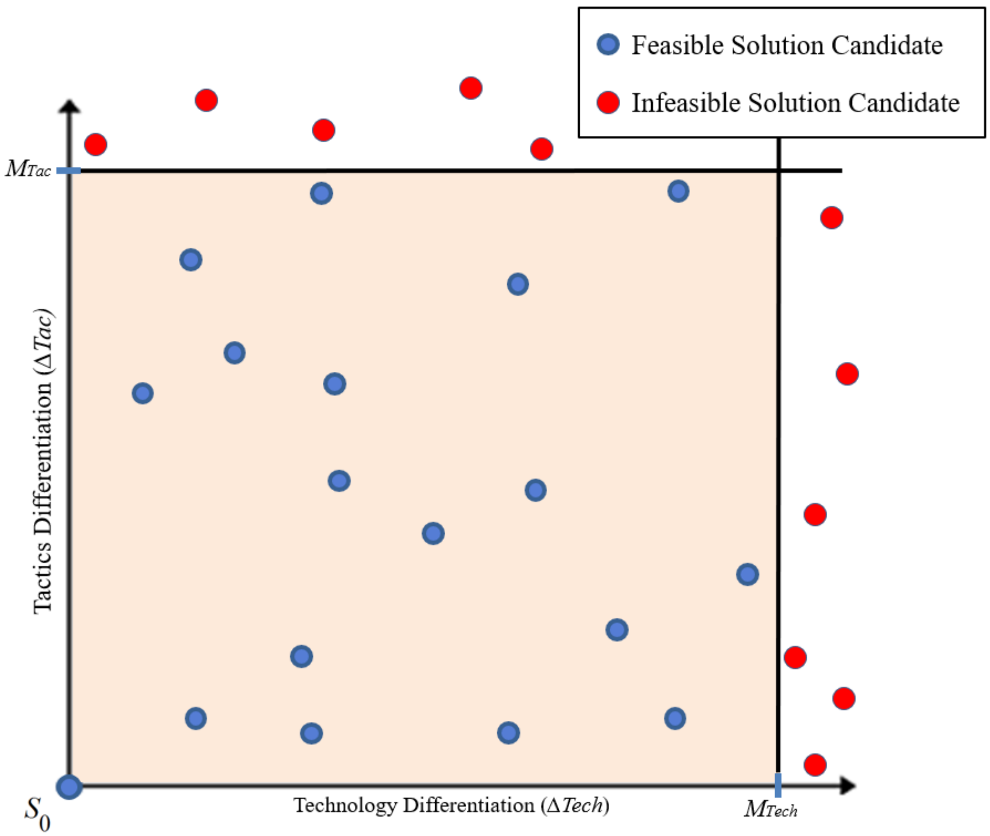

Figure 2.5: The Relative Difference Plot, with an outer boundary marking the point where differentiation of the concepts from S_0 become too extreme, though some infeasible concepts still exist inside the boundary based on other criteria

the plot grows as more concepts are added. This simple plot helps teams identify where in the design space additional exploration maybe beneficial.

A challenge associated with the general Tech/Tac plot is that the upper and lower limits are more difficult to define than the limits of the user-centric and design team-centric Tech/Tac plots, which characterize financial cost and/or time cost. Additionally, it should be noted that no plot on its own captures all relevant information. The limits can only note the value, in terms of the axes, beyond which no more concepts would be feasible. They do not account for other factors that may cause concepts to be infeasible, even though they are feasible relative to bounds of that plot. For example, the team-centric plots may show that a concept can be completed given the design team's resources, but costs incurred by the user is not specified, so some concepts well within the design team's constraints may still be infeasible due to other factors.

When establishing upper limits on differentiation in technology and differentiation in tactics, it is possible to define a limit where the market will no longer accept a solution because it is too different from what they are used to. Lower limits on differentiation in technology and differentiation in tactics may also be possible; the client who commissions or funds the development is likely to have expectations regarding a minimum level of change or differentiation beyond existing solutions. Setting meaningful limits on any of the variations requires significant understanding of the design problem. For example, limits can be established through critical interactions with stakeholders where these limits can be discussed and explored. Goodson et al. discuss recent attempts by students and faculty to establish and use such limits in funded senior design projects [23].

The Design Team-Centric Tech/Tac Plots

Design team-centric plots illustrate which concepts are feasible for the team to develop given limited development resources. Three resources that commonly restrict feasibility are development time, money, and skill required.

A generic design team-centric financial cost plot is shown in Fig. 2.6. This plot evaluates concepts with respect to the financial cost to develop them. This cost plot focuses exclusively on the design team and their budget for the project.

While upper limits can be added on this plot at the maximum technology development budget and maximum tactics development budget for the project. In some special cases, the limit curve will be a line defined by (*Tactics cost*) + (*Technology cost*) = Max Budget, as shown in Fig. 2.7.

Additional team-centric plots include time to develop and skill to develop each concept. The time plot is analogous to the financial plot in its structure and use – substituting time to develop for financial cost to develop.

The skill plot focuses on plotting concepts relative to the abilities of the team in terms of development skill. This Tech/Tac plot allows the team to explicitly evaluate how well the concept set is evolving relative to what the team actually has skills to further develop. This plot can be used to encourage the team to both push the limits of their skills and pull wild ideas into the realm of feasibility.

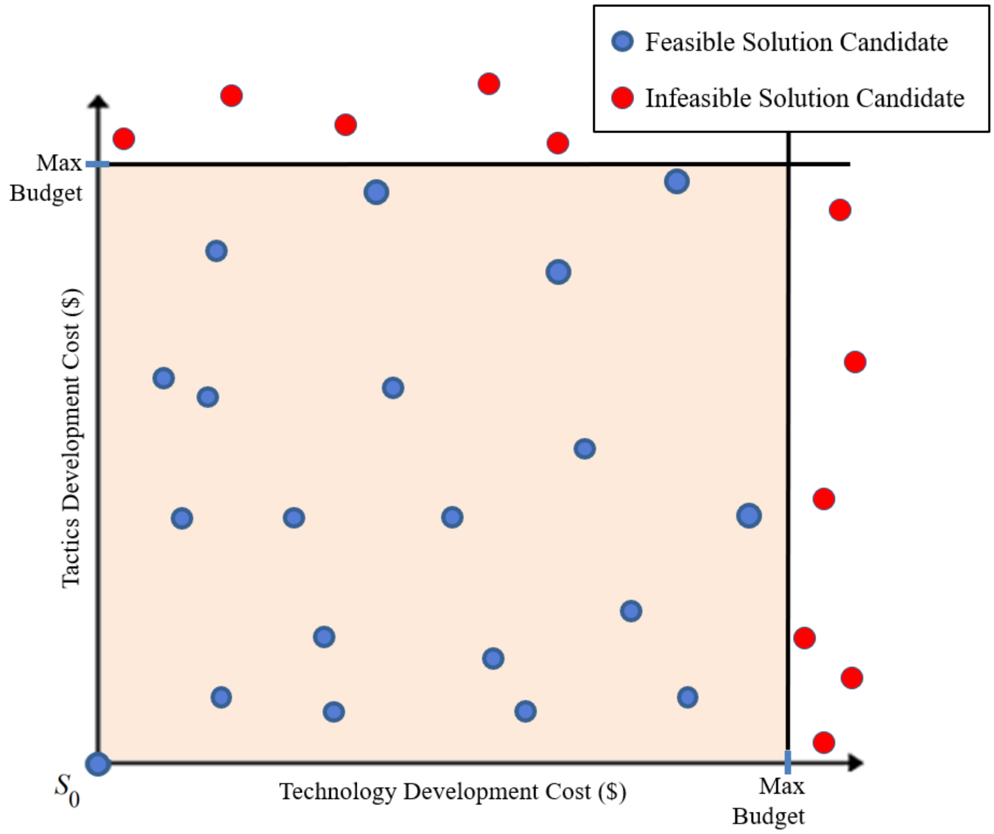

Figure 2.6: The Design Team-Centric Financial Cost Plot: Upper limits based on point where concepts become too costly for the design team to pursue

The User-Centric Tech/Tac Plots

As concepts emerge during the ideation process, each one places a burden on the user in some way. These are the costs associated with the user accessing material in the control volume. We include a set of user-centric plots on the following basis:

- Principle 1: Time, money and skill to cross the control volume boundary is likely different for users than for development teams
- Principle 2: The costs imposed by a solution on a user in terms of time, money and skill influences the desirability of a solution
- Principle 3: Design decisions influence a solution's imposed costs to the user's time, money and skill

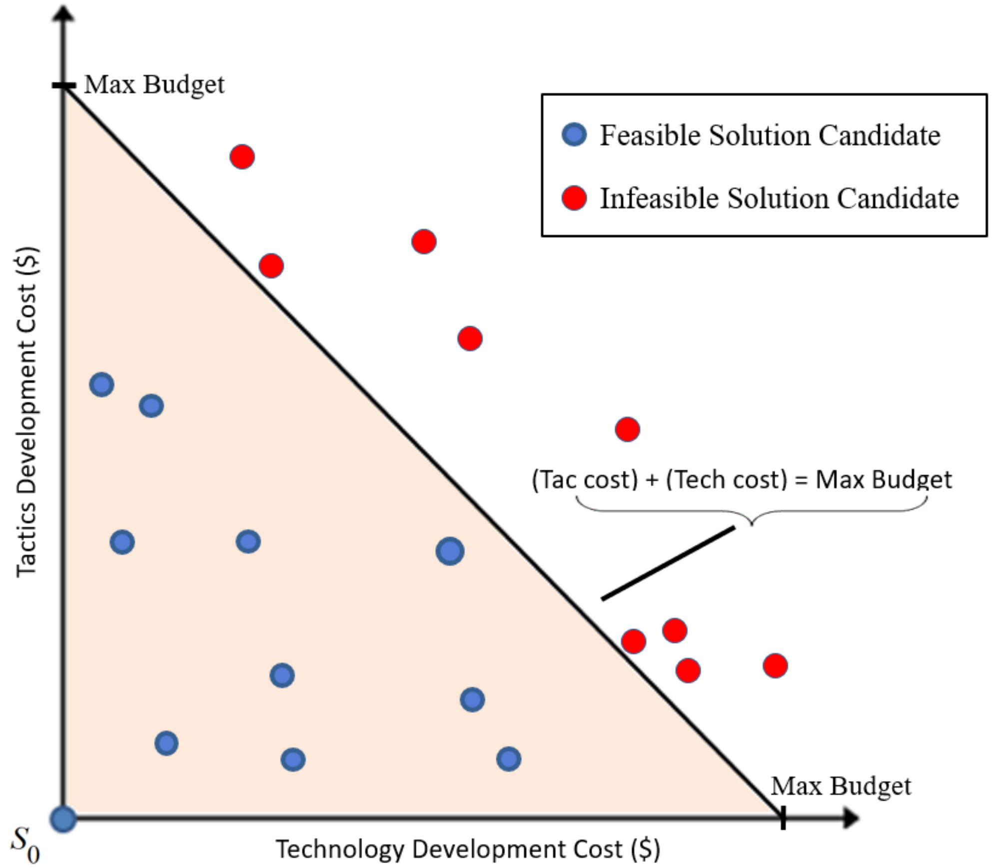

Figure 2.7: The Linear Limit Case: High cost of developing more complex Tactics means less money available for Technology development

- Principle 4: It is essential for development teams to consider the design space from the consumer's perspective [24–26]

When evaluating concepts relative to the user's burden, the team can ask: what costs will be incurred by the user to acquire, access, or learn how to use the final product resulting from this concept? Analogous to the design team perspective, these costs can also be broken down into financial cost, time, and skill.

From the user's perspective, financial costs can include cost to purchase the technology, costs to train people on using the new technology, or other financial costs related to implementing a new technical system. The burden associated with time can include the learning curve for users to become proficient with the new tactic. The skills required by the user can simply be an assessment of what the design team expects the users to do; is the user expected to adjust or fine tune the system

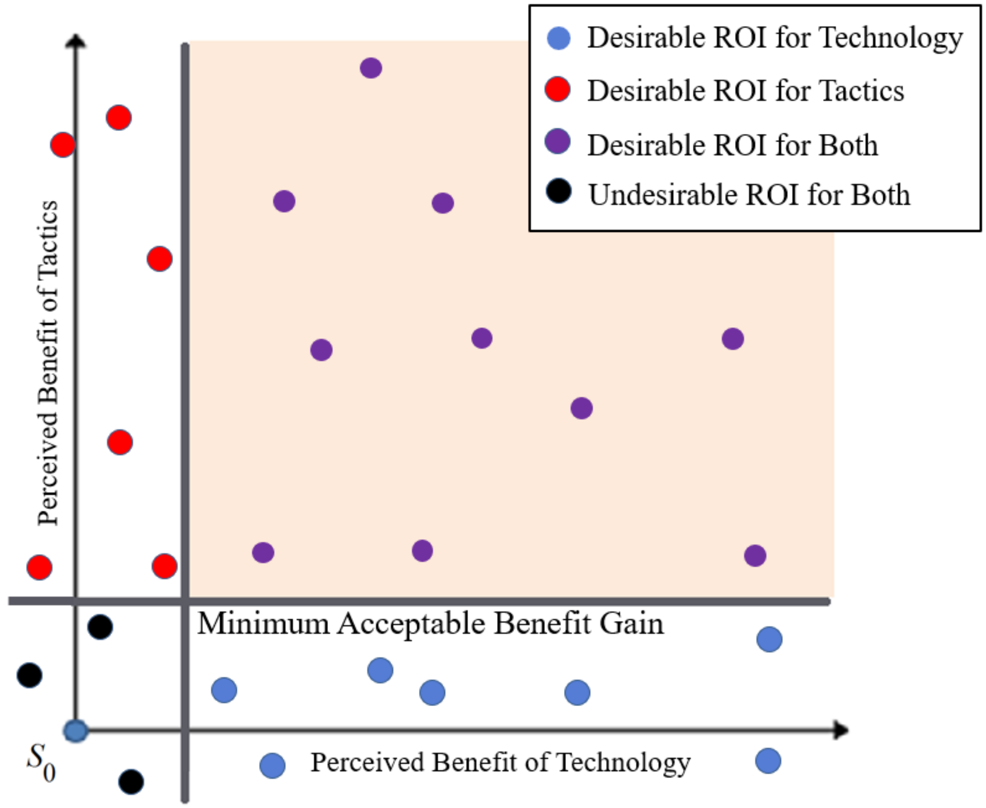

Figure 2.8: Design Team-Centric Benefit-Added Plot: Concepts that provide high benefits to the design team in terms of Return on Investment (ROI) from the technology or tactics aspects of the solution are marked, as well as solutions that have a desirable ROI in both categories or in neither. Note the bounds on the plot are lower bounds in this case. No upper bound has been found

to their environment; is the user expected to have skill in a particular field of knowledge such as machine maintenance or deploying a missile? Setting the limits of user-centric plots requires teams to investigate and understand the user, including their skills and resources. This is likely essential to finding solutions the user will adopt.

The user-centric plots appear identical in structure to the design team plots, with one exception: S_0 is less likely to be located at (0,0). Where there is likely no development cost associated with allowing the existing solution to continue, there is always a cost (in time, money, or skill) to the user to employ any solution. This means the S_0 will likely be non-zero. The space below and left of S_0 in this case is valuable, as it shows solutions that will reduce the user's costs.

There is one additional type of Tech/Tac plot that will be mentioned here but not developed or discussed deeply, as it is the focus of a different work by the authors. It is a benefit added plot, as illustrated in Fig. 2.8.

The benefit-added plot illustrates the perceived benefit of technology innovation and the perceived benefit of tactics innovation to the user or to the design team. As concepts are placed on the benefit plot, the team can evaluate if the concept set is appropriately focusing on what users would find beneficial, or on innovations that may have particular benefit to the design team.

A total of 9 specific Tech/Tac plots have now been introduced. They are:

- The general (relative difference) Tech/Tac plot
- The financial cost to develop Tech/Tac plot
- The time to develop Tech/Tac plot
- The skill required to develop Tech/Tac plot
- The perceived benefit to the design team Tech/Tac plot
- The financial cost for users to acquire or learn to use the new product Tech/Tac plot
- The time for users to acquire or learn to use the new product Tech/Tac plot
- The skill for users to acquire or learn to use the new product Tech/Tac plot
- The perceived benefit to the user Tech/Tac plot

It is not necessary that all of these plot types be considered to ideate, or to evaluate the effectiveness of the ideation process, but these and others may be considered if the team deems it valuable to do so.

2.3 Placing Concepts On Tech/Tac Plots and Using Them For Exploration

In this section, we provide a process by which a design team explores the design space, in that it discovers the size and content of the feasible design space. We recommend that this process be adapted to fit the desired fidelity of the design space analysis. To plot individual concepts and explore the design space:

1. Generate a set of concepts for the design problem at hand. No specific ideation process is recommended here.

2. Begin the evaluation process by choosing which perspective will be used. The options are (i) relative difference perspective, (ii) design team perspective, and (iii) user perspective.

3. Establish S_0, which is the existing solution (or the solution that will be pursued if no development is done). It is useful to articulate what technology and what tactics are associated with S_0.

4. Choose whether S_0 will be located at the origin (0,0) or another point in the design space. (Refer to the section on user-centric plots)

5. Establish Tech/Tac plot limits, if there are any. These limits are likely to be discovered through interactions with project stakeholders.

6. Evaluate each concept relative to S_0 and the Tech/Tac plot limits using the evaluation perspective chosen in (2) above. For example, if the relative difference perspective is chosen in (2), then explicitly evaluate how different the concept is from S_0 in terms of technology and tactics. If it is similar, place it near S_0 on the Tech/Tac plot. If it is dissimilar, place it far from S_0. If concepts are deemed to be infeasible relative to the perspective chosen in (2), place them beyond the limits established in (5). Repeat this process for all perspectives chosen in (2). This could result in as few as 1 or as many as 9 Tech/Tac plots.

7. Search for empty space on the plot(s). Consider new tactics or technologies for nearby concepts and consider where these should be placed on the plot as new concepts. Over time, this may fill the empty areas.

8. If desired, transfer feasibility information from the development team perspective and/or the user perspective to the relative difference plot by indicating which points in the relative difference plot are feasible across all perspectives and which are not.

9. Choose ideation metrics to use in the evaluation of the concept set, and evaluate it. A common choice is to consider the quantity, variety, novelty, and quality of the concept set.

10. Use the evaluation results of (8 and 9) to decide if additional ideation is needed, and where in the design space improved quantity, variety, novelty, or quality are needed.

11. Repeat steps 1-10 until the results of the ideation process are satisfactory.

During the exploration process, it is valuable to keep in mind two truths. The first is that there are boundaries to concept feasibility, and the full set of concepts within those boundaries constitute the feasible design space. The second truth is that there are boundaries to the *explored space*. One goal of the exploration process is to expand the explored space until it meets or exceeds the feasible space. Often it is necessary to exceed the feasible boundaries in order to identify where those boundaries are. When the exploration process begins, the team is likely to have only a vague understanding of the feasible boundaries. As the exploration process proceeds, a clearer understanding of the feasible boundaries begins to emerge.

To illustrate this, consider the feasible design space shown in Fig. 2.9. Notice the presence of S_0 and the feasible boundary in the plot. As the ideation process begins, the design team generates concepts without a certain knowledge of the feasible boundary, resulting in concepts that may be inside or outside the feasible space. Imagine that the ideation process results in Fig. 2.10.

As the team evaluates each concept in this set, relative to feasibility, three scenarios occur. (i) all concepts are infeasible (this is unlikely), (ii) all concepts are feasible, or preferably (iii) a portion of the concepts are feasible and a portion are infeasible.

Under the preferred scenario (iii), the exploration process begins to define the feasible boundaries. Under scenarios (i) and (ii), the team's understanding of the feasible boundary is not improving. For scenario (i), the team should generate solutions that are more similar to S_0. For scenario (ii), depicted in Fig. 2.11, the team needs to expand the explored space by generating additional concepts that are more distinct from S_0.

While the feasible design space is generally fixed by the constraints of the project, and therefore unchanging during the design process, the explored design space is generally growing as the team adds to the concept set. If the design team develops a good understanding of the feasible design space boundaries, it will be able to declare with greater confidence that the quantity, variety, novelty, and quality of the concept set is sufficient.

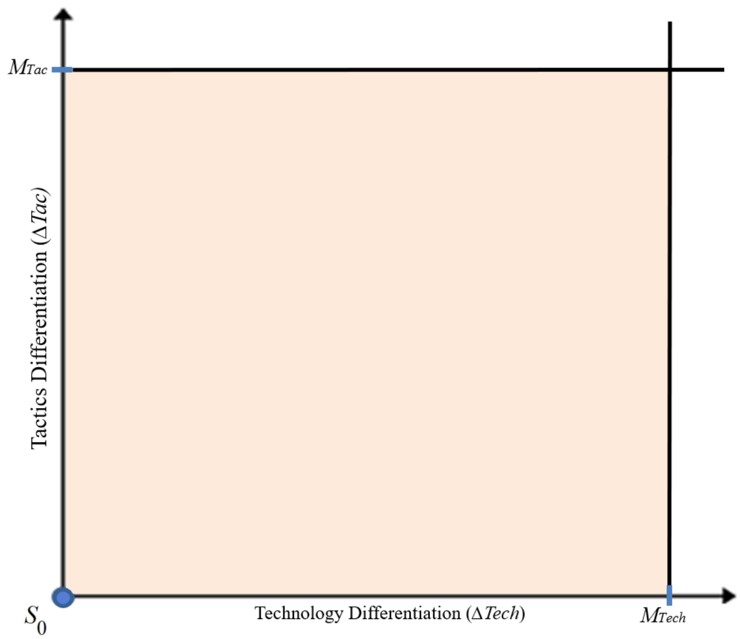

Figure 2.9: The Feasible Design Space on a Tech/Tac Plot: The actual placement of the upper bound will depend on the basis of the plot

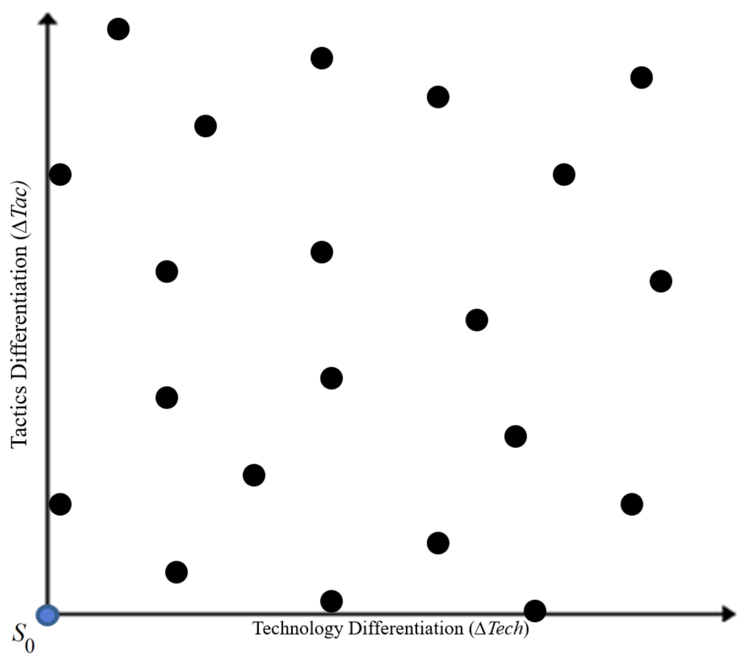

Figure 2.10: A Sample Candidate Set: Note that in this representation, the set appears to fill the entire design space

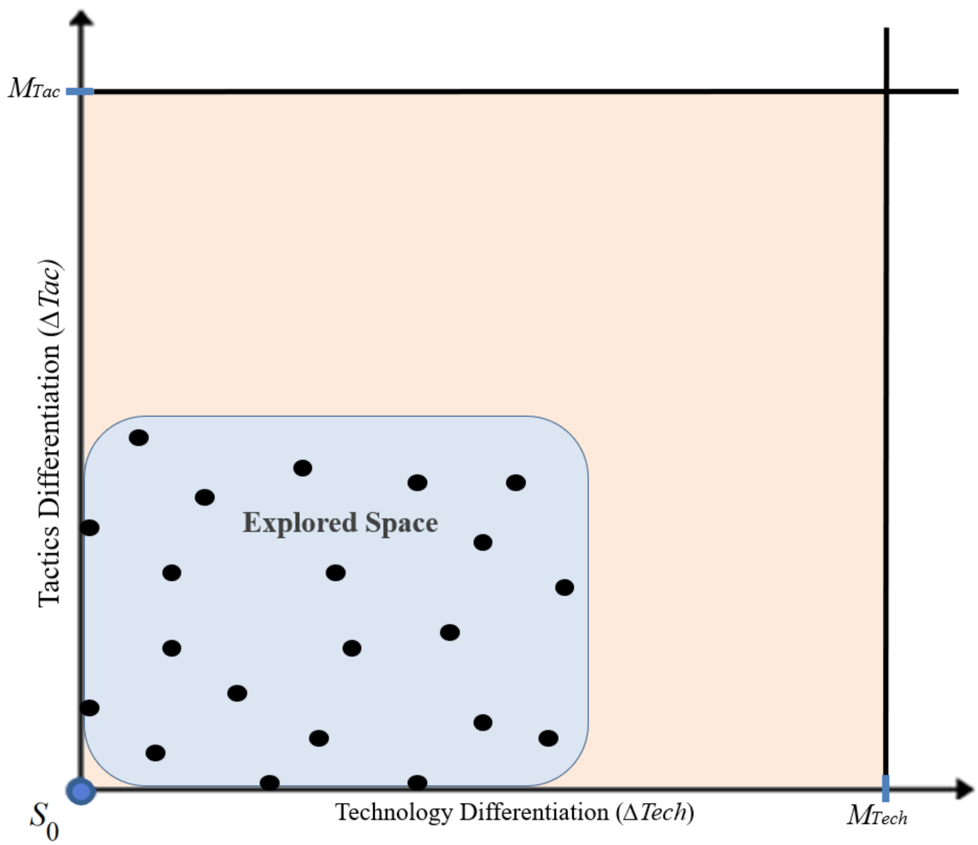

Figure 2.11: The Explored Design Space, which in this case only fills a portion of the entire design space. Discovery of the actual upper bound on the space reveals empty space we can explore

2.4 Empirical Findings

Six tests engaging a total of 36 teams were used to develop the Tech/Tac plot and ultimately evaluate the performance of the teams during divergent concept generation, in terms of the variety, novelty and quantity scores of the Tech/Tac plots they created. This section contains the experimental process, as well as our method for evaluating the resulting concept sets from these experiments and the key findings from that evaluation.

2.4.1 Experimental Process

The six experiments performed in this research examined the effectiveness of using Tech/Tac plots to increase the novelty, variety and quantity of concept sets. The experiments also examined to what degree the principles of Tech/Tac can be understood and applied by designers to build meaningful Tech/Tac plots.

All experiments were carried out with student design teams. The following process was used to engage each team.

1. Introduction of general information and the design prompt
2. Round 1: Initial ideation session using any means (10-15 minutes)
3. Introduction of the principles of Tech/Tac and plot
4. Creation of Tech/Tac plots by the teams using the concepts created in round 1, identification of empty space on the plot (10 minutes)
5. Round 2: Teams ideate with the goal of filling empty spaces in their Tech/Tac plot (10-15 minutes)
6. Closing and gathering of feedback from participants

After engaging with design teams and collecting data, the research team evaluated the data following this general process:

1. Count concepts from round 1 and 2 to find the quantity of the set after each round.

2. Create OPED trees (see section 2.4.2) from concept descriptions, evaluate total variety and allocated variety (see section 2.4.2).

3. Identify judges to evaluate novelty, randomize concept descriptions under each objective and give to judges for evaluation (see section 2.4.2). Gather novelty ratings from judges, reorganize concepts and find total novelty and concept novelty scores.

4. Superimpose individual concept novelty and allocated variety scores over images of Tech/Tac plots and OPED trees. Use scores together with qualitative analysis of resulting Tech/Tac plots to find impact of Tech/Tac on the revised concept set and the additional individual concepts produced.

5. Examine participant feedback for information regarding the quality of the team discussion, changes in concepts examined, impact of encouraging discussion past slowing ideation in round 1, etc.

Two tests involved senior mechanical engineering cadets at the US Air Force Academy, and four tests involved students at Brigham Young University in mixed disciplines and at various levels of college education; many were graduate students. Observations during the experiments were recorded, and the resulting concept descriptions and Tech/Tac plots after round 1 and round 2 were recorded for analysis. These experiments were carried out at different points during the research and drove the evolution of the theory described in this paper.

2.4.2 Novelty and Variety Metrics

In order to evaluate the novelty and variety of the concept sets resulting from each experiment, metrics for novelty and variety were established that are applicable to both technology and tactics. These metrics apply the principles presented by Shah [2], but new developments were needed to transition Shah's technology-centric calculations to capture both technology and tactics. The full variety metric is presented in a paper by the authors, and is included as Appendix E, but an overview is provided here.

OPED Model

The novelty and variety metrics are both based on what we call the OPED model (which stands for Objective, Principle, Embodiment, Detail). The model organizes the concepts of a set into a tree structure that groups similar concepts together based on the four levels of objective, principle, embodiment and detail. The levels are defined as:

- Objective: The desired outcome driving the ideation, that on its own describes the benefit provided by any design in the set to the user or customer. (e.g. Decrease spread of disease at airports). This should be common to all concepts in the set.

- Principle: The intended outcome of a design that describes the means of accomplishing the objective. This should fill in the blank in the sentence, "In principle, our design does _____" (e.g. Separate healthy and sick people)

- Embodiment: The wireframe description of the process tools that will bring about the intended outcome (e.g. Physical barrier between seats on the airplane)

- Detail: Any information in the concept description that isn't needed to understand how the principle is achieved, but adds additional information about the design that may make it more desirable or feasible (e.g. Barrier automatically expands between seats if sneeze is detected)

An example tree formed using the OPED model is shown in Fig. 2.12. This model highlights similarities and distinctions between concepts in the set, which are needed to evaluate Variety and Novelty. Under this representation, a full branch from principle to detail represents a concept. For example, a concept description written by this team suggested scaring deer away from a garden (principle) with a loud sound (embodiment) which will be motion-triggered (detail). Some concepts have only principle- and embodiment-level elements.

Novelty Evaluation

Novelty is a measure of how unusual or unexpected an idea is as compared to other ideas already in existence [2]. The metric we created to evaluate the novelty of concepts therefore requires understanding of what exists in the relevant field. Once the OPED tree is built, judges

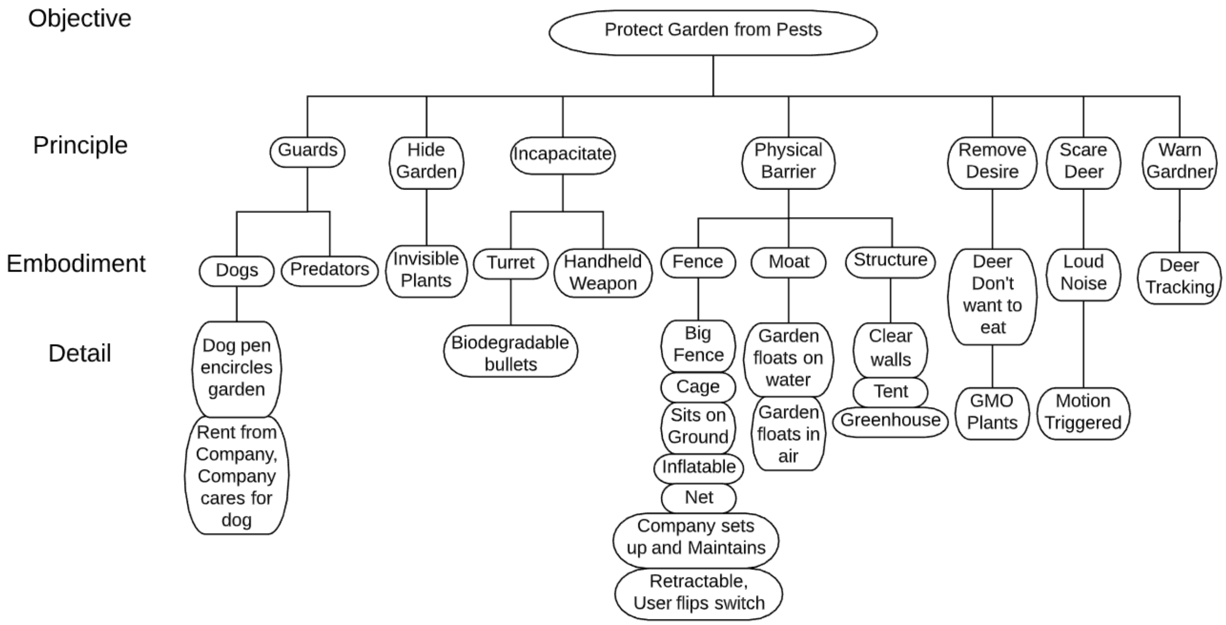

Figure 2.12: An OPED tree, built from the concept tree of Garden Team 1, Round 1. Note in this representation, detail-level elements sharing the same parent are listed vertically to save horizontal space

with understanding of the relevant field evaluate each principle, embodiment and detail in the OPED tree using a rubric such as the one in Tab. 2.1. Note that this rubric was effective for this experiment, but may not be ideal for every case.

Table 2.1: Novelty Rubric: Judges assign scores to concepts based on these categories

Rating	Novelty Description
5	This idea is completely new. I have **not seen** this idea **anywhere**.
4	This idea is new to this application. I have seen/heard of concepts like this in **other application areas**, but have **never** heard it **applied to this area**.
3	This idea is a rare idea. **I have seen/heard of the concept before in this area** but have **never seen it implemented**.
2	This idea is an uncommon idea. I have seen/heard of some application of it in this area, but **it has not moved to mainstream use**.
1	This idea is a common idea. I see this idea **commonly implemented for this application** and would expect any design team to have this solution.
0	This idea is a well-known solutionin this application and other applications. I consider this an **obvious/expected** solution/idea.

Once the scores were assigned for each element in the tree (N_{ki}), a weighted sum was calculated to find the total novelty for each concept (N_i). In this case, the weights ($w_{N,k}$) of 3 for principle, 2 for embodiment and 1 for detail (for a maximum total score of 30) were used. While these weights proved effective for comparisons to be made between concepts for a qualitative analysis of the results, they have not yet been shown to be meaningful in statistical analysis. The equation for the total novelty score N_i of concept i is

$$N_i = \sum_{k=1}^{k_{max}} w_{N,k} * (N_{ki}) \tag{2.2}$$

where $w_{N,k}$ is the novelty weighting for level k in the tree (k=1 for detail, k=2 for embodiment, etc.), and N_{ki} represents the novelty score assigned (per Tab. 2.1) to the element in level k belonging to concept i.

Variety Evaluation

Variety is a measure of the explored design space during the idea generation process [2]. It describes how different concepts in the set are from the other concepts in the set. When applied to OPED trees, variety differs from novelty in that it is a measure of the relatedness between concepts on the tree, rather than an attribute belonging to each concept.

This variety metric increases as branches are added to the tree, where branching at the detail level (representing two concepts sharing the same embodiment and principle) adds less variety than branching at the embodiment level, which adds less than branching at the principle level. The added variety also decreases as more children are added to the same parent, because this represents many similar concepts being added to the set.

The *Branch Variety* (B_{kj}), shows the variety belonging to an element's (E_{kj}) branch in the tree, thus, it is dependent on both the element and its descendants. The *Total Variety* (V) for the set is equal to the sum of B_{kj} of the highest level in the tree (Objective, in our case). B_{kj} is given as

$$B_{kj} = w_{V,k} * S_{kj} + D_{kj} \tag{2.3}$$

where j represents an element in level k belonging to a certain parent, $w_{V,k}$ is the variety weighting for level k (in our case given by 2^{k-1}), S_{kj} is the *Sibling Variety* and D_{kj} is the *Descendent Variety*.

Sibling Variety (S_{kj}) ensures that the variety added by each new child of the same parent decreases as the number of children increases, and is given by

$$S_{kj} = \frac{\sum_{i=1}^{n(C_{kj})}(1+\beta^{i-1})}{n(C_{kj})} \tag{2.4}$$

where C_{kj} is the total number of children belonging to the parent of element j and β in this case is 0.7.

Descendent Variety (D_{kj}) is the sum of branch variety for all the children of element E_{kj}

$$D_{kj} = \sum_{i=1}^{c_{kj}} B_{(k-1)i} \tag{2.5}$$

where c_{kj} is the total number of children of element E_{kj}.

Though variety is a measure of the relationships between concepts, it is possible to allocate the total variety measure across the concepts, in order to examine the amount of variety added by the concept to the overall set. This is done by distributing the weighted *Sibling Variety* of the parents equally among the children. This *Allocated Variety* (A_{kj}) is represented by

$$A_{kj} = P_{kj} + w_{V,k} * S_{kj} \tag{2.6}$$

where P_{kj} is the *Allocated Parent Variety*. This is represented as

$$P_{kj} = \frac{A_{(k+i)p_{kj}}}{C_{kj}} \tag{2.7}$$

where p_{kj} is the index of the parent of E_{kj}. The allocated variety score of a concept is equal to the allocated variety of the lowest-level element belonging to that concept. Note that the sum of the allocated variety of all concepts is equal to the total variety of the tree (V).

Table 2.2: Novelty (N), Variety (V) and Quantity (Q) Totals calculated after rounds 1 and 2 for nine teams

Team Name	Number		Round 1	Round 2
Maintenance T1	1	N	277.5	399.5
		V	139.2	209.4
		Q	22	34
Maintenance T2	2	N	162.5	248.5
		V	75.5	125.5
		Q	13	21
Transport T1	3	N	281.5	338.0
		V	118.1	143.1
		Q	20	23
Transport T2	4	N	333.5	388.0
		V	124.2	186.8
		Q	18	30
Airport Naps T1	5	N	332.5	476.5
		V	87.0	143.8
		Q	17	26
Airport Naps T2	6	N	206.5	295.5
		V	88.8	129.1
		Q	17	23
Airport Disease T1	7	N	130.0	189.5
		V	104.7	142.2
		Q	19	28
Garden T1	8	N	195.0	290.5
		V	105.8	153.4
		Q	22	32
Garden T2	9	N	138.5	210.0
		V	79.3	122.5
		Q	18	27

2.4.3 Overview of Data Collected

Data was collected during all experiments and used to improve the Tech/Tac plot and its introduction to teams. The data provided here, however, is for the final experiment, which represents our final instantiation of the tool and which involved 9 teams.

Calculated Data

Nine teams participated in the final experiment. The total novelty, variety and quantity values calculated from the concept sets produced after rounds 1 and 2 for the nine teams is shown in Table 2.2.

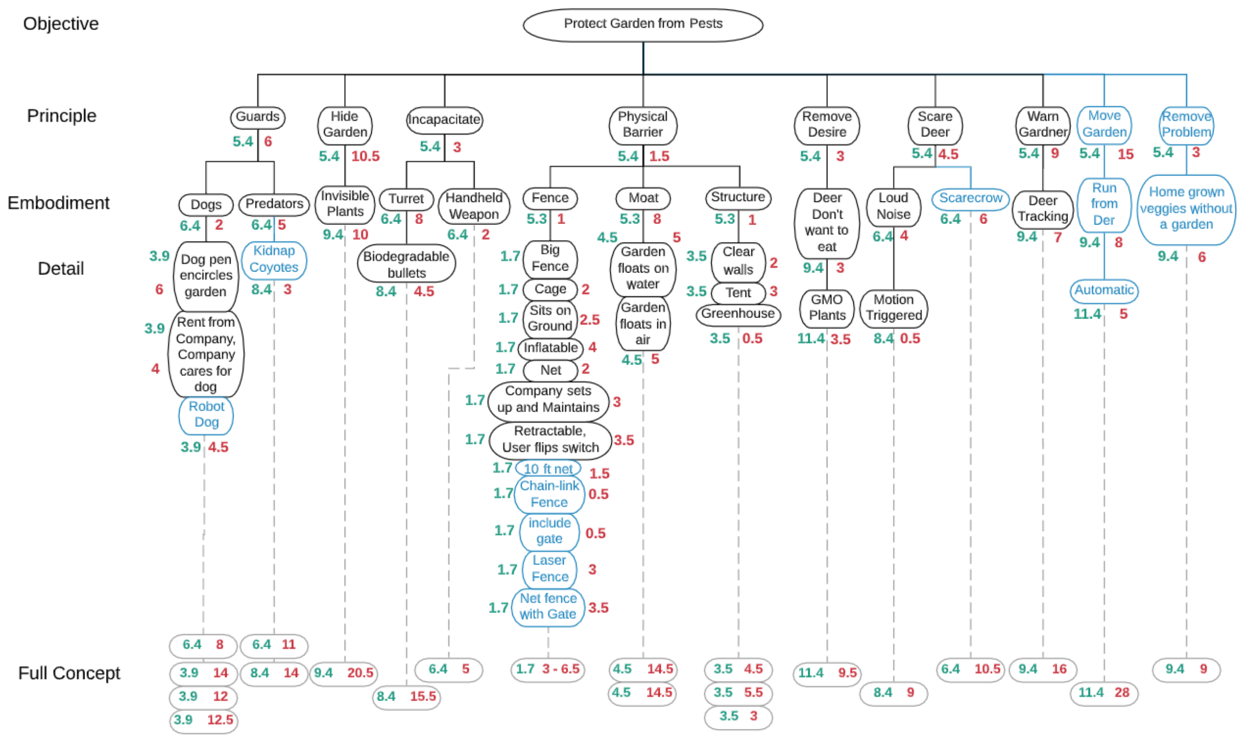

Figure 2.13: The Team 9 OPED tree, with round 2 additions in blue. Element novelty is shown in red and allocated element variety is shown in green, with the full values for novelty and allocated variety shown for each concept at the bottom. The concept variety score is equal to the lowest-level allocated variety of the branch, and the concept novelty score is equal to the sum of the elements on its branch.

Individual allocated variety and novelty scores for each concept were also found. These were superimposed both on the OPED tree for each concept set (see Fig. 2.13), and on the Tech/Tac plots after the second round (see Fig. 2.14), to give the resulting scores some context. In Fig. 2.14, first round concepts are written on yellow sticky notes and second round concepts on blue notes. Allocated variety scores for each concept are shown in green, and novelty scores are shown in red. Figure 2.13 shows the element novelty and allocated variety scores calculated for each element in the example tree in Fig. 2.12, after second round concepts have been added. Total scores for each concept are also shown below its branch in the tree.

Qualitative Data

The novelty and variety metrics were used as indicators of the value added by round 1 and round 2 ideation. With the values plotted over the OPED tree, it can be seen to what degree the principle, embodiment or detail of a concept impacts the overall novelty score. The metrics plotted over the Tech/Tac plots provide the placement of concepts, upper and lower bounds and empty spaces in the plot as determined by the teams. Examining these plots and the placement of concepts within empty spaces or in relation to upper and lower bounds gives indication of how concepts were produced from the process of creating and examining Tech/Tac plots.

Comments and feedback from the participants were also collected from each experiment. Though some of these comments are no longer applicable to the final instantiation of Tech/Tac, the comments regarding those aspects of the Tech/Tac plot and experimental process which were kept in the final instantiation can be used as the basis for the conclusions in this paper. An overview of these comments includes:

- "The activity helped us come up with a variety of ideas."
- "The Tech/Tac plot showed which areas of the plot I hadn't considered."
- "Focusing on empty areas in the plot helped generate ideas with specific requirements."
- "The activity made me elaborate on ideas I would have previously disregarded. I also went more in depth/elaborated more on simple concepts."
- "The activity forced us to include out there ideas and recognize niches we were not investigating until we recognized they were holes we were not filling. Helped us to see some of the problem from new angles."
- "The activity allowed us to have ideas stem from other ideas."
- "The Tech/Tac plot identified unexplored areas of possibility."
- "The activity is helping us stay productive discussing as a team, rather than just throwing our own ideas out there.
- "[We placed one idea above another] because it's more complicated for the user to work out."
- "[We placed one idea above another] because it changed a bunch of things of how the chair worked."

Figure 2.14: The Tech/Tac plot of Team 9 after round 2. Yellow sticky notes represent round 1 concepts, while blue or green sticky notes represent round 2 concepts. Novelty (in red) and allocated variety (in green) scores for each concept have ben superimposed over each concept. The highlighted concept is a high-scoring round 2 concept that was found in an empty space identified by the team

- "[We placed one idea to the right of another] because the tech would be harder for us to build. It uses more processes that we'd have to work in."

2.4.4 Key Findings and Results

The key results of this work are based on observations from all the experiments performed, and will be discussed in this section. The results include:

- Use of Tech/Tac plots increased the quantity, novelty and variety of each concept set in the study from round 1 to round 2

- Most teams stalled in their ideation during round 1, yet all teams were able to produce many useful ideas in round 2 at a level similar to round 1 in terms of novelty and variety
- Participants reported the Tech/Tac plot helped promote useful ideation discussions and allowed them to explore further into the design space
- Experiment participants can be taught the principles of Tech/Tac and build a defensible Tech/Tac plot within a 60-minute workshop
- *Differentiation in Tech & Tac* as a definition for the axes of a Tech/Tac plot leads to better ideation behavior than *Complexity of Tech & Tac*
- Simpler descriptions of $\Delta Tech$ and ΔTac lead to better ideation behavior than complex descriptions
- Requiring all concept descriptions to include both technology and tactics reduced the number of fragmentary concepts produced and improved the teams' ability to plot defensibly

Tech/Tac Increases Quantity, Novelty and Variety

Nine concept sets were produced during the final experiment. Examination of these sets revealed that the quantity, novelty and variety measures increased after the use of Tech/Tac plots during the second round (see Table 2.2). Furthermore, each team was able to find one or two concepts scoring in the top 10% of the entire set (in terms of novelty and/or allocated variety) in round 2, while no teams had decreases in the novelty or allocated variety of the ideas produced under Tech/Tac.

Tech/Tac Enables Continuing After Stalling

In two experiments it was observed that most of the teams stalled after 10-12 minutes of ideation in round 1. Discussion would die or move on to other topics, and ideation would slow significantly or stop. However, after discussing Tech/Tac and creating a Tech/Tac plot, all teams were able to produce many useful ideas in round 2 adding novelty and variety to the set at a level similar to round 1 (see Tab. 2.2). Many concepts scored much higher in terms of novelty and allocated variety. Examining these higher-scoring concepts from round 2 shows them coming directly from the process of creating a Tech/Tac plot, discovering empty spaces in the plot, and generating concepts for those empty spaces. In the example in Fig. 2.14, the empty spaces in the plot that were identified by the team are outlined in purple. Many concepts were added in these blank spaces in round 2 (blue sticky notes). The added concepts have a similar distribution of novelty (superimposed in red) and allocated variety (superimposed in green) scores to round 1, with two concepts scoring in the top 25% of the entire set in both variety and novelty. The highlighted concept was added in round 2 and is the highest-scoring concept in the set. Examination of nine teams showed similar results in each case.

Tech/Tac Improves Team Discussions

Comments from the participants reported the activity was “very useful.” Many noted the activity was allowing them to find empty spaces they were not considering; “It forced us to recognize niches we were not investigating until we recognized they were holes we were not filling. Helped us to see some of the problem from new angles,” and “it identified unexplored areas of possibility.” Others reported how the process enabled them to build ideas off of existing concepts; “it made me elaborate on ideas I would have previously disregarded,” “it allowed us to have ideas stem from other ideas” and “being able to look at others’ ideas helped me come up with more.” Team members also noted the plot encouraging them to add novelty; “it forced us to include out there ideas,” “it helped us come up with a variety of ideas,” and “it encouraged us to avoid prematurely judging ideas.”

Comments such as these give some indication of the quality of the conversation of the team during the activity. The members describe the conversation as useful and focused on the ideation. They comment on being able to produce many ideas they don’t believe they would have found, and encouraging them to think more deeply about changes they can make to existing ideas in order to create new ones. This shows that using Tech/Tac, from the participants point of view, leads to productive and creative discussion for the design team.

Tech/Tac Can be Taught in Reasonable Time

It is important for the principles of Tech/Tac to be made easily accessible to the designer for them to be useful in the design process. To that end, one goal of the experiments carried out was to determine if Tech/Tac could be taught and applied within a reasonable amount of time. Three of the experiments were carried out in a 60-minute session. In each of these, researchers were able to teach the principles of Tech/Tac and the participants were able to effectively create and utilize a Tech/Tac plot in their ideation, though this required the use of simple descriptions and focusing only on the plot examining $\Delta Tech$ and ΔTac.

Differentiation* More Effective Than *Complexity As a means of distinguishing concepts from one another on the Tech/Tac plot, technology and tactics differentiation ($\Delta Tech$ and ΔTac) were found to be more effective than *complexity* in encouraging desirable ideation behavior from the teams. In an attempt to improve the team members' understanding of the Tech/Tac plot as well as how to plot points consistently, one experiment examined whether using axes describing the *complexity* of the technology and tactics from primitive to advanced would enable the participants to produce more defensible plots when compared against experiments using $\Delta Tech$ and ΔTac. In this experiment, team members were again found to spend much more time analyzing the components included in concepts and debating placement when using complexity than when using $\Delta Tech$ and ΔTac. The debating team members struggled to reach consensus on where points should be placed and no distinguishable improvement in how well the team could defend their resulting plots could be found.

Simpler Descriptions Reduce Over-Analysing In four experiments it was found that teams could create a more defensible placement of points with a simpler description of $\Delta Tech$ and ΔTac than with a complex description. This description included defining $\Delta Tech$ as "difference in the technology from (S_0)" and ΔTac as "difference in the tactics from (S_0)", with definitions for M_{Tech} ("The point where the differences in the technology has become so great that the team doesn't have the capability to develop it") and M_{Tac} ("The point where the new tactics are so different that the user wouldn't consider adopting the solution") given as context.

Several of these experiments employed a more complex description with the intent of increasing understanding of the concepts. At this early stage in the design process, it is most productive for teams to spend only minimal time examining and discussing the technology and tactics changes of each concept, in order to maximize the quantity of concepts produced. However, in each experiment, it was found that teams, rather than relying on basic analysis of $\Delta Tech$ and ΔTac, spent much of their time deeply examining each concept and debating the "correct" placement, rather than spending time ideating new concepts. Basic descriptions of $\Delta Tech$ and ΔTac were generally more effective in encouraging teams to avoid this deep analysis and continue with more useful activities.

Removing Fragmentary Concept Descriptions

Early experiments found that team members would often give only fragmentary concept descriptions when no other guidance was given. These concept descriptions often focused on a single technology component in a design (such as "tripwire" or "shotgun"), with other components and tactics left to interpretation. It was also found that design teams attempting to place these fragmentary concepts on a Tech/Tac plot would struggle with different understandings of the implicit components in the design. These issues made it very difficult to build defensible plots as well as analysing the results.

It was later found that, even before teaching the principles of Tech/Tac, if the teams were required to include "some aspect of the equipment involved" and "something about what the user is doing with the design" into their concept descriptions, far fewer fragmentary concepts would come from either round of ideation, and participants had more success plotting concepts defensibly.

2.5 Conclusion

In this paper, we have introduced tactics as a design space dimension for exploring potential solutions in tandem with technology. We have examined the merits of exploring the feasible design space as a 2D vector space, and established the mapping of solution concepts within the Tech/Tac plot. A process for bounding the feasible design space with measurable constraints has been shown, and a definition for the placement of points and constraints on the space in terms of a control volume has been created. We have also investigated how the plot may be adapted to examine at least 9 major aspects of common projects and shown how both the concept set and the individual concepts within the set can be evaluated.

The principles of Tech/Tac help design teams to avoid the pitfall of under-examining the design space during ideation, especially when it comes to examining the tactics dimension. The Tech/Tac plot provides a means whereby both ideation-effectiveness evaluations can occur, namely: 1) It requires teams to spread their concepts across the design space, examining the set from multiple reference points to increase the quantity, variety, quality, and novelty of the set, and 2) it provides a simple means for comparing concepts against each other in terms of differentiation, cost on limiting resources, and benefits to the design team and the user, including finding the limits on feasibility to quickly identify the most promising concepts.

The plot is a map by which the design space can be explored. When the team has successfully expanded their concept set to span the feasible design space, they are left with a concept set that is more likely to find and produce a superior final result. The merits of Tech/Tac when applied just to this initial portion of the design process are encouraging and point to opportunities for research into the applications of this theory to other portions of the design process as well.

CHAPTER 3. DISCUSSION OF RESEARCH PERFORMED

This chapter provides a discussion of the limitations of the research performed as well as notes on how this work could be furthered by future graduate students.

3.1 Limitations of This Research

This thesis serves as an initial exploratory work into the impact that could be possible with the use of Tech/Tac. It contains many important definitions that serve as a foundation for Tech/Tac, lays out how the effectiveness of Tech/Tac could be evaluated and provides tools to enable its application to design work. The major limitation of this work, however, is that it does not provide any comparative data to establish to what degree Tech/Tac encourages good ideation when compared against other common ideation methods. This means we cannot separate the impact of using Tech/Tac, in terms of novelty, variety and quantity, from the impact of allowing additional time in the second round, or from the impact of using other ideation methods.

A major goal in moving this research forward would therefore be to perform more comparative studies, with treatment groups that are exposed to Tech/Tac principles and the Tech/Tac plot compared against control groups who are simply given more time to ideate using the same methods as in round 1 or are given some generic ideation instruction before the second round.

This work is also limited in that we did not record or examine the discussions of the teams during ideation, limiting the conclusions we can draw regarding the quality of team discussion. Only comments and feedback were collected from students after the workshops, and while these provided valuable information, it has become very clear during the analysis of the data that more in-depth records of the discussions that occurred during the experiment and/or more detailed surveys of the student's reactions to Tech/Tac would be an extremely valuable addition to this work. These records of team discussions would enable us to evaluate the impact Tech/Tac has on the collaboration of the team, see where teams become confused or where ideation slows, and track the order and rate of concepts produced. We also recommend that metrics, such as Likert scales, be used when further surveys are used to enable better quantitative analysis of the results.

Finally, the tests carried out during this work engaged design teams comprised exclusively of students. Performing these experiments with professional designers would improve the claims we can make of the usefulness of Tech/Tac in the field, and not as a teaching tool.

3.2 Future Work

Several recommendations for future work have already been made in section 3.1. Though we will not list those again here, we stress the importance of conducting improved experimentation of Tech/Tac during ideation. The application of Tech/Tac to ideation has potential to produce significant value for designers, and more focused data is needed to demonstrate that value. Beyond this additional experimentation, we recommend four specific focuses for future work.

First, at the time of this writing, additional work involving Tech/Tac has resulted in two papers published in the 2019 and 2020 IDETC conferences. These address topics such as how to establish the limits of project stakeholders with regard to technology and tactics, what an artifact of design that represents a tactic would look like and how to ideate and evaluate the quality of a tactic. It is important that this research continue, as understanding these topics will be valuable when applying Tech/Tac beyond ideation.

The second recommendation is to carry the application of Tech/Tac to other portions of the design process. This paper focused primarily on the divergent portion of ideation. There is significant potential for Tech/Tac to influence and provide value to other portions of the design process. Tech/Tac is a brand new method for viewing a design throughout the design process, and as such leaves significant room for more investigation.

A specific recommendation would be to apply Tech/Tac to convergent ideation. Though this paper focused primarily on divergent ideation, many applications of Tech/Tac plots, especially the design-team-centric and user-centric plots, as a means of eliminating infeasible or undesirable designs from the design space were observed. Furthermore, through the experiments carried out in this research, we observed that many teams continued to use the Tech/Tac plots after the workshop. Some used them as an artifact to present their concept set to a skateholder and get further input. Some also examined their upper bounds and discovered information that helped them shrink their feasible design space, which helped them to converge their set. There appears to be significant opportunity to apply Tech/Tac plots specifically to this use, though this went beyond the scope of this paper.

The third recommendation is to continue to develop and apply the metrics for novelty and variety to future work in design, including research outside of Tech/Tac. These metrics were developed in conjunction with this research when it was discovered that Shah's proposed metrics were directed toward engineering design only (i.e. they could only evaluate the technology of a design, not its tactics). This work proposes that technology and tactics are viewed simultaneously, but tactics design on its own is also fairly common, especially outside of the engineering field. The addition of novelty and variety metrics that are functional for concepts that may be technology-only, tactics-only, or technology and tactics combined is a major contribution, but both metrics were produced late in this research, and their full impact has not been investigated. Further work with these metrics could improve their usefulness for a wider set of design problems. Specifically, at the time of this writing it is still only marginally understood how the novelty scores of elements in the OPED tree should be used to calculate the full score of a concept, or how these scores should be used to calculate a cumulative novelty score for the entire concept set.

Finally, some examination of how the costs or benefits of technology could be compared to the costs or benefits of tactics could be conducted. Understanding the trade-off between a concept with high technology costs and low tactics costs and one with high tactics costs and low technology costs could improve the evaluation of concepts and better inform team discussions during ideation.

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APPENDIX A. ANNOTATED TECH/TAC PLOTS

Tech/Tac plots from the final experiment with novelty (in red) and variety (in green) scores superimposed are provided here as a reference for future work.

Car Maintenance 1

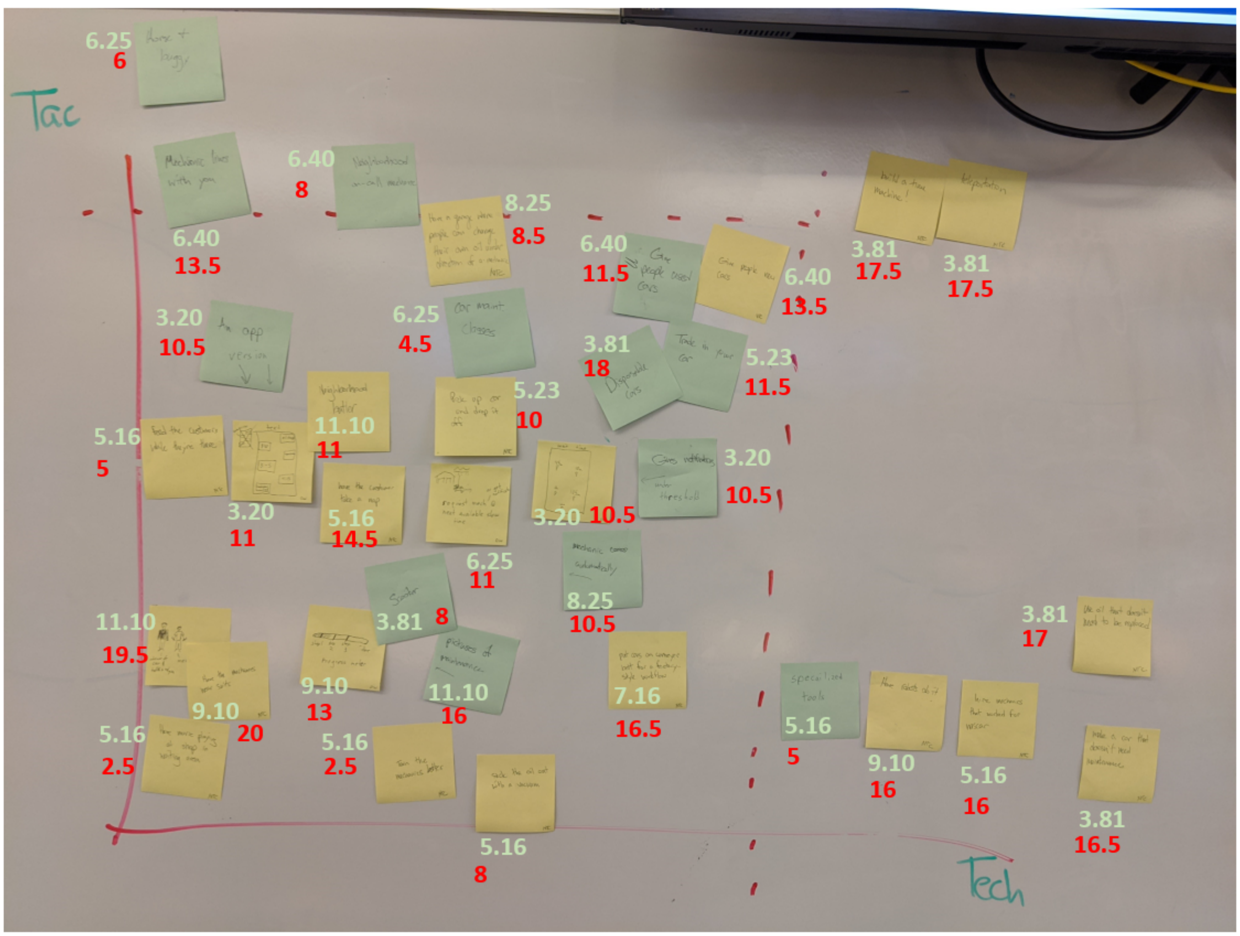

Figure A.1: Annotated Tech/Tac Plot for Group 1, Car Maintenance 1. The objective is to make the process of taking a car to a mechanic more convenient for the customer.

Car Maintenance 2

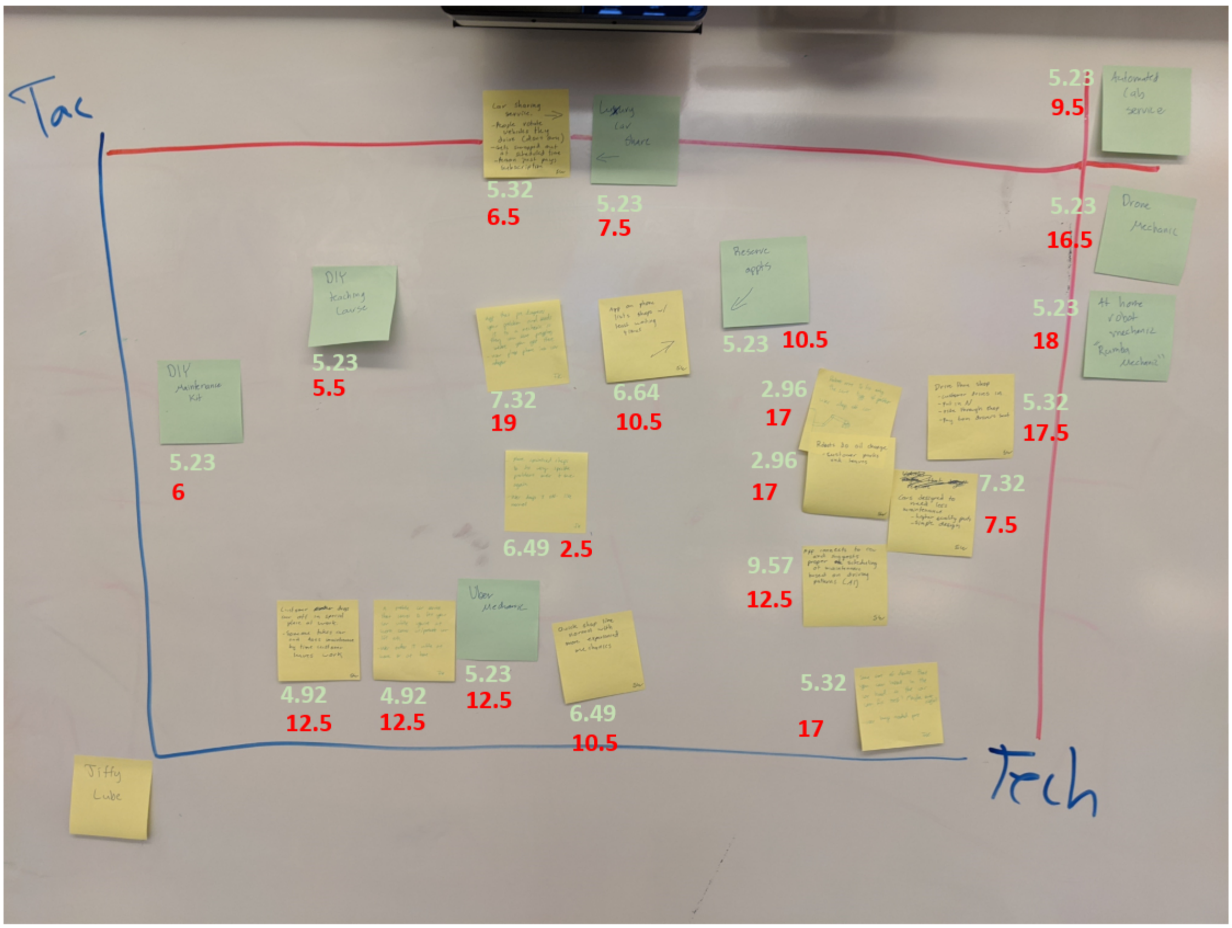

Figure A.2: Annotated Tech/Tac Plot for Group 2, Car Maintenance 2. The objective is to make the process of taking a car to a mechanic more convenient for the customer.

Transportation 1

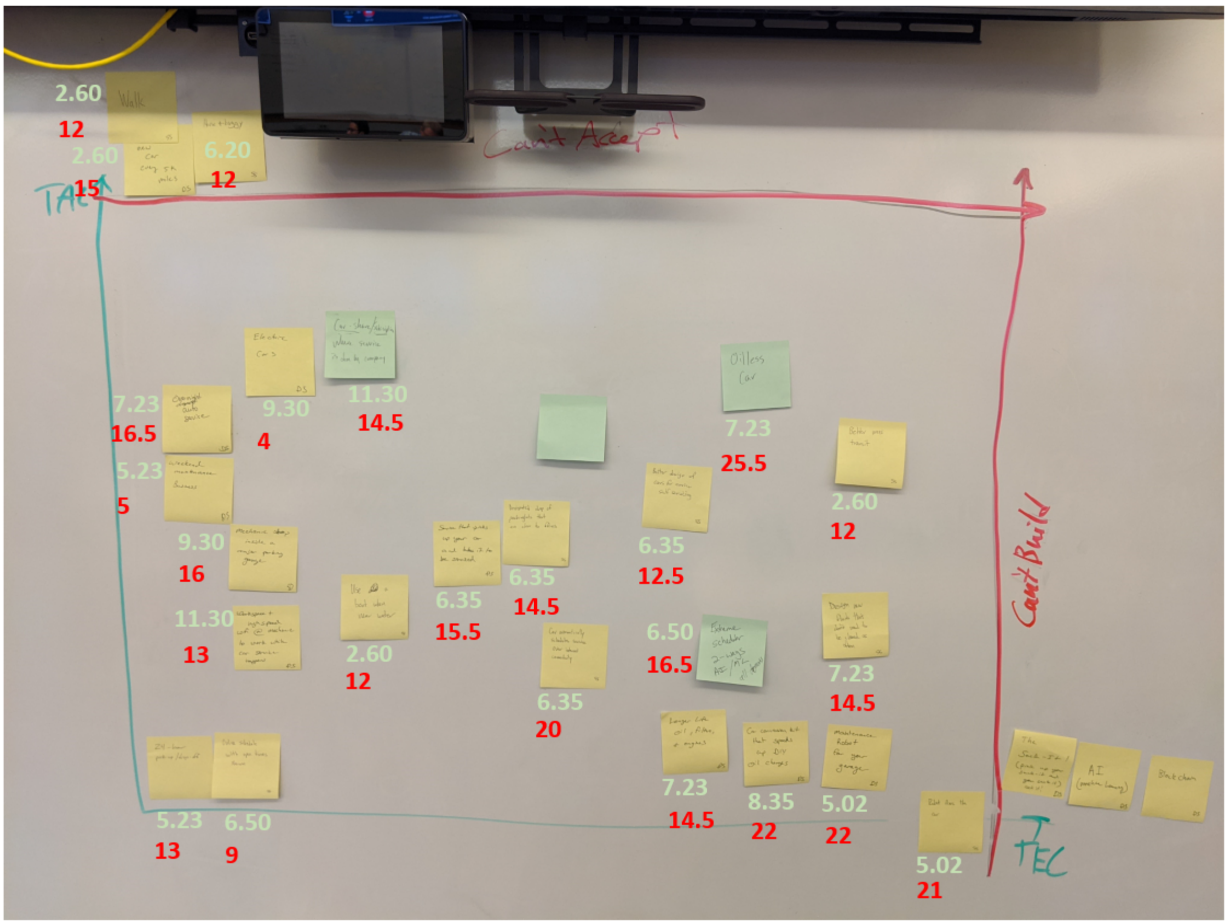

Figure A.3: Annotated Tech/Tac Plot for Group 3, Transportation 1. The objective is to make the process of taking a car to a mechanic more convenient for the customer.

Transportation 2

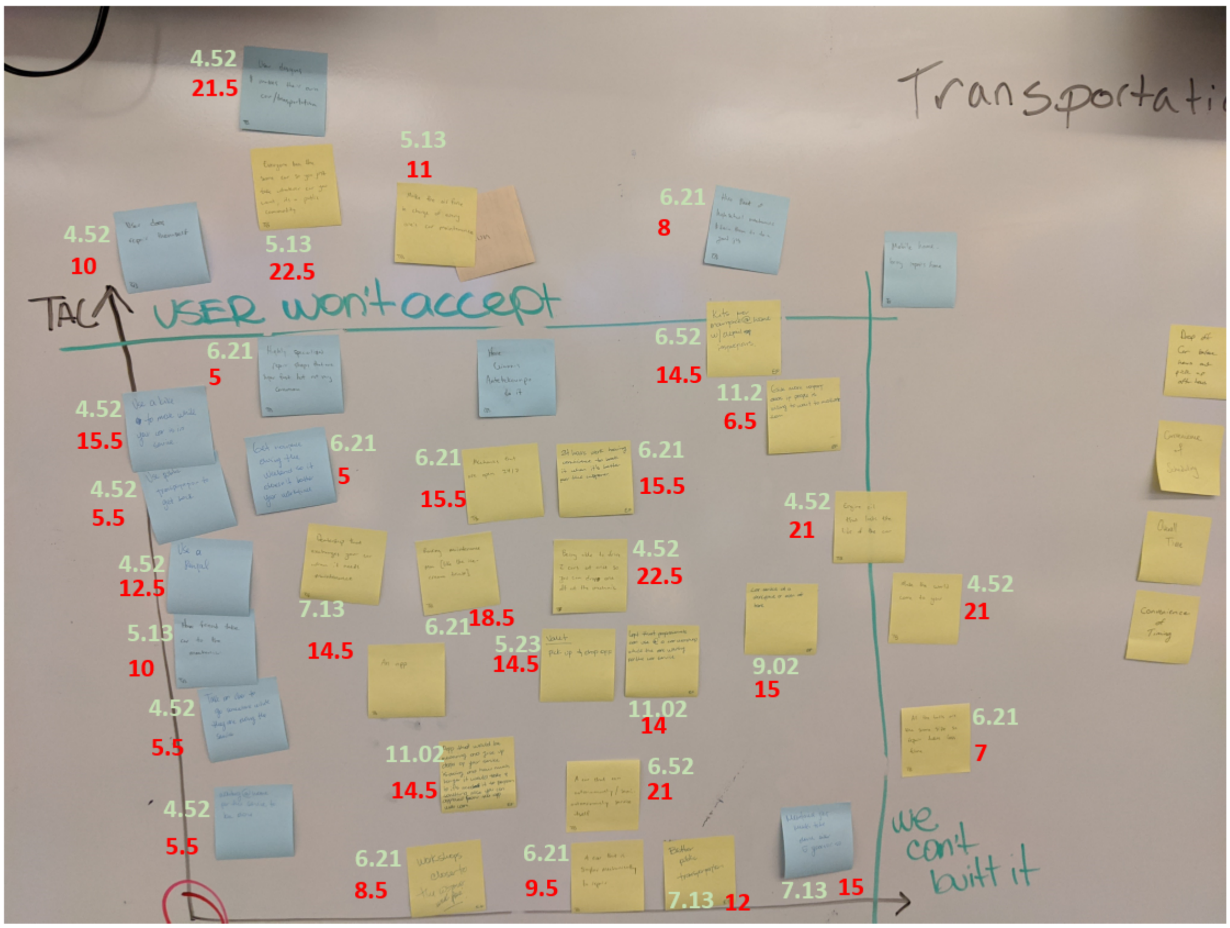

Figure A.4: Annotated Tech/Tac Plot for Group 4, Transportation 2. The objective is to make the process of taking a car to a mechanic more convenient for the customer.

Airport Naps 1

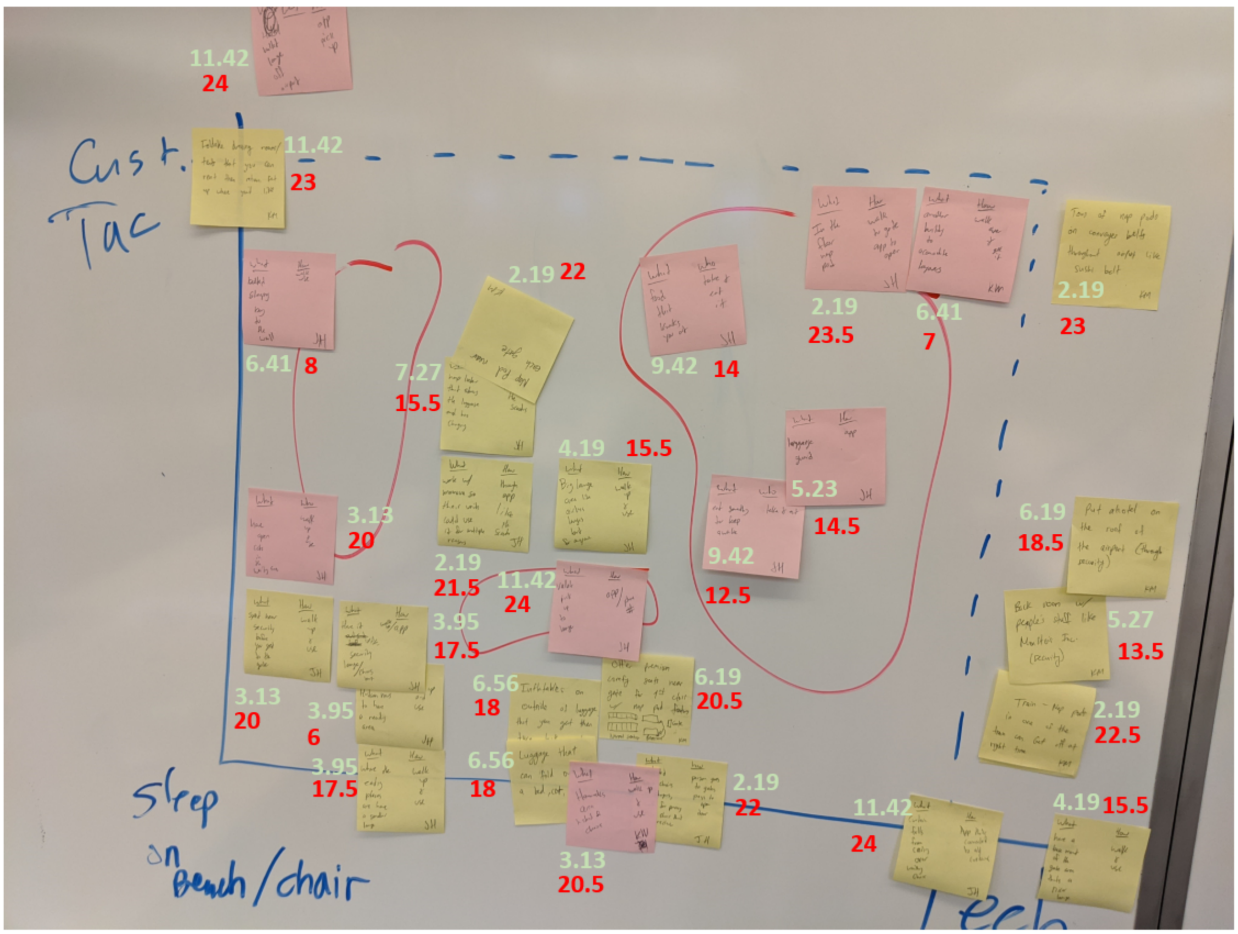

Figure A.5: Annotated Tech/Tac Plot for Group 5, Airport Naps 1. The objective is to provide a more comfortable means for individuals to take a nap at the airport.

Airport Naps 2

Figure A.6: Annotated Tech/Tac Plot for Group 6, Airport Naps 2 The objective is to provide a more comfortable means for individuals to take a nap at the airport.

Airport Disease

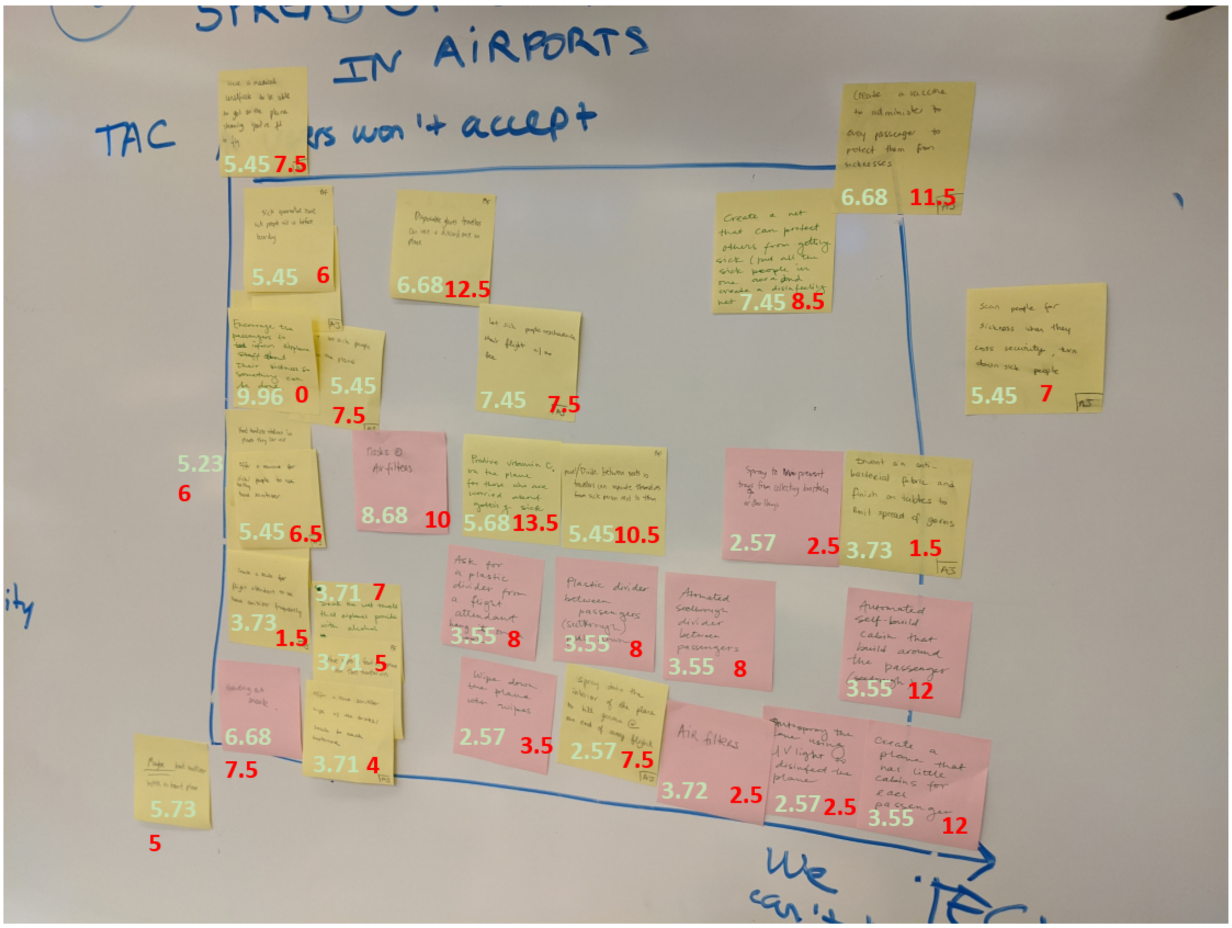

Figure A.7: Annotated Tech/Tac Plot for Group 7, Airport Disease. The objective is to decrease the spread of disease at airports.

Garden 1

Figure A.8: Annotated Tech/Tac Plot for Group 8, Garden 1. The objective is to keep pests (primarily deer) out of homeowner gardens.

Garden 2

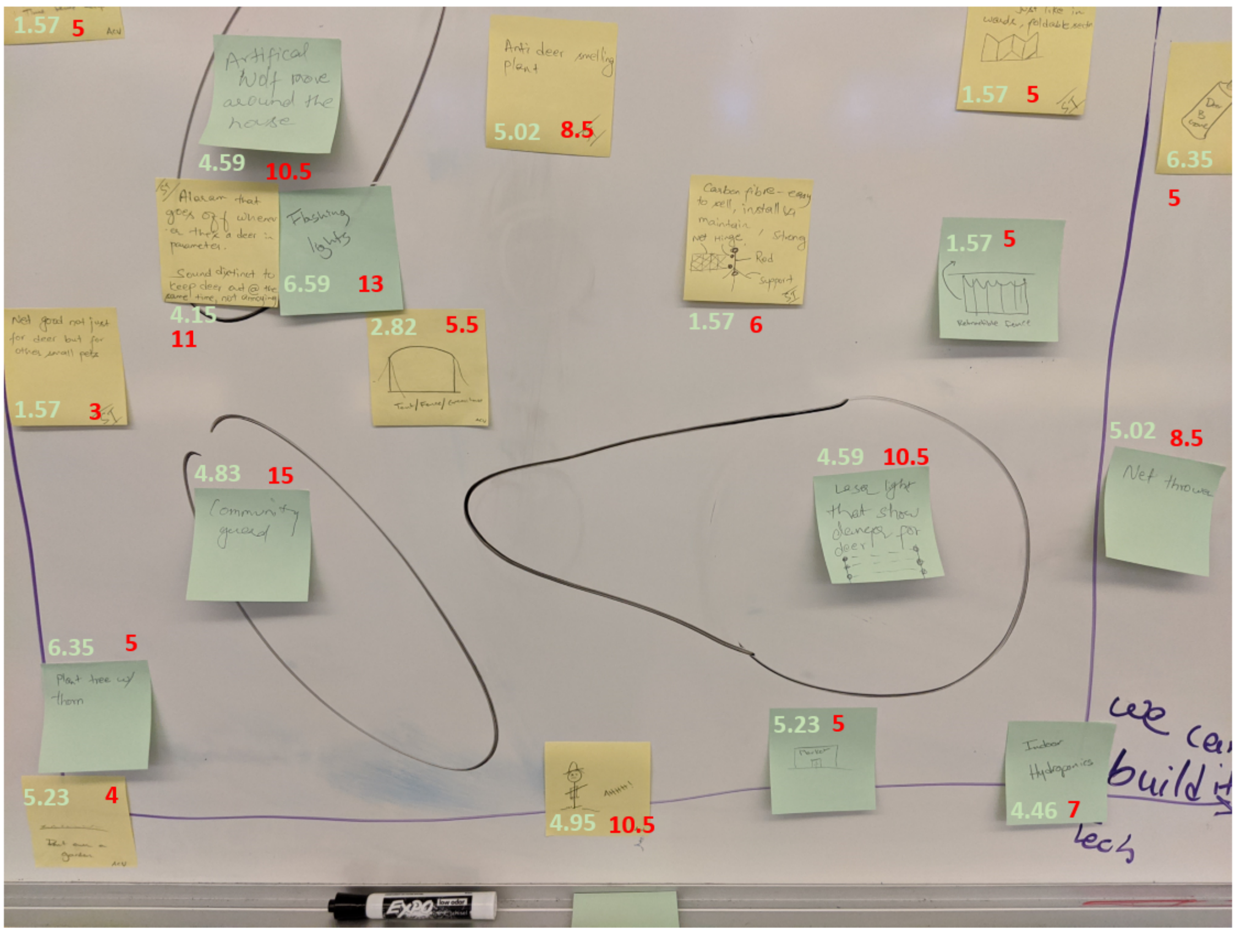

Figure A.9: Annotated Tech/Tac Plot for Group 9, Garden 2. The objective is to keep pests (primarily deer) out of homeowner gardens.

APPENDIX B. OPED TREES

OPED Trees from the final experiment, with Round 2 concepts in red, are provided here as a reference for future work.

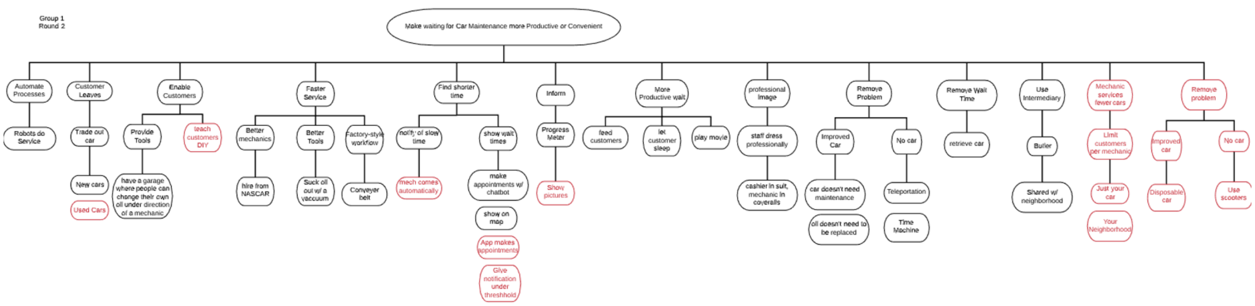

Figure B.1: Round 2 OPED Tree for Group 1, Car Maintenance 1

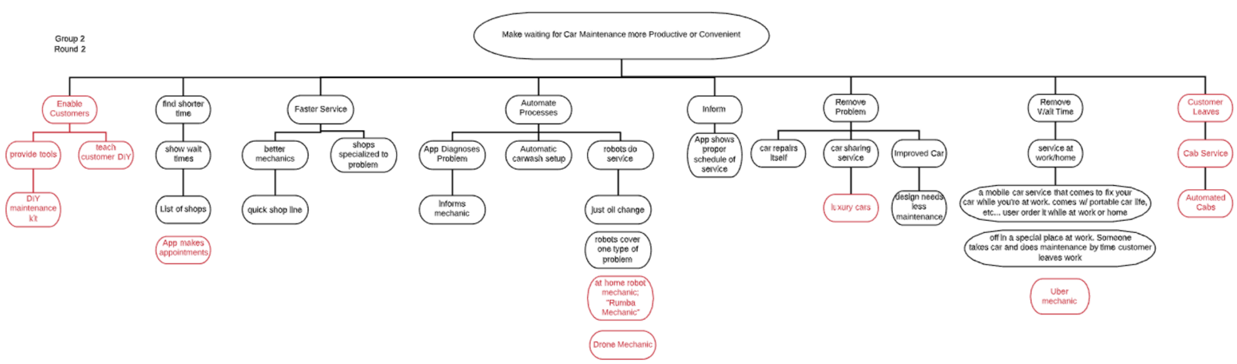

Figure B.2: Round 2 OPED Tree for Group 2, Car Maintenance 2

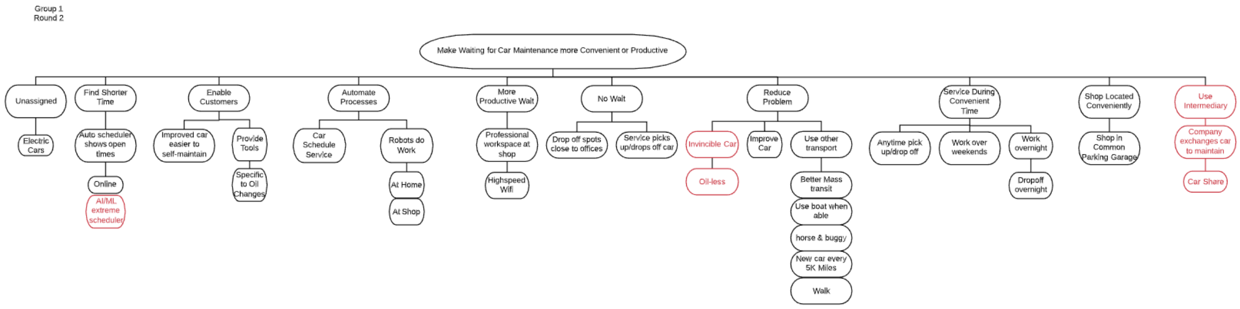

Figure B.3: Round 2 OPED Tree for Group 3, Transportation 1

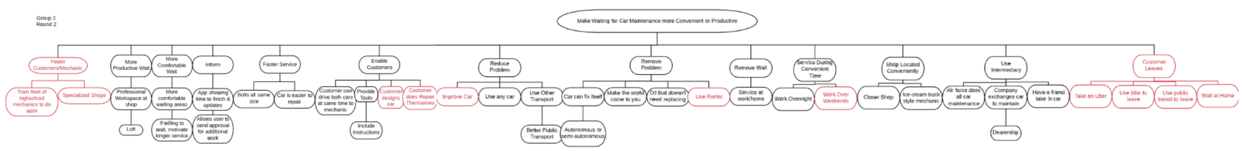

Figure B.4: Round 2 OPED Tree for Group 4, Transportation 2

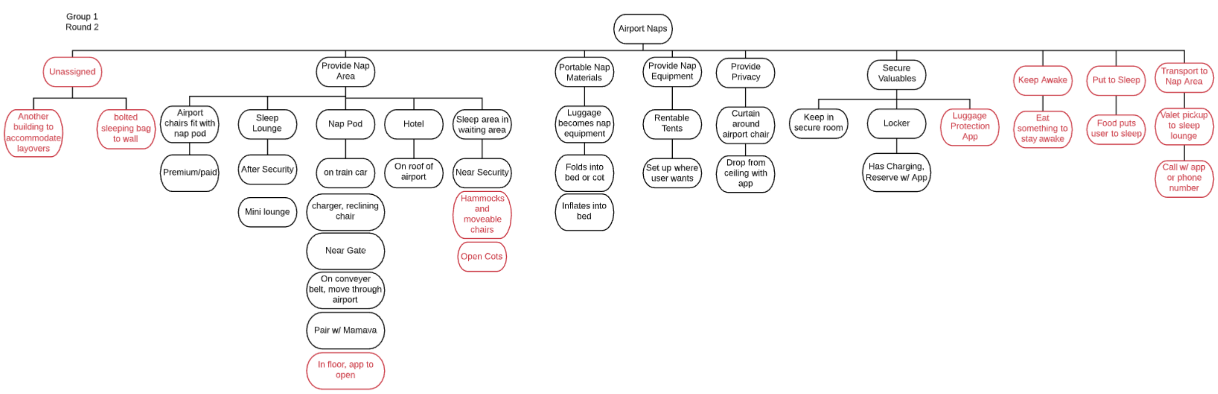

Figure B.5: Round 2 OPED Tree for Group 5, Airport Naps 1

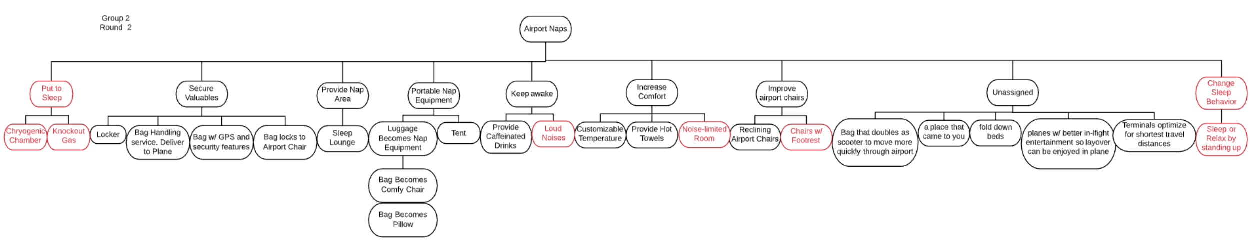

Figure B.6: Round 2 OPED Tree for Group 6, Airport Naps 2

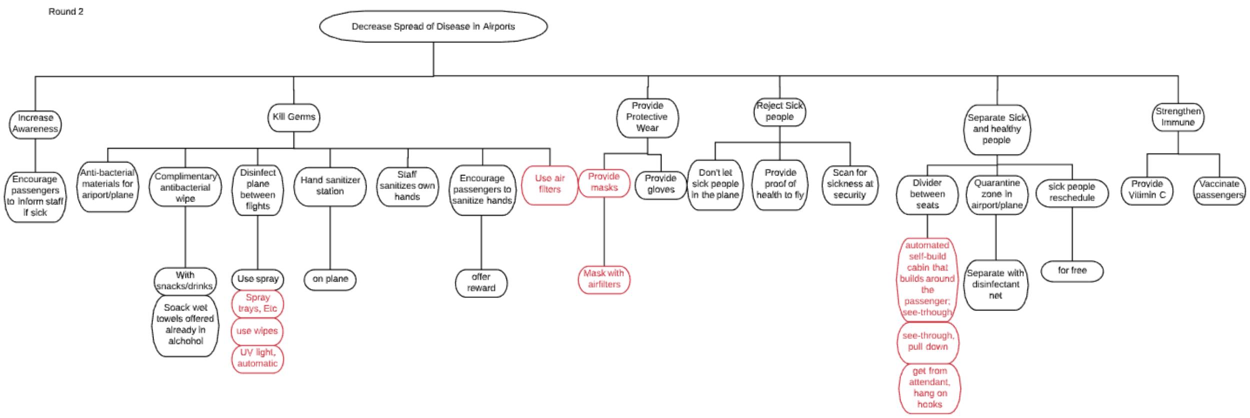

Figure B.7: Round 2 OPED Tree for Group 7, Airport Disease

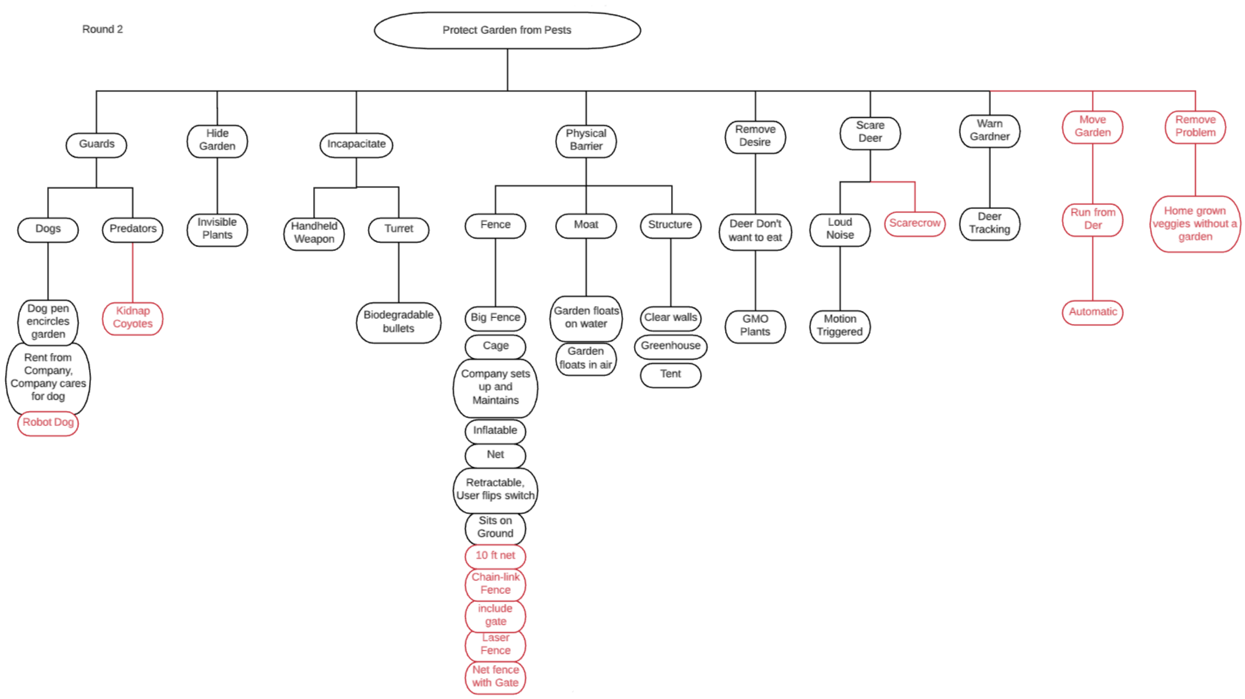

Figure B.8: Round 2 OPED Tree for Group 8, Garden 1

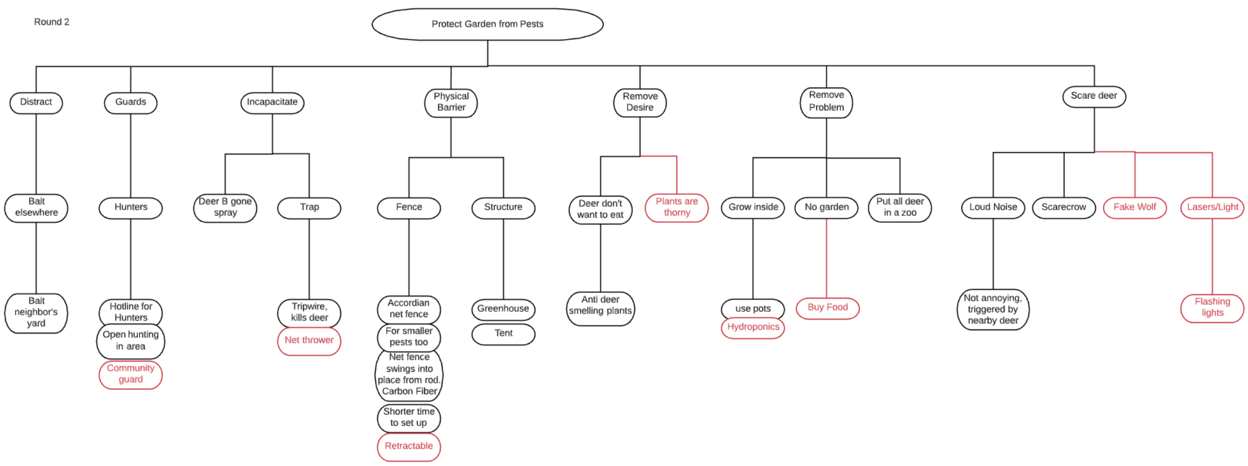

Figure B.9: Round 2 OPED Tree for Group 9, Garden 2

APPENDIX C. OTHER TECH/TAC PLOTS

Tech/Tac plots from other experiments are provided here as a reference for future work. Note that, as these plots were created during earlier experiments, some variations in the definitions as well as how Tech/Tac was taught exist between experiments.

C.1 Air Force Academy Experiment 1

The objective for each team was to reduce school shooting incidents for their customer

Figure C.1: Tech/Tac Plot for Group 1, with round 2 concepts in blue

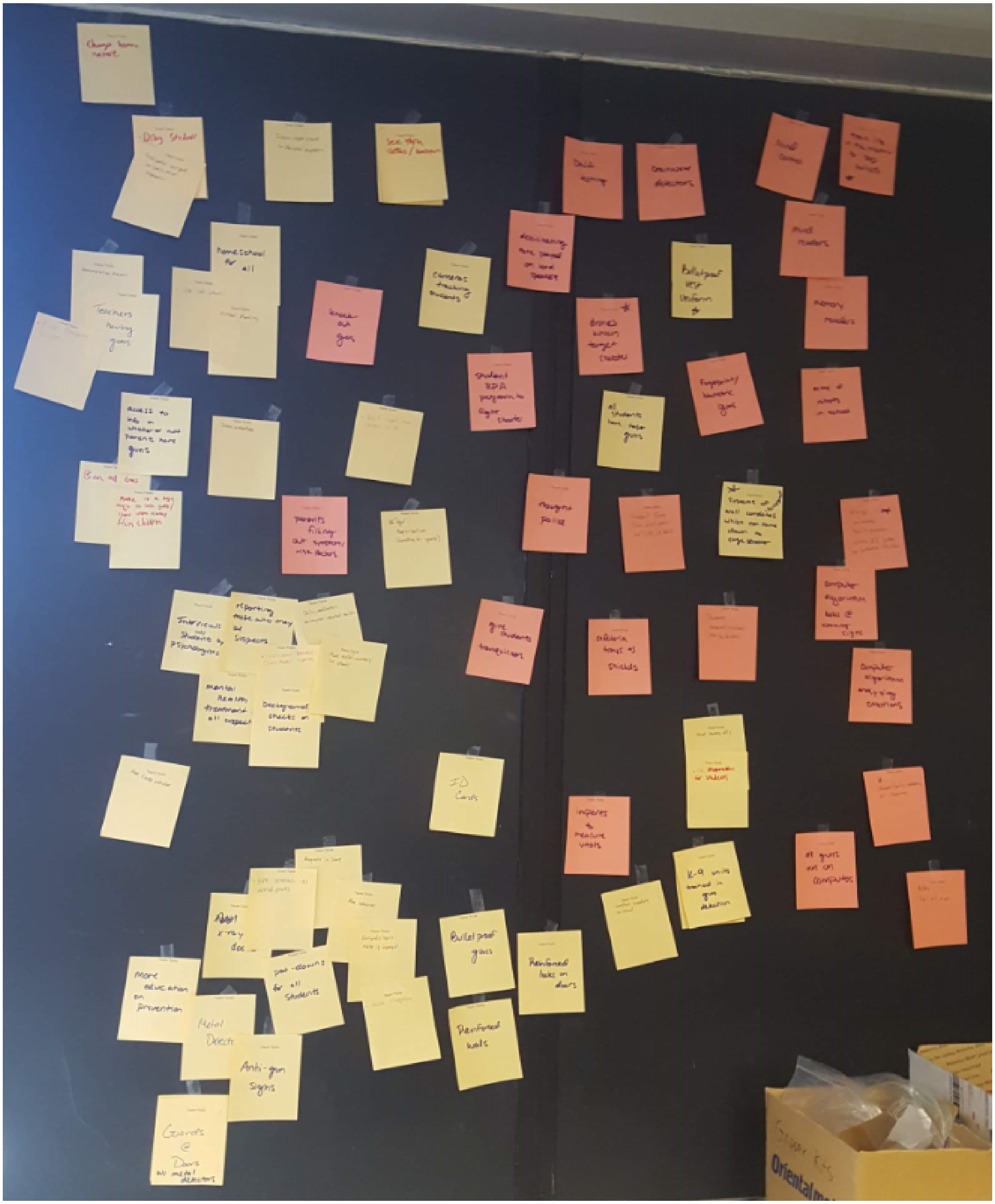

Figure C.2: Tech/Tac Plot for Group 2, with round 2 concepts in red

C.2 Air Force Academy Experiment 2

This experiment tested how effectively teams could ideate in round 2 using *Complexity of Tech and Tac* rather than $\Delta Tech$ and ΔTac. Each plot in this section used *Complexity* as their axes.

Figure C.3: Tech/Tac Plot for Group 1, with round 2 concepts in yellow

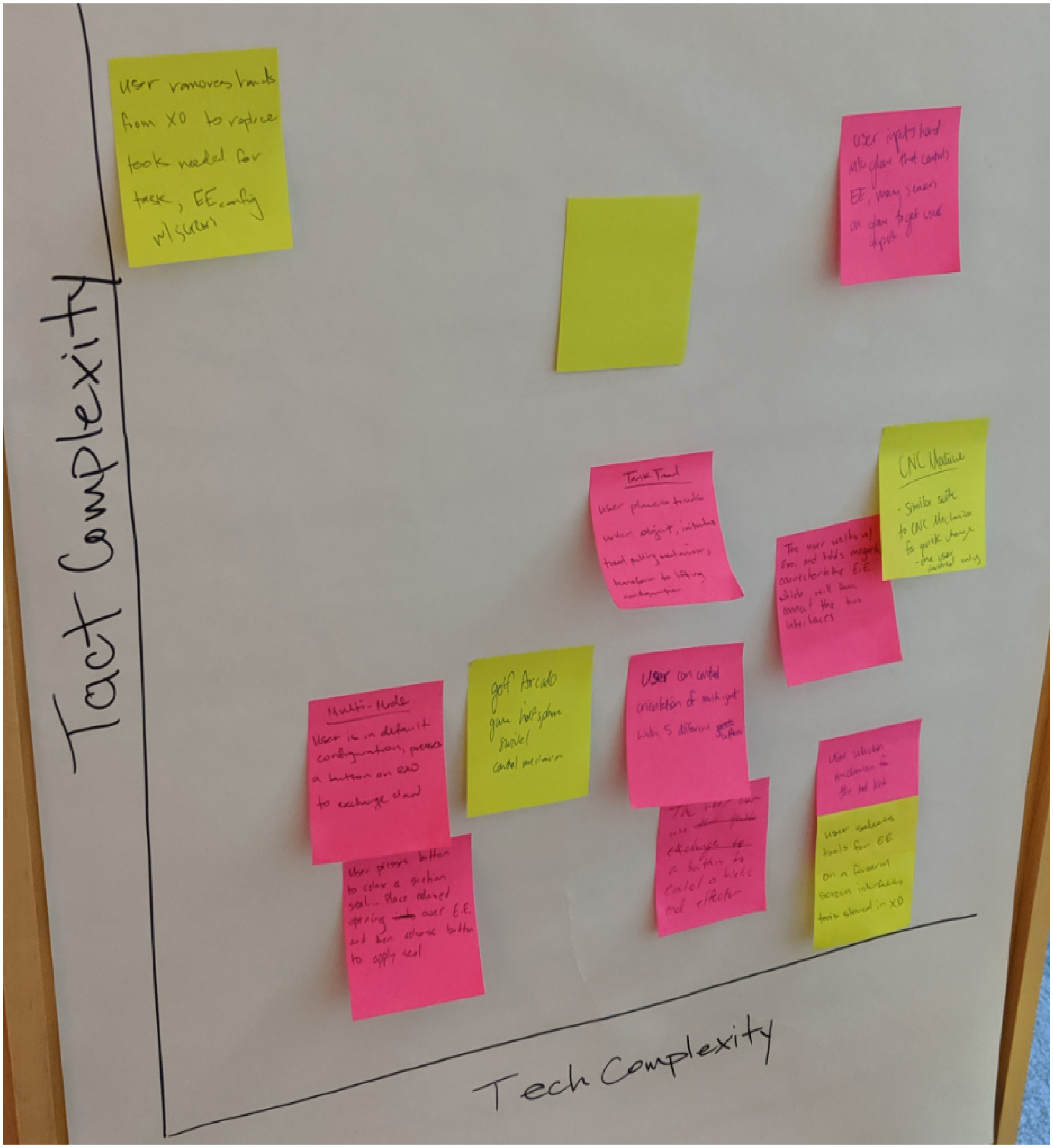

Figure C.4: Tech/Tac Plot for Group 2, with round 2 concepts in yellow

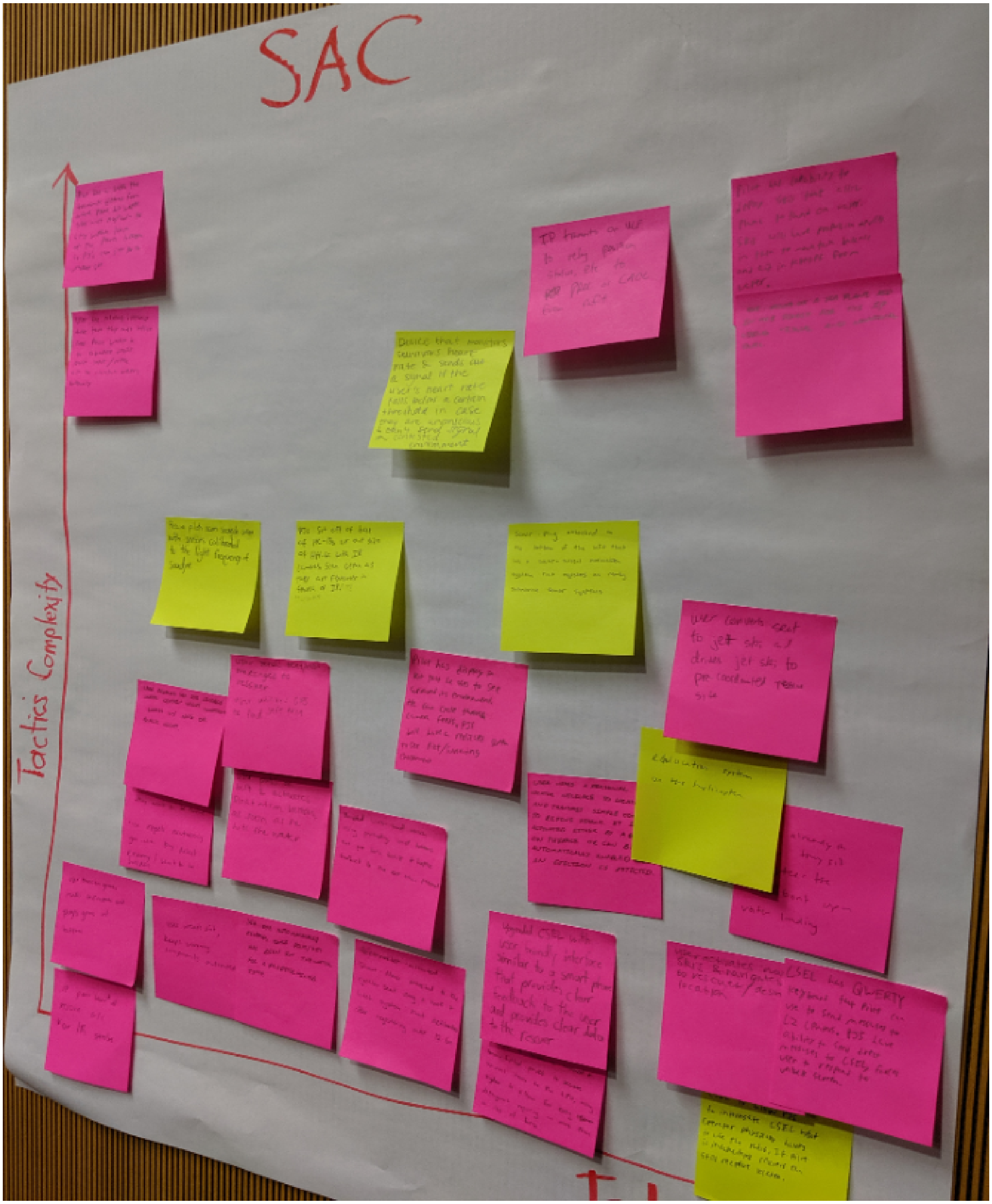

Figure C.5: Tech/Tac Plot for Group 3, with round 2 concepts in yellow

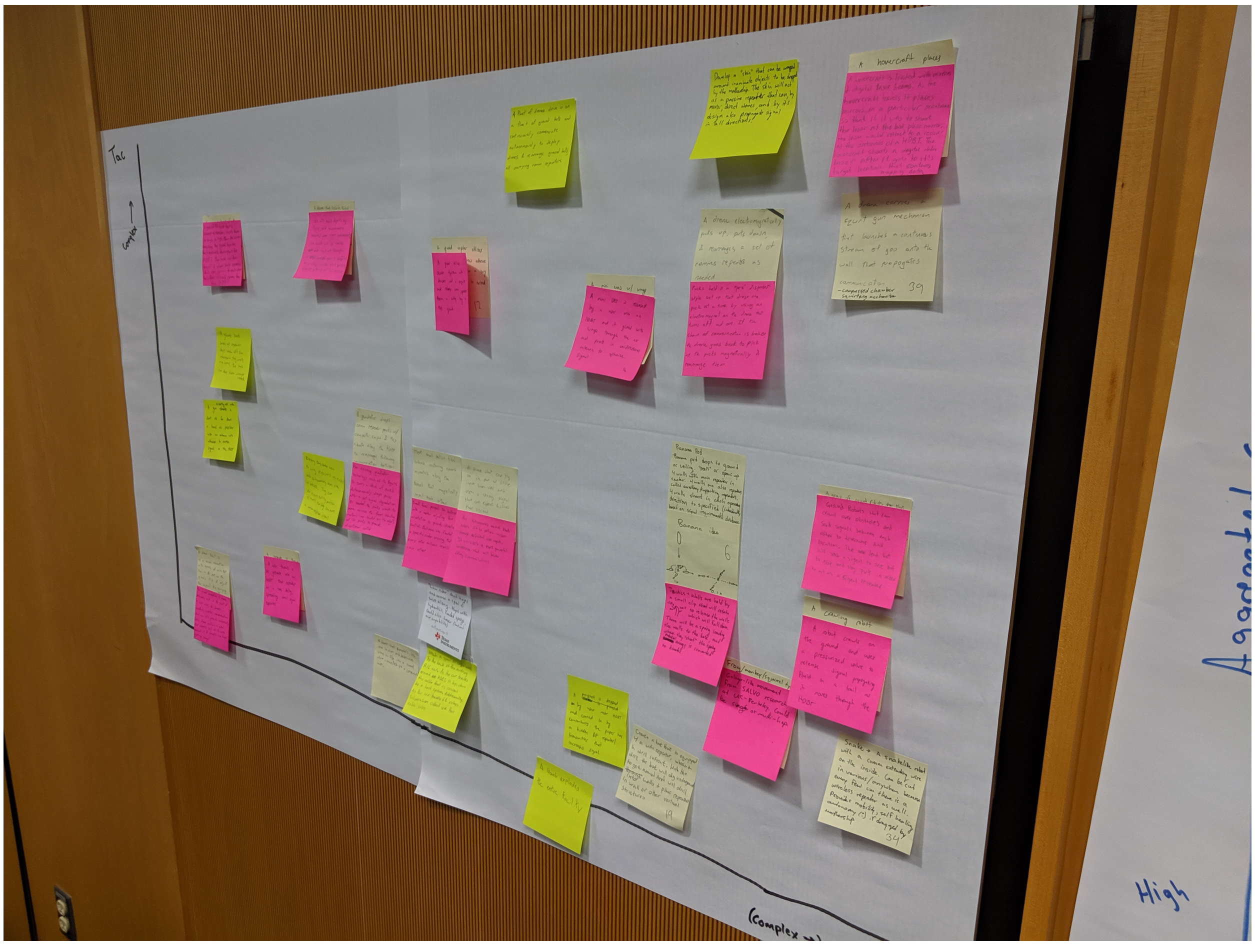

Figure C.6: Tech/Tac Plot for Group 4, with round 2 concepts in yellow

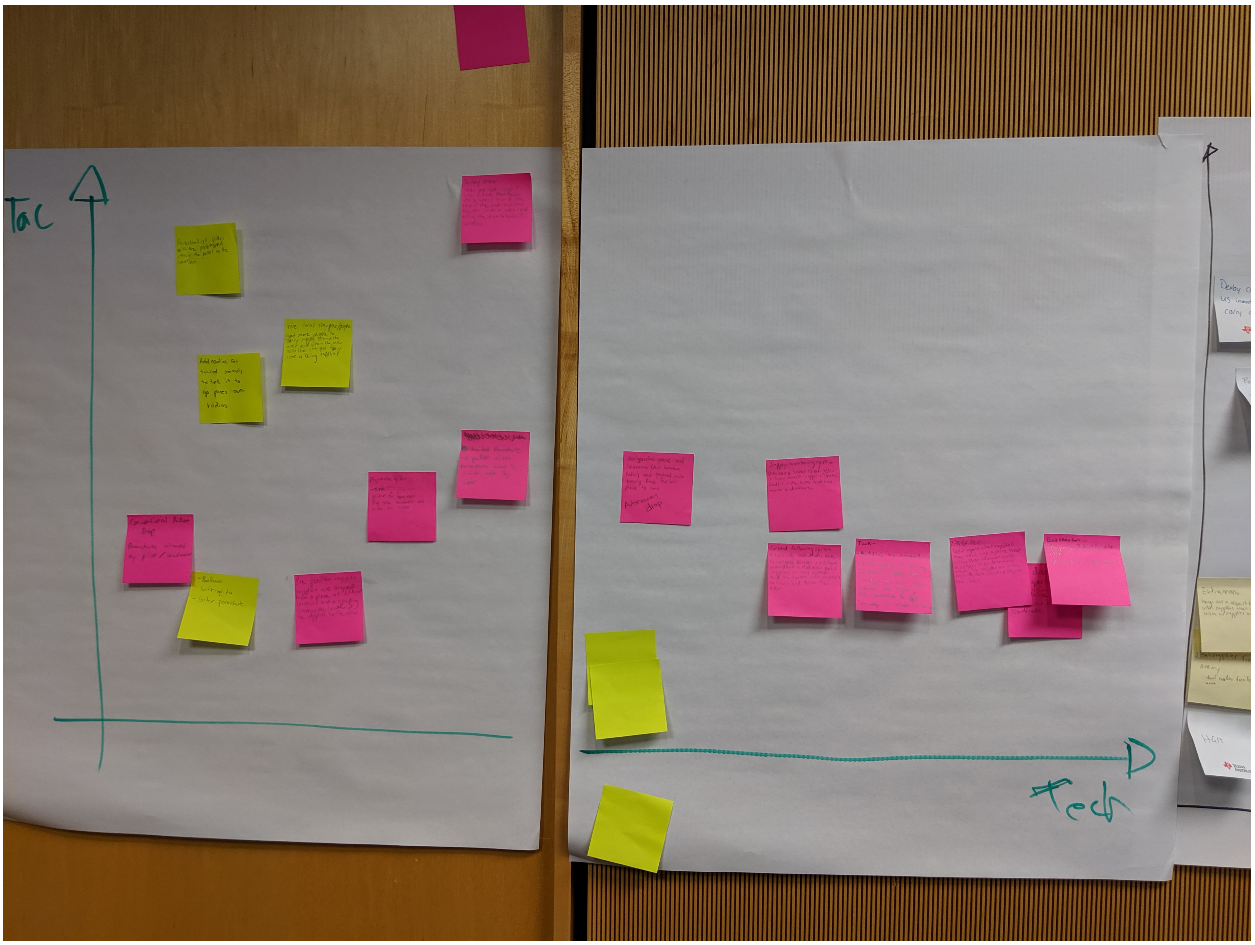

Figure C.7: Tech/Tac Plot for Group 5, with round 2 concepts in yellow

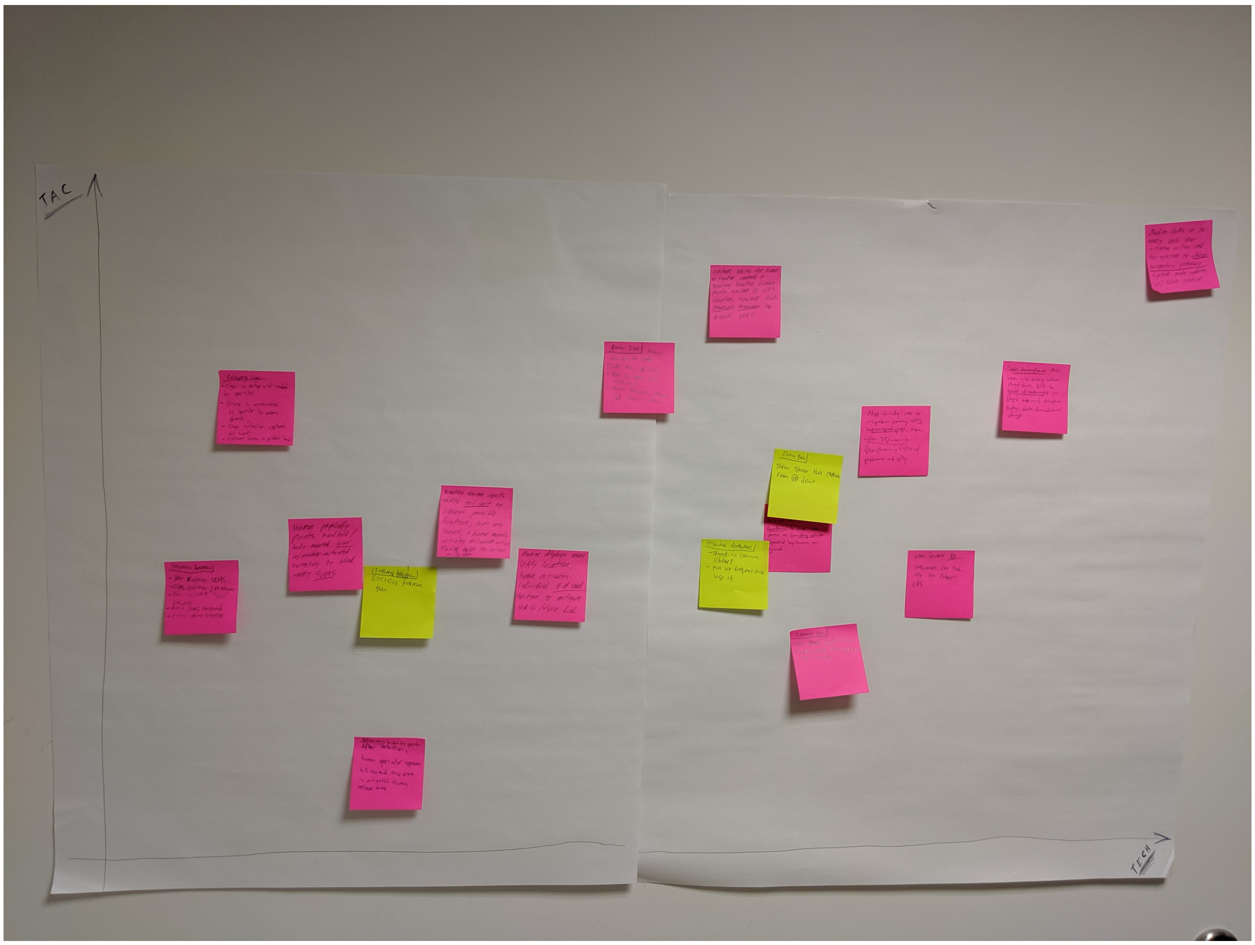

Figure C.8: Tech/Tac Plot for Group 6, with round 2 concepts in yellow

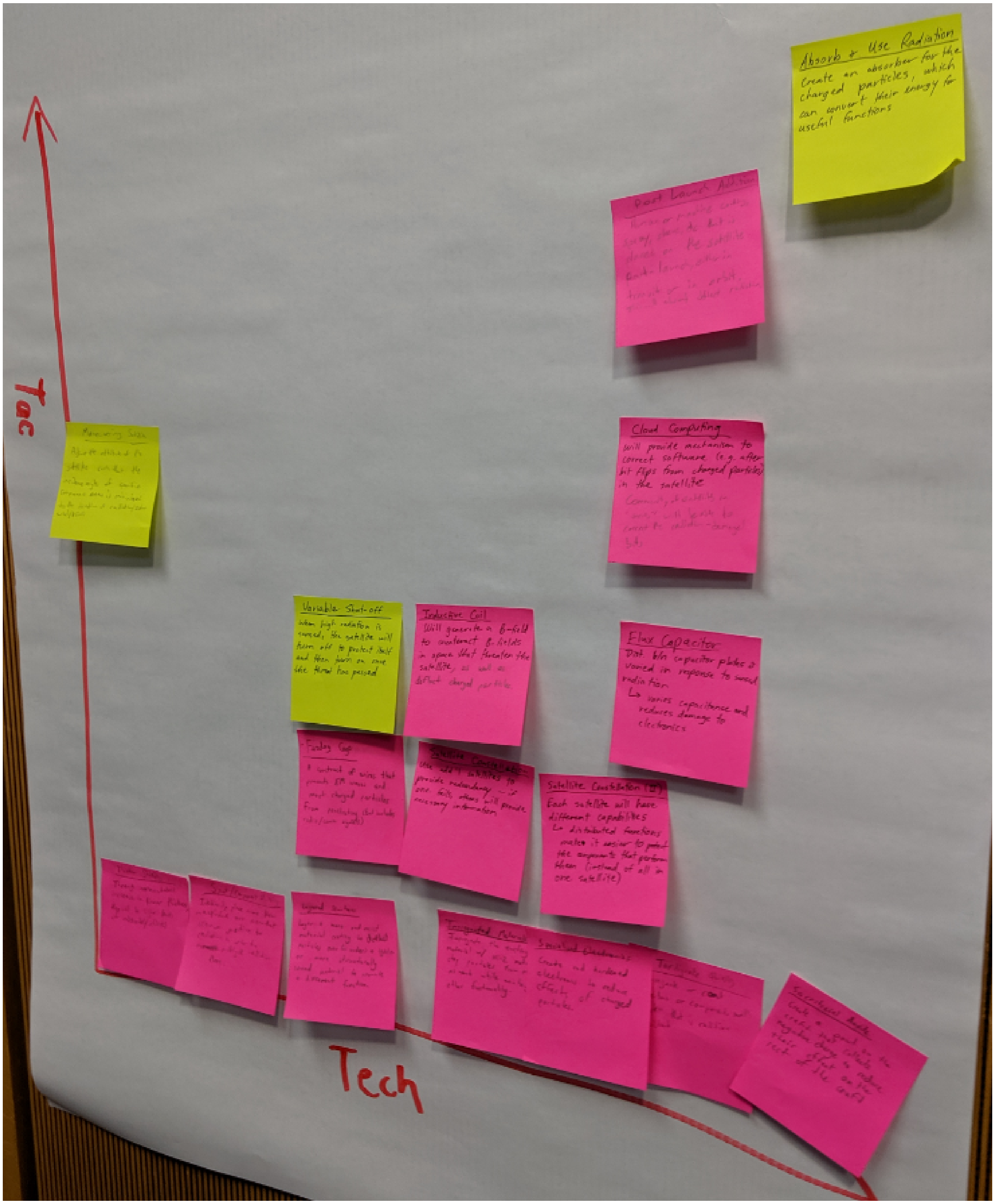

Figure C.9: Tech/Tac Plot for Group 7, with round 2 concepts in yellow

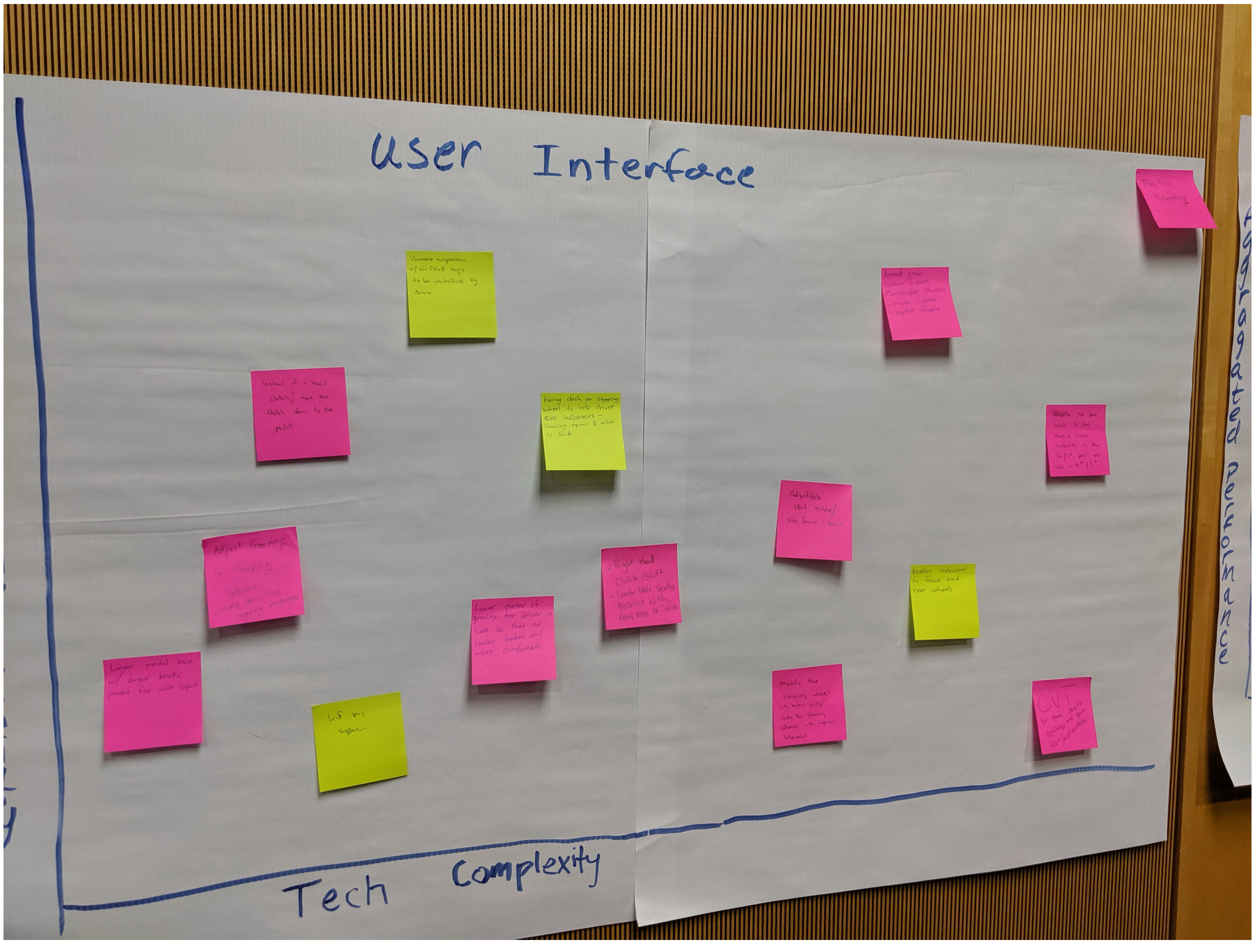

Figure C.10: Tech/Tac Plot for Group 8, with round 2 concepts in yellow

C.3 BYU Experiment 1

This experiment tested only how well teams could build a defensible Tech/Tac plot using the definitions for Tech and Tac given in this paper. There was no round 2.

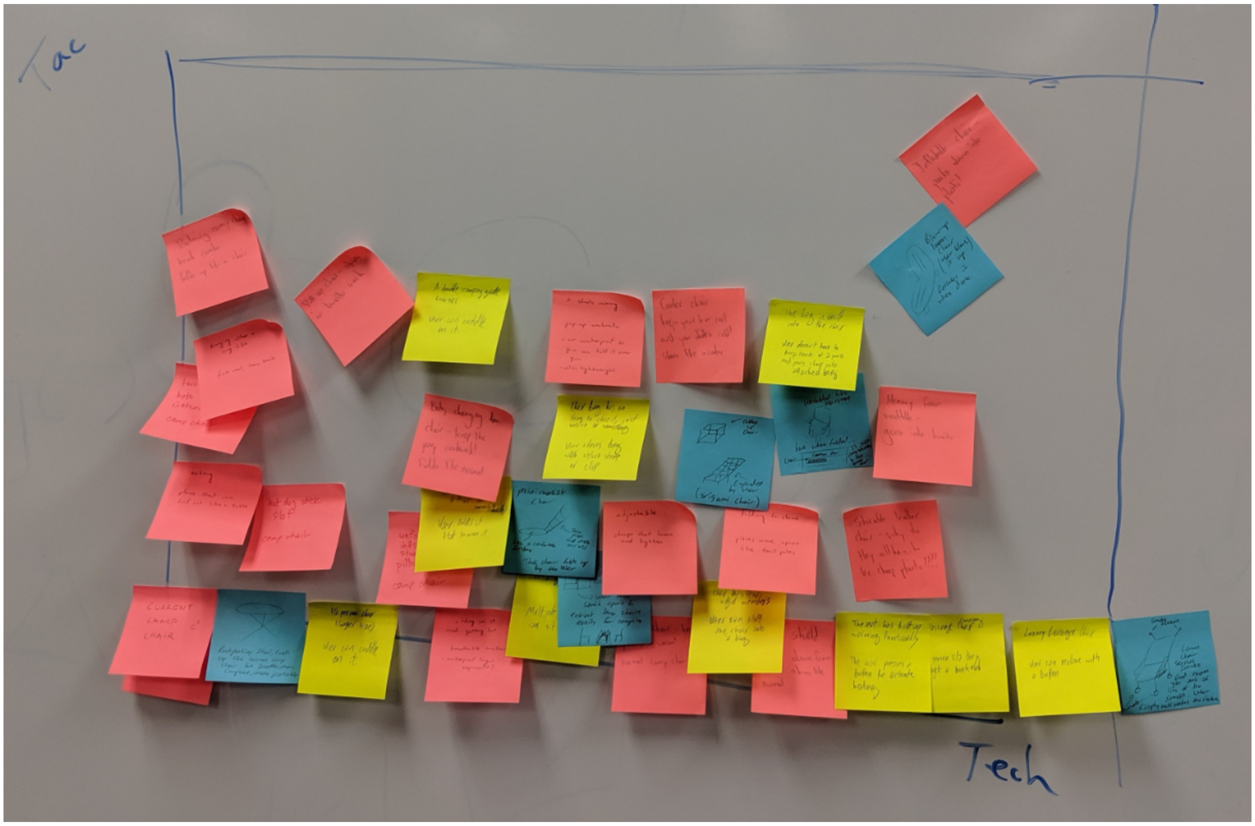

Figure C.11: Tech/Tac Plot for Group 1, note there was no round 2 in this case

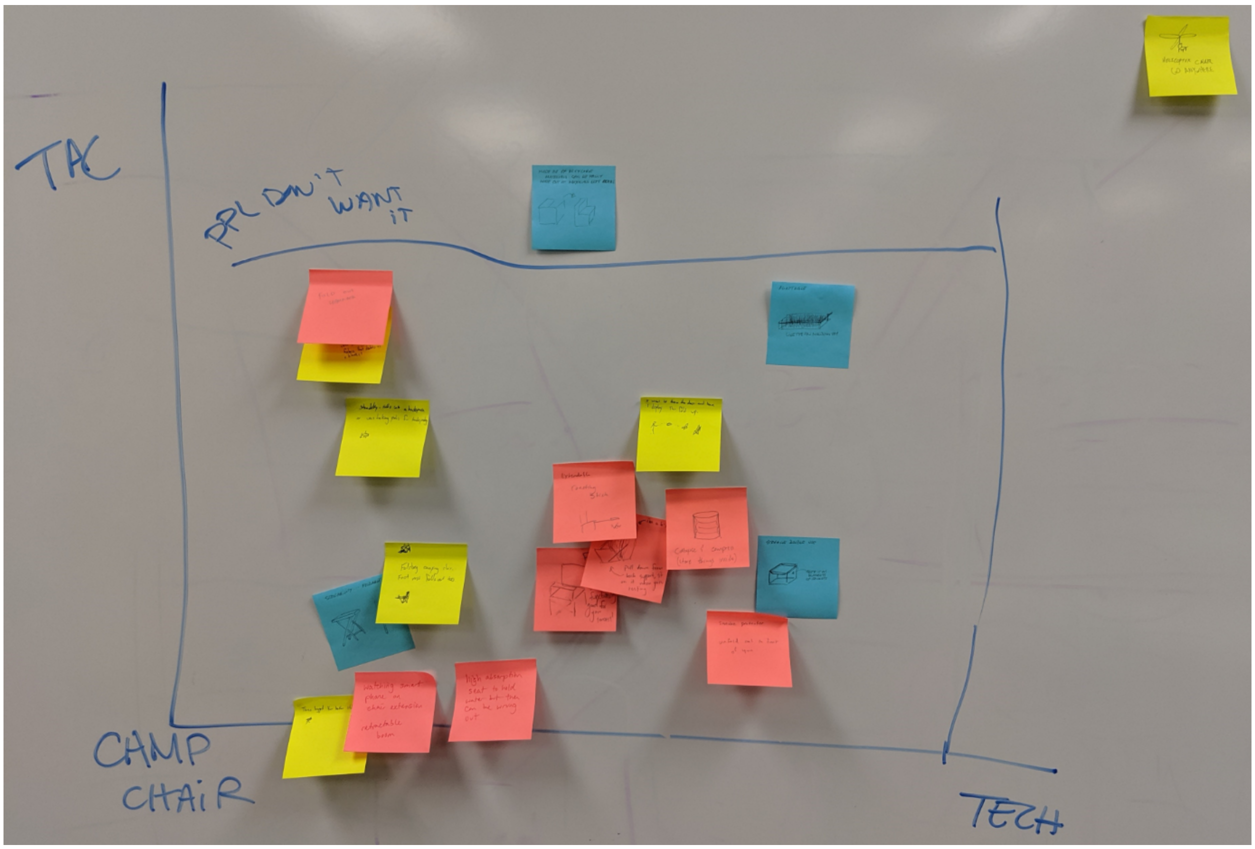

Figure C.12: Tech/Tac Plot for Group 2, note there was no round 2 in this case

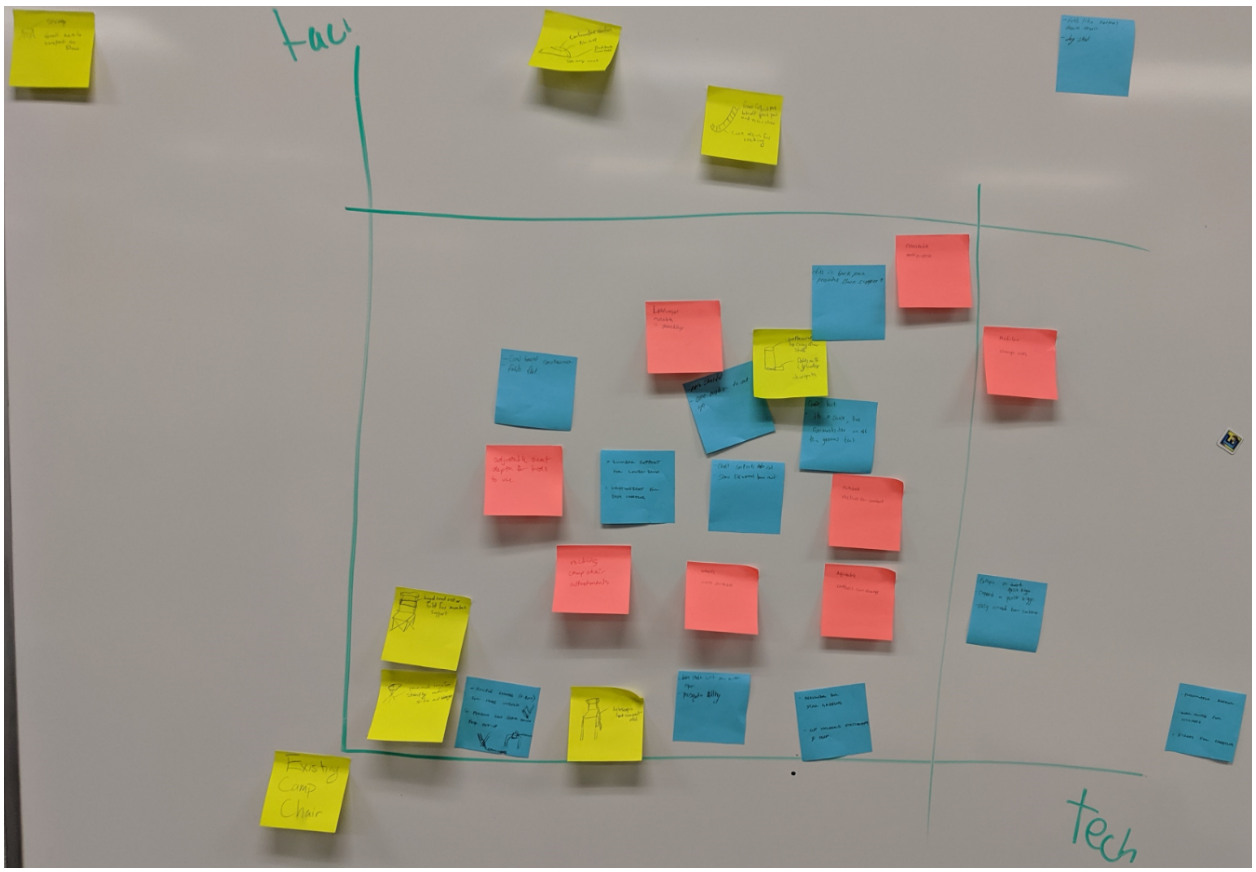

Figure C.13: Tech/Tac Plot for Group 3, note there was no round 2 in this case

APPENDIX D. ASSESSING VARIETY IN CONCEPT SETS

Assessing Variety in Concept Sets

Carl D. Sorensen, Tyler Stapleton

July 14, 2020
Revision 3.3

1 Introduction

Four attributes of a concept set that can be evaluated to determine its overall quality are Quantity, Variety, Novelty, and Quality. Our current proposal is that Quantity is evaluated just by counting the number of concepts present, Quality and Novelty are evaluated by experts using subjective judgement with some provided guidelines, and Variety is evaluated by examining the structure of the given concept set.

This paper explores options for assigning a numerical Variety score to a given concept structure.

2 Basics

The fundamental organization we propose using for evaluating Variety is an Objective - Principle - Embodiment - Detail (OPED) organization. In this OPED structure each concept in the set is aimed at achieving a desired design Objective. The most general classification of a concept is a Principle, or the general means of achieving the outcome. The next level down is an Embodiment, which is a general statement about the concept used to apply the Principle to the design challenge. The lowest level is a Detail, which contains the specific implementation details for the Embodiment.

It is expected that during ideation there will be concepts generated at each level of the PED structure. Some ideas may be expressed only at the Principle or Embodiment level. However, in order for a concept to actually be implementable, it must ultimately contain information at the Detail level.

The variety of a concept set increases at the numbers of Principles, Embodiments, and Details in the concept set increase.

3 Evaluating variety

When evaluating novelty, Shah uses a method that considers the OPED level of an idea as part of the novelty score[1] Thus, a novel principle adds more novelty to the concept set than a novel

[1] J.J. Shah, N. Vargas-Hernandez, and S.M. Smith,"Metrics for measuring ideation effectiveness", *Design Studies* 24:2 (2003), pp. 111 – 134.

embodiment. Similarly, a novel detail adds less novelty to the set than a novel embodiment. It is believed that the same is true for variety.

Consider the two concept sets shown in Figure 1. Both sets have two principles, two embodiments, and four details. If the variety score is based solely on the number of principles, embodiments, and details, sets A and B are indistinguishable. We believe that the two sets are similar in variety, but that set B has higher variety because the details are more evenly distributed between the embodiments and principles, rather than being mostly clustered in a single principle and embodiment.

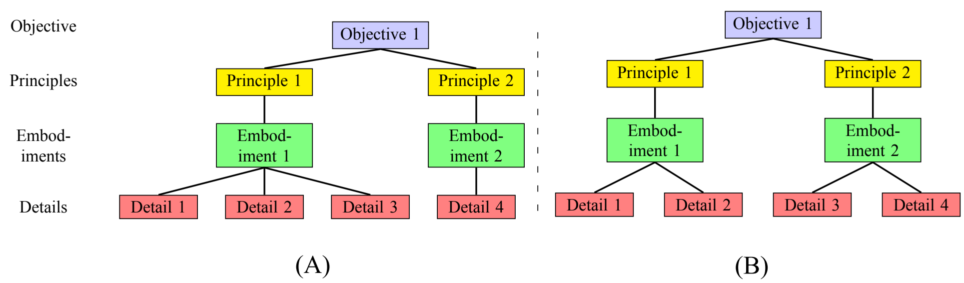

Figure 1: Two concept sets with equivalent numbers of structures, behaviors, and functions. The authors believe that set (B) has a larger variety, because the gap in design space is likely to be larger between embodiments than between details. So set (B) is likely to sample a larger area in the design space. Thus, the variety score for set (B) should be larger than that for set (A).

However, when looking at the concept sets in Figure 1, one would also think that Embodiment 1 in set (A) would likely have a larger variety than Embodiment 1 in set (B).

We propose that variety can be considered a property of the structure of a set of ideas. For our metric, we ask that the ideas be structured as a tree, as our variety metric uses the concepts of parents and children. Any tree structure is acceptable; we will use examples containing levels of Objective, Principle, Embodiment, and Detail.

4 Measuring variety

4.1 Axioms of variety

It is challenging to come up with an absolute measure of variety from first principles. However, the following axioms seem appropriate to describe how variety should change when adding new elements to a concept tree.

We propose the following axioms for changes in variety:

Axiom 1: Adding a unique entry to any level of the tree should increase the total variety of the tree.

Axiom 2: Adding a unique entry to a high level of the tree should increase the total variety more than adding a unique entry to a lower level.

Axiom 3: Adding a unique entry to a parent with few children should increase the total variety more than adding a unique entry to a parent with many children.

4.2 Nomenclature

The following variables are used in defining variety.

k – the level number. The lowest (most detailed) level is $k = 1$, and levels increase as you go up the tree. For the OPED model we use in this paper, the detail level is 1, the embodiment level is 2, the principle level is 3, and the objective level is 4.

C_{kj} – the set of element indices for all children of E_{kj}, that is, all indices i such that $p_{ki} = j$. i

$n(C_{kj})$ – the size of the set C_{kj}; the number of children of the parent element of E_{kj}.

D_{kj} – the descendant variety score for E_{kj}.

E_{kj} – element number j at level k of the tree. Element ordering at a given level is arbitrary.

A_{kj} – the allocated variety for node E_{kj}, which includes both the within-level variety and a fraction of the allocated variety of the parent.

W_{kj} – the within-level variety score for element number j at level k of the tree.

L – the total number of levels in the tree.

N_k – the number of elements at level k of the tree.

P_{kj} – variety allocated to an element from the characteristics of its parent.

p_{kj} – the index in tree level $k + 1$ of the element that is the parent of E_{kj}. That is, the parent of E_{kj} is $E_{(k+1)p_{kj}}$.

S_{kj} – the sibling variety score for E_{kj}.

B_{kj} – the branch variety score for E_{kj}, which includes both the within-level variety and the sum of the branch varieties of the children.

V – the total variety of a concept tree.

w_k – the sibling variety weighting for level k.

We propose that variety measurements include two fundamentally different relationships: the relationships between other concepts on the same tree level, and the relationships between different levels of the tree.

5 Within-level variety

In quantifying these relationships, we begin with the relationships within a specific tree level. Within-level variety depends on the number of siblings sharing a common parent in the tree, called sibling variety. It also depends on the tree level under consideration.

The within-level variety score W_{kj} is the product of the level weighting w_k and the sibling variety S_{kj}

$$W_{kj} = w_k S_{kj} \tag{1}$$

where w_k and S_{kj} are defined below.

5.1 Sibling variety

The sibling variety function is chosen to ensure that Axiom 3 is met.

The sibling variety score for element E_{kj} is given by

$$S_{kj} = \frac{\sum_{i=1}^{n(C_{kj})}(1+\beta^{i-1})}{n(C_{kj})} \tag{2}$$

where β is a positive number less than 1.

The sum in the numerator of equation (2) can be simplified as follows [2]

$$\sum_{i=1}^{n(C_{kj})} \left(1+\beta^{i-1}\right) = n(C_{kj}) + \sum_{m=0}^{n(C_{kj})-1} \beta^m = n(C_{kj}) + \frac{\beta^{n(C_{kj})}-1}{\beta-1} \tag{3}$$

With this simplification, equation (2) can be simplified to

$$S_{kj} = 1 + \frac{\beta^{n(C_{kj})}-1}{n(C_{kj})(\beta-1)} \tag{4}$$

β is chosen so that the sibling variety is higher for families with fewer siblings than for families with many siblings, in accordance with Axiom 3. Regardless of the value of β, the variety added by child one will be twice the variety added by child infinity. The smaller the value of beta, the quicker the bonus variety disappears as the number of siblings increases.

For $\beta = 0.5$, the variety added by child ten is 0.2% greater than the variety added by child infinity.

For $\beta = 0.7$, the variety added by child ten is 8% greater than the variety added by child infinity.

For $\beta = 0.8$, the variety added by child ten is 20% greater than the variety added by child infinity.

For $\beta = 0.95$, the variety added by child ten is 52% greater than the variety added by child infinity.

A plausible value of β for many concept trees is 0.7. To facilitate showing examples, we have included a table showing sibling variety values for various family sizes, shown in Table 1.

[2]https://www.oxfordreference.com/view/10.1093/oi/authority.20110803095848737

Table 1: Sibling variety for various family sizes for $\beta = 0.7$.

Number of Children $n(C)$	Sibling Variety S
1	2.00
2	1.85
3	1.73
4	1.63
5	1.55
6	1.49
7	1.44
8	1.39
9	1.36
10	1.33
11	1.30
12	1.27
13	1.25
14	1.24
15	1.22
16	1.21

5.2 Level weighting

The sibling variety score is dependent only upon the number of children for a given parent. However, the variety should depend on the level. At a higher level of generality, each concept represents greater variety.

In order to ensure that Axiom 2 is met, we include a weight factor w_k for each level of the tree. w_k is given by

$$w_k = 2^{k-1} \tag{5}$$

6 Cross-level variety

In addition to the variety existing at a given level, variety also propagates between the different levels of a tree. We have found two different propagation mechanisms that are useful in analyzing variety. The first is *branch variety*, which measures the total variety present in a branch (or subtree). The second is *allocated variety*, which measures the portion of the total variety that is attributable to a particular element of the tree.

In this discussion, we consider element E_{kj} to be one of the concepts on the tree at level k. We will also be concerned with the parent of E_{kj}, namely $E_{(k+1)p_{kj}}$, which is element p_{kj} of level $k+1$. Finally, we are concerned about the descendants of E_{kj}, primarily the children that are on level $k-1$.

6.1 Branch variety

Tree variety depends on both the element and its descendants. For element E_{kj} the branch variety B_{kj} is given by

$$B_{kj} = W_{kj} + D_{kj} = w_k S_{kj} + D_{kj} \tag{6}$$

where W_{kj} is the within-level variety defined in Section 5 and D_{kj} is the descendant variety defined below.

The descendant variety score is the sum of the branch variety scores for all children of the current element. To represent this mathematically, we define the set of child indices C_{kj} to be all values of i that satisfy the relationship $p_{ki} = j$. In other words

$$\forall i \in C_{kj}, \quad p_{ki} = j \tag{7}$$

The descendant variety score, D_{kj}, is given by

$$D_{kj} = \sum_{i \in C_{kj}} B_{(k-1)i} \tag{8}$$

Note that because $B_{(k-1)i}$ depends on the descendant variety $D_{(k-1)i}$, the descendant variety of any element will include the tree variety of all the descendants of that element.

6.2 Allocated variety

Allocated variety measures the portion of the total variety for which a given element is responsible.

The allocated variety A_{kj} is given by

$$A_{kj} = P_{kj} + W_{kj} \tag{9}$$

where P_{kj} is allocated parental variety, defined below, and W_{kj} is the within-level variety of the element defined in Section 5.

The allocated parental variety P_{kj} depends on the number of children of the parent, and the allocated variety of the parent.

$$P_{kj} = \frac{A_{(k+1)p_{kj}}}{n(C_{kj})} \tag{10}$$

6.3 Total variety

The total variety for a tree, V, equal to the sum of the branch varieties for all branches at the highest level of the tree. For a tree having a single branch at the top level (a trunk), the total variety is the branch variety of the trunk.

The total variety for a tree is also equal to the sum of the allocated varieties of the leaves of the tree (that is, the elements that have no children).

7 Examples

To illustrate these calculations, we return to the concept trees found in Figure 1. Using a value of $\beta = 0.7$ we calculate the within-level, tree, and allocated variety of the trees.

When reviewing these examples, please note that the parental variety P is the same for all siblings, as are the sibling variety S and the level weighting w. Therefore, the allocated variety A must also be the same for all siblings.

Siblings can have different descendancy structures, so D and B can vary among siblings.

Note that, as expected, set (B) has a higher variety than set (A).

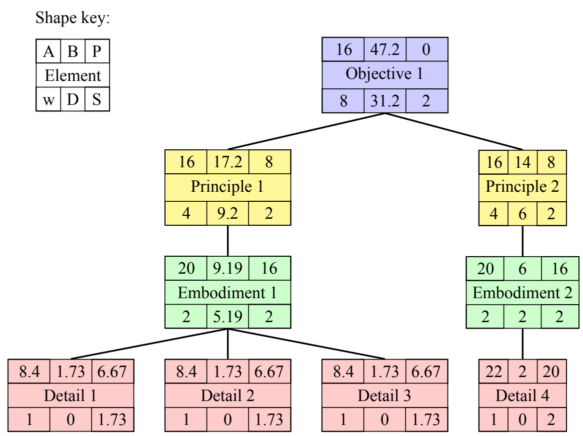

Figure 2: Completed variety calculations for tree (A) from Figure 1. The total variety of this set is 47.2. Details 1, 2, and 3 each have an allocated variety of 8.4. Detail 4 has an allocated variety of 22. The allocated variety of Detail 4 is high because it gets allocated all of the variety from Embodiment 2, while Details 1–3 are each allocated 1/3 of the variety from embodiment 1. The sum of the allocated varieties for the leaves Details 1–4 is 47.2, which is the total variety of the set.

7.1 Adding concepts for maximum variety

If our goal is to maximimize variety, we would like to generate new concepts that lie in the most promising location of the concept tree. Considering the tree in Figure 2, there are five possible unique locations for a new detail concept Detail 5:

1. As a sibling to Detail 1, Detail 2, and Detail 3, and a child of Embodiment 1.
2. As a sibling to Detail 4, and a child of Embodiment 2.
3. As a new detail as a child of a new Embodiment 3, which is a sibling to Embodiment 1 (and hence a child of Principle 1).
4. As a new detail as a child of a new Embodiment 3, which is a sibling to Embodiment 2 (and hence a child of Principle 2).

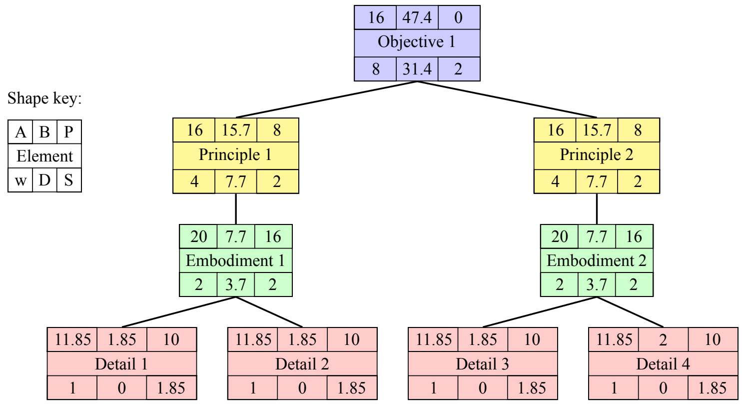

Figure 3: Completed variety calculations for tree (B) from Figure 1. The total variety of this set is 47.4, which is higher than tree (A), as expected. Details 1 through 4 each have an allocated variety of 11.85. The sum of the allocated varieties for Details 1–4 is 47.4, which is the total variety of the set.

5. As a new detail as a child of a new Embodiment 3, which is a child of a new Principle 3.

We now consider how each of these locations affects the overall variety of the concept set.

7.1.1 Case 1

Case 1 results in four children for Embodiment 1. As shown in Table 1, the sibling variety for each of the children is 1.63. The branch variety for each of these concepts will be 1.63, so the dependent variety for Embodiment 1 becomes 6.52. This increases the branch variety for Embodiment 1 (and the descendant variety for Principle 1) to 10.52. The branch variety for Principle 1 is now 18.52, and the total variety of the concept set is 48.52. Thus, the addition of one detail concept in Case 1 leads to an increase in branch variety of 1.33.

Because the parental variety and the allocated variety do not depend on the branch variety, there is no change in the parental variety and allocated variety of Principle 1 or Embodiment 1. Details 1-4 now have a parental variety of 20/4=5. Thus, the allocated variety of each of these concepts is now 6.63.

The increase in branch variety is given by 4(6.63)-3(8.4) = 1.32 as expected (within rounding error).

The scoring for this case is shown in Figure 4.

7.1.2 Case 2

Case 2 results in two children for Embodiment 2. As shown in Table 1, the siblling variety for each of the children is 1.85. The branch variety for each of these concepts will be 1.85, so the dependent variety for Embodiment 2 becomes 3.7. This increases the branch variety for Embodiment 2 (and the descendant variety for Principle 2) to 7.7. The branch variety for Principle 2 is now 15.7, and

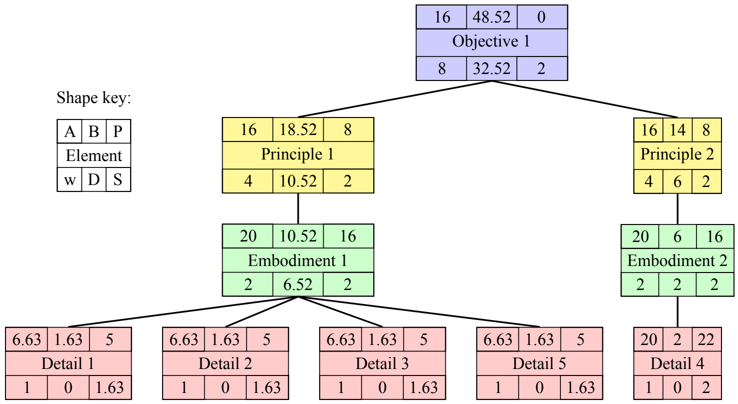

Figure 4: Completed variety calculations adding Detail 5 as a sibling to Details 1 – 3 in Figure 2, corresponding to Case 1. Total branch variety has increased to by 1.33, corresponding to an increase of the total allocated variety for the children of Embodiment 1 from 25.2 to 28.52.

the total variety of the concept set is 48.19. Thus, the addition of one detail concept in Case 2 leads to an increase in branch variety of 1.70.

Because the parental variety and the allocated variety do not depend on the branch variety, there is no change in the parental variety and allocated variety of Principle 2 or Embodiment 2. Details 4 and 5 now have a parental variety of 20/2=10. Thus, the allocated variety of each of these concepts is now 11.85.

The increase in branch variety is given by 2(11.85)-1(22) = 1.70 as expected.

The scoring for this case is shown in Figure 5.

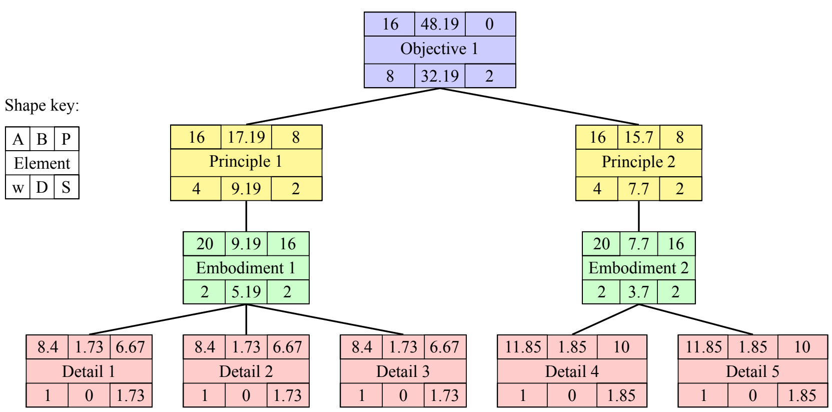

Figure 5: Completed variety calculations adding Detail 5 as a sibling to Detail 4 in Figure 2, corresponding to Case 2. Total branch variety has increased by 1.7, corresponding to an increase of the total allocated variety for the children of Embodiment 2 from 2 to 3.7.

7.1.3 Case 3

Case 3 results in a new embodiment, Embodiment 3, that is a sibling of Embodiment 1 and a parent of Detail 5. As shown in Table 1, the sibling variety for Detail 5 is 2, and the sibling variety for Embodiments 1 and 3 is 1.85.

The branch variety for Embodiment 1 becomes 8.89. The branch variety for Embodiment 3 becomes 5.7.

The descendant variety for Principle 1 becomes 14.59. The branch variety for Principle 1 becomes 22.59.

The descendant variety for Objective 1 becomes 36.59, and the total variety of the concept set is 52.59. Thus, the addition of one detail concept plus one embodiment concept in Case 3 leads to an increase in total variety of 5.19.

The parental varieties for Principles 1 and 2 remain at 8. The parental varieties for Embodiments 1 and 3 now become 8, leading to an allocated variety of 11.7.

The parental variety for Details 1 – 3 now becomes 3.9. The allocated variety for these details is 5.63.

The parental variety for Detail 5 now becomes 11.7, and the allocated variety for Detail 5 is 13.7.

The parental variety for Detail 4 remains at 20, and the allocated variety for Detail 4 is 22.

The total allocated variety is 3(5.63) + 13.7 + 22 = 52.6, which matches the branch variety to within the limits of rounding.

Note that, although the addition of a new detail and a new embodiment increased the total variety of the concept set as a whole, the allocated variety for Details 1 – 3 decreased. This is because the level variety of Principle 1 was shared between two children, which reduced the parental variety of Embodiment 1 and Details 1 – 3.

The total decrease in allocated variety for Details 1 – 3 was more than compensated for by the new allocated variety for Detail 5.

The scoring for this case is shown in Figure 6.

7.1.4 Case 4

Case 4 results in a new embodiment, Embodiment 3, that is a sibliing of Embodiment 2 and a parent of Detail 5. As shown in Table 1, the sibling variety for Detail 5 is 2, and the sibling variety for Embodiments 1 and 3 is 1.85.

The branch variety for Embodiments 2 and 3 becomes 5.7.

The descendant variety for Principle 2 becomes 11.4. The branch variety for Principle 2 becomes 19.4.

The descendant variety for Objective 1 is 36.59. The total variety of the concept set is 52.59. Thus, the addition of one detail concept plus one embodiment concept in Case 4 leads to an increase in total variety of 5.19.

The parental varieties for Embodiments 2 and 3 now become 8, leading to an allocated variety of 11.7. The parental variety for Details 4 and 5 is 11.7. The allocated variety for Details 4 and 5 is 13.7.

The total allocated variety is 3(8.4) + 2(13.7) = 52.6, which matches the branch variety within rounding limits.

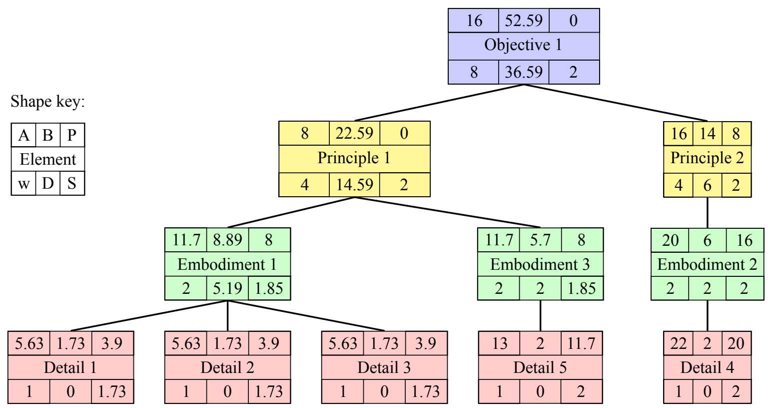

Figure 6: Completed variety calculations adding Detail 5 as a child of a new Embodiment 3 which is a sibling to Embodiment 1 in Figure 2, corresponding to Case 3. Total branch variety has increased by 5.19, corresponding to a decrease of the total allocated variety for the children of Embodiment 1 from 25.2 to 16.89, plus an increase due to the allocated variety of 13.5 for Detail 5.

The scoring for this case is shown in Figure 7.

7.1.5 Case 5

Case 5 results in a new principle, Principle 3, that is the parent of a new embodiment, Embodiment 3, that is the parent of a new detail, Detail 5. This results in duplicating the part of the tree including Principle 2, Embodiment 2, and Detail 4.

The the descendant variety for Objective 1 is now 17.19 + 14 + 14 = 45.19. The total variety is 61.19.

The parental variety for Principles 1, 2, and 3 becomes 5.33, with the allocated variety of each of them at 13.33.

The parental variety for Embodiments 1, 3, and 3, is 13.33, with the allocated variety of 17.33 for each embodiment.

The parental variety for Details 1, 2, and 3 is 5.78. The allocated variety is 7.51.

The parental variety for Details 4 and 5 is 17.33, and the allocated variety is 19.33.

The total allocated variety is 3(7.51) + 2(19.33) = 61.19, which matches the branch variety.

The scoring for this case is shown in Figure 8.

7.1.6 Summary of cases

From this set of experiments, we can draw the following conclusions:

- When adding a new detail, the added variety will be greatest when the detail is a child of a new embodiment and a grandchild of a new principle.

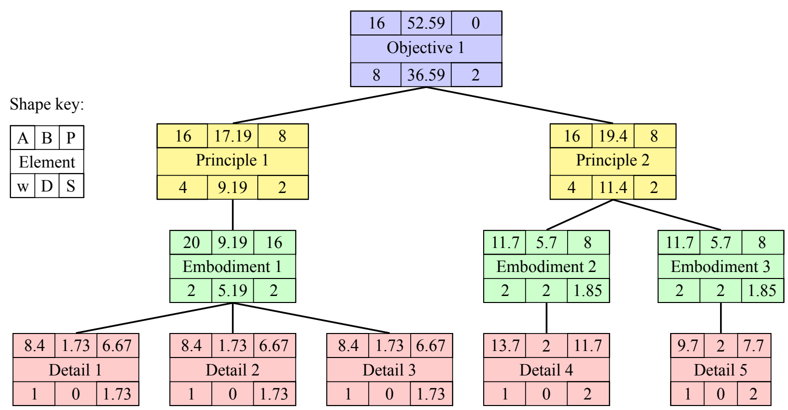

Figure 7: Completed variety calculations adding Detail 5 as a child of a new Embodiment 3 which is a sibling to Embodiment 2 in Figure 2, corresponding to Case 4. Total branch variety has increased by 5.4, corresponding to a decrease in the allocated variety of Detail 4 from 22 to 13.7, coupled with increase of the allocated variety for the new Detail 5 from 0 to 13.7.

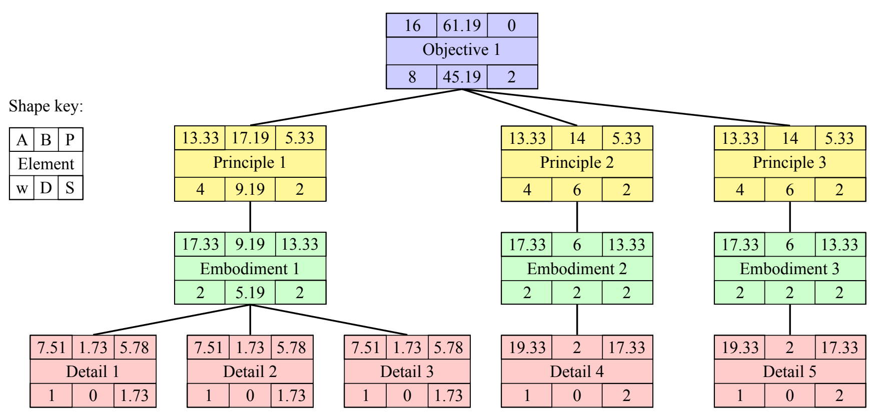

Figure 8: Completed variety calculations adding Detail 5 as a child of a new Embodiment 3 which is child to a new Principle 3 to Figure 2, corresponding to Case 6. Total branch variety has increased to by 14, corresponding an increase in the allocated variety of 19.33 for Detail 5, and decreases in allocated variety of 0.89 for Details 1 – 3 and 2.67 for Detail 4.

- When adding a new detail that creates a new embodiment but works with an existing principle, the greatest variety is added by adding the embodiment to to a principle with the fewest children.
- When adding a new detail that fits under an existing embodiment, the greatest variety is added by adding a concept where the fewest siblings exist.
- The amount of variety to be added is roughly proportional to the allocated variety of the siblings to which concepts are added.

APPENDIX E. EXPERIMENT DETAILS

Details for the participants of each experiment performed during this research are provided in Tab. E.1.

Table E.1: Team composition for each of the experiments

BYU 1				
Team	**# Participants**	**% Male**	**% Engineer**	**Experience**
1	3	66	100	Undergrad Sophomore
2	3	100	100	Undergrad Sophomore
3	Not Collected	Not Collected	100	Undergrad Sophomore
4	Not Collected	Not Collected	100	Undergrad Sophomore
5	Not Collected	Not Collected	100	Undergrad Sophomore

AFA 1				
Team	**# Participants**	**% Male**	**% Engineer**	**Experience**
1	3	66	100	Undergrad Senior
2	3	66	100	Undergrad Senior
3	2	50	100	Undergrad Senior
4	3	100	100	Undergrad Senior
5	4	50	100	Undergrad Senior

AFA 2				
Team	**# Participants**	**% Male**	**% Engineer**	**Experience**
1	Not Collected	Not Collected	100	Undergrad Senior
2	Not Collected	Not Collected	100	Undergrad Senior
3	Not Collected	Not Collected	100	Undergrad Senior
4	Not Collected	Not Collected	100	Undergrad Senior
5	Not Collected	Not Collected	100	Undergrad Senior
6	Not Collected	Not Collected	100	Undergrad Senior
7	Not Collected	Not Collected	100	Undergrad Senior
8	Not Collected	Not Collected	100	Undergrad Senior

BYU 2				
Team	**# Participants**	**% Male**	**% Engineer**	**Experience**
1	2	100	100	Graduate Student
2	2	100	100	Graduate Student

BYU 3				
Team	**# Participants**	**% Male**	**% Engineer**	**Experience**
1	4	Not Collected	100	Variable
2	3	Not Collected	100	Variable
3	3	Not Collected	100	Variable

BYU 4					
Team	**Team Name**	**# Participants**	**% Male**	**% Engineer**	**Experience**
1	Maintenance T1	2	100	50	Graduate Student
2	Maintenance T2	2	100	0	Graduate Student
3	Transport T1	2	100	100	Graduate Student
4	Transport T2	2	50	50	Graduate Student
5	Airport Naps T1	2	100	0	Graduate Student
6	Airport Naps T2	2	100	0	Graduate Student
7	Airport Disease T1	3	33	0	Graduate Student
8	Garden T1	2	100	0	Graduate Student
9	Garden T2	2	100	0	Graduate Student

APPENDIX F. EXPERIMENT DETAILS

All survey questions and responses are recorded here. Figure F.1 gives the average rating and shows the curve of scores given for the question ”How useful was the following thing?”

Question: How did the workshop help you generate more concepts? (16 responses)

- “It allowed us to have ideas stem from other ideas.”
- “Being able to look at others’ ideas helped me come up with more.”
- “It encouraged us to avoid prematurely judging ideas.”
- “It gave a specific area of interest to begin generating ideas. It narrowed the focus and gave opportunity to begin combining other ideas to form new ones in effort to completely fill up the chart.”
- “No judgement helped with generating crazy ideas.”
- “It threw out a lot of different ideas that we could build off of. Some of the new concepts were just a more technological or tactical version of what was already up there.”
- “The cram session to list ideas was really helpful.”
- “It identified unexplored areas of possibility.”
- “Lack of criticism made it easier to generate ideas and get them in the open. Once in the open they could be improved by others or could inspire others.”
- “It helped us come up with a variety of ideas.”
- “It made me elaborate on ideas I would have previously disregarded. I also went more in depth/elaborated more on simple concepts.”

- "It allowed us to see that we hadn't been thinking technologically, only tactically."
- "It showed which areas I hadn't considered."
- "It forced us to include out there ideas and recognize niches we were not investigating until we recognized they were holes we were not filling. Helped us to see some of the problem from new angles."
- "Focusing on empty areas helped generate ideas with specific requirements."
- "The topic made it difficult to sort ideas based on tactical versus technical innovation."

Question: Describe the workshop in one word (45 responses, may be multiple from each participant). Responses are listed in order of frequency (exact frequency not recorded).

1. Scholarly
2. Interesting
3. Innovative
4. Subjective
5. Enjoyable
6. Dynamic
7. Refreshing
8. Structured
9. Fun
10. Unique
11. Visual
12. Engaging
13. Outside the box

14. Elaborative

15. Entertaining

16. Low stress

17. New

18. Hectic

19. Crazy

20. Spiffy

21. Critical

22. Productive

Question: How useful was the following thing? (14 Responses)

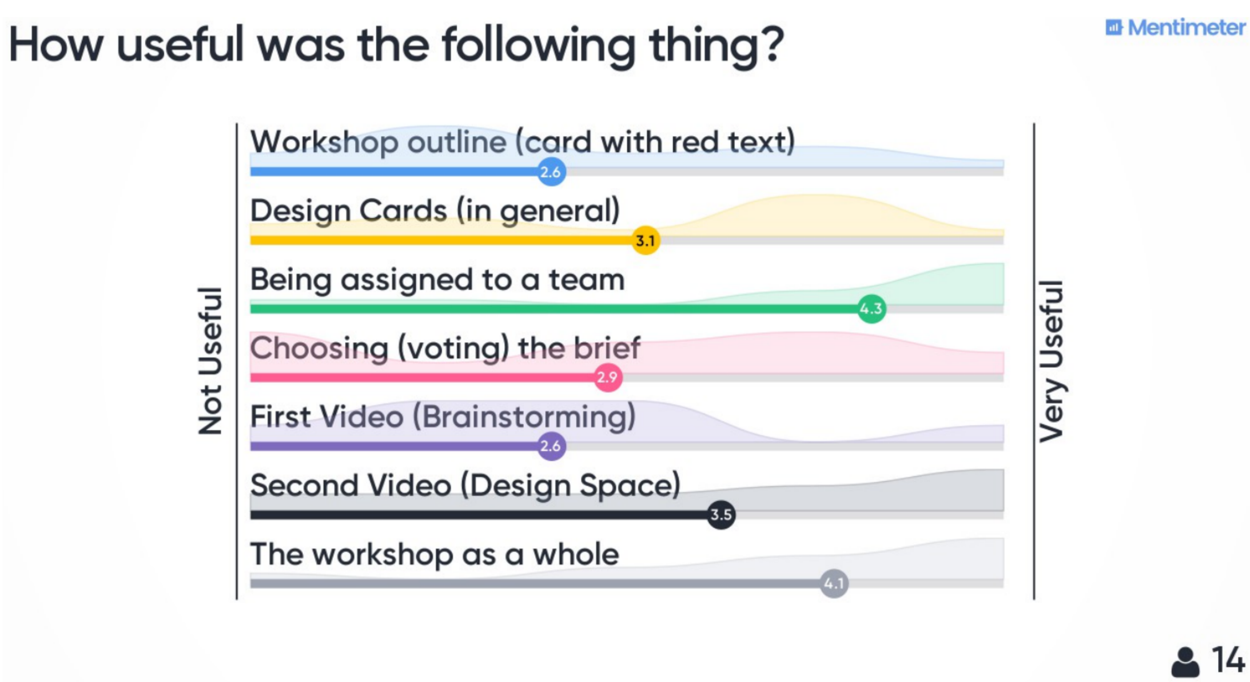

Figure F.1: Responses for the question, "How useful was the following thing?" Responses gave a score out of 5, average score shown with the curves showing the spread of the responses.