

Promoting Desirability and Transferability in Engineering Design through Customized Development Processes

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THE TECHNOLOGY/TACTICS (TEC/TAC) PLOT: EXPLICIT REPRESENTATION OF USER ACTIONS IN THE PRODUCT DESIGN SPACE

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ABSTRACT

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. They also tend to be the most unstructured portion of the project, and are often marginalized by teams who assume they already understand stakeholder needs and the best solution paths to pursue. Design researchers have developed methods shown to increase the creativity and divergent thinking of the design team during these initial phases of design. Nevertheless, these methods often rely on only a vague or amorphous representation of the design space (the set of all possible concepts the design team could feasibly select to meet the objective of the project). In this paper, we introduce a particular design-space structure that can help teams ideate and evaluate their ideation, thus improving the early phases of the design process. The design space presented here is a vector space with a basis of technology (the physical product people will use) and tactics (the procedure for using the product). Also presented are definitions, principles, and sub-theories that facilitate the creation and use of technology-tactics plots to represent the design space. Considering the design space in this structured way, the design team can gain valuable insights that improve the effectiveness of the initial stages of design, and may yield additional

benefits to the design process as a whole, if further developed.

Keywords— Design space exploration, Technology tactics plot, Bi-objective

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].

As teams seek 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. Metrics for evaluating the concept set generally involve examining the quantity, variety, novelty, and quality of a 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.

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 often represented only theoretically and

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amorphously since the actual limits of the design space are not known precisely in the early phases of the design process. Further, concepts in the concept set are often represented as points in the design space. As such, the quantity of points represents the quantity of concepts in the set; the distribution of point locations within the design space represents variety within the concept set, and so on. Importantly, the notion of a design space, coupled with metrics for evaluating a concept set, can guide the design team during ideation, as teams choose to deliberately pursue greater quantity or variety in poorly represented regions of the design space, for example.

While the amorphous design space may be placed on 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 coordinate system that we believe has the potential to help teams think more broadly during the ideation process, thus enhancing the early stages of the design process. The system used here encourages the design team to ideate in terms of two classes of concepts: concepts related to the actual product (termed Technology or TEC), and concepts related to how the product will be used/deployed (termed Tactics or TAC). As shown in this paper, at least 9 different design space plots involving technology and tactics can be used during the ideation process, or used to evaluate it. These different plots consider various perspectives such as technology innovation versus tactics innovation relative to current solutions, technology development cost versus tactics development cost, development team skill in creating new technology versus creating 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 with (ii) the philosophy that there is innovation potential in both the product itself and in how it is used. Set in the early phases of the design process, this unique combination of philosophies encourages teams to plot the concept set on two orthogonal axes; the technology innovation axis and the tactics innovation axis. Importantly, we find that this approach helps teams explicitly ideate on user tactics at the same time they are ideating on the technology/products that will be used. Such an approach recognizes the existence of both technology and tactics, and promotes their co-development and helps prevent their conflation.

Literature Survey

Evaluation of Concept Sets. In this section, we briefly review the principles found in the literature related to evaluating the concept set as a whole. Many researchers have used or further developed these principles in order to better understand the outcome of ideation [2] [3] [4] as opposed to the process of ideation [2]. Researchers have produced many indicators that can be used to evaluate the desirability of a 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, variety of concepts across the set, novelty within the set when comparing concepts in the set to products already in use, and quality of concepts in the set at meeting the design requirements on average. Generally, the desired state is that all of these indicators be maximized,

though there currently exists no measure to determine if any of these indicators are sufficiently maximized.

The basic principles relative to concept set evaluation are:

- **Design Space:** There exists a set of all possible solutions to solve a problem, which is called the design space. [5]
- **Coverage:** It is desirable to consider as many solution candidates within the design space as possible. [6]
- **Exploration:** It is desirable that the solutions considered be noticeably different from one another. [2]
- **Expansion:** It is desirable to consider a portion of concepts that are perceived to be impossible or infeasible. These points lay outside the (feasible) design space. [2]
- **Quality:** It is desirable to identify/generate multiple candidates that are considered good at meeting/balancing design objectives collectively and individually. [7]

Evaluation of Individual Concepts. When considering how individual concepts can be evaluated, some of the metrics used to evaluate the concept set no longer apply, and other metrics are needed. For example, 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] [11] [12] [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. Therefore, the presence of innovative solutions in the candidate set is one indication that ideation has been effective.

The graphical representation of the design space used to evaluate concept sets has a parallel when considering individual concepts — 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 [14]. Romer proposed a number of performance objectives for use in the field of wireless sensor design including mobility and deployment [15]. 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 might be necessary.

THEORETICAL DEVELOPMENTS

In this section, the core contribution of this paper is presented, which centers on the creation and use of technology-tactics plots.

The Technology-Tactics Plot (TEC/TAC)

The technology-tactics plot (or TEC/TAC plot) is shown in Fig. 1. The plot shows two orthogonal axes; TEC (representing technology — the products developed as a result of the design process) and TAC (representing tactics — the way the products will be used or deployed). These axes characterize the two dimensions of the feasible design space considered in this paper. The red points on the plot represent individual concepts for a design problem. The blue point, labeled (S_0), represents the existing solution (if there is one) to a design problem. It is the solution that will be pursued if the design team does no development. With

the brief introduction given above, we can now be more specific about the nature of the TEC/TAC plot axes. The horizontal axis is specifically the change in technology beyond the existing solution (S_0). Likewise, the vertical axis is the change in tactics beyond the tactics of the existing solution (S_0). Qualitatively speaking, if a concept employs similar technology/hardware as the existing solution and is used with the same tactics as the existing solution, the concept is plotted near S_0 . If it employs different technology/hardware and/or different tactics, it is plotted far from S_0 . In this way, the concepts emerging from ideation may be plotted in this space according to how much they differ from the existing solution in terms of both technology and tactics. In this graphical representation, S_0 is the origin and change in technology/tactics are only plotted in the positive region of the coordinate system.

Once the concept set has been represented in the TEC/TAC plot (each concept illustrated as a point within the design space), the TEC/TAC plot will show where in the design space sufficient ideation has occurred and where it has not. This guides the team to where in the design space they need to explore in more detail.

Considering the cloud of points in the TEC/TAC plot, it becomes natural for the team to discover and impose upper and lower limits on the space (these are represented as light-weight lines in Fig. 1. For example, limits can be established through critical interactions with stakeholders where these limits can be discussed and explored. Teams might ask: how different does the final product need to be (from the existing solution) to motivate customers to invest in the upgrade? How different can the final product be and still appeal to the market; would the market accept a dramatically different kind of product? To what degree can we expect users to learn a new tactic in order to use a new product? These limits may also be derived from other development information such as the development resources available. There may simply not be enough resources to pursue concepts that differ too much from existing products. Setting these limits gives the team a better understanding of the full size of the feasible design space, allowing them to evaluate how well their concept set is expanding to fill the feasible space.

The TEC/TAC plot offers design teams the opportunity to think beyond the physical product by explicitly considering how those products would be used or deployed. Without considering the TEC/TAC plot, or the principles it represents, it is common for teams to conflate technology and tactics and thereby ideate without knowing to what degree the concepts generated differ in terms of product tactics or technology. In short, when ideation results in great concept diversity along the TEC axis with minimal diversity along the TAC axis the team has missed an essential dimension of ideation and the opportunity to co-develop the product and how it will be used.

The TEC/TAC Plot as the Full Design Space. The TEC/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 design space.

For this paper, change in technology and change in tactics are suitable qualities for a vector basis, as they can be reasonably established

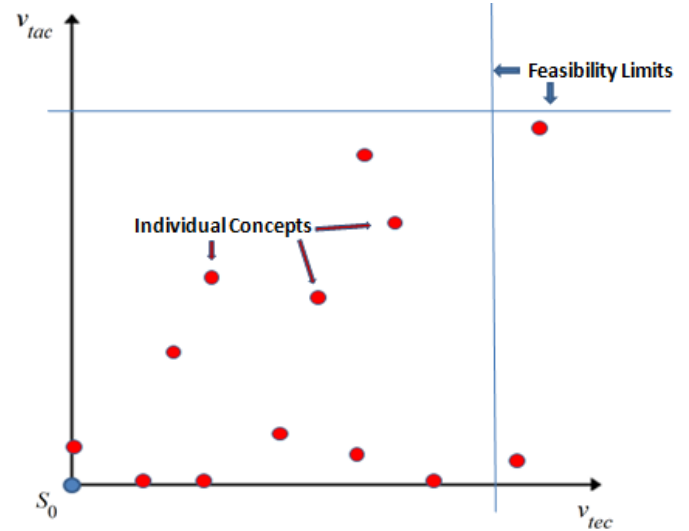


FIGURE 1. The Technology-Tactics (TEC/TAC) Plot, in which horizontal distance from the origin represents differences in technology of a given idea, while vertical distance represents difference in usage or tactics

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 [16]. Under this philosophy, the design process starts with a problem to solve (termed: job to be done). To improve 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 change in the actions of the user with regard to the job to be done constitutes a tactics change.
- Principle 2: Any change in the equipment utilized by the user with regard to the job to be done constitutes a technology change.
- Principle 3: If the actions of the user with regard to the job to be done are held perfectly constant, the only option for change with regard to the job to be done must be a technology change, and vice-versa

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

Therefore a vector measuring changes in technology (v_{tec}) and a vector measuring changes in tactics (v_{tac}), forms a basis of a vector space and the axes of the design space if they share an origin. This two-vector basis constrains the vector space in R^2 , creating a simple and useful 2D graphical representation of the space with the existing solution at the origin (S_0).

Generalization of the Origin. The TEC/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 staged 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 change in technology and change in tactics that define the TEC/TAC plot. As such, any point on the TEC/TAC plot is defined by the vector V_i , where

$$V_i = (x_i - x_0) + (y_i - y_0) \quad \forall \quad x_0 \leq x_i \leq x_{up}, y_0 \leq y_i \leq y_{up} \quad (1)$$

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

Distinguishing Between Technology and Tactics

During the ideation process, at intervals deemed appropriate by the team, concepts can be plotted on a TEC/TAC plot. To do so effectively, the team must be able to distinguish between a concepts technology and its tactics. To assist teams with this we propose the use of control volumes, which are generally used in thermodynamics and elsewhere to simplify the evaluation of complex systems. Here, control volumes are useful because they allow for a definitive definition of the control volume boundary and an analysis of what crosses that boundary.

In the context of the design process, imagine that a control volume contains everything the design team controls that is sent to the user at the end of the design process, regardless of how it is actually sent. Generally speaking, the control volume for engineered products will contain a product and whether explicit or not, instructions on how to use the product. 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, where the dashed line represents the control volume boundary. One reason why control volumes are meaningful to TEC/TAC plots is that they clarify whether a concept has just a technology change, just a tactics change, or whether it has both associated with it. When a team wishes to place a concept on the TEC/TAC plot, the team should ask: i. 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, and the concept is plotted to the right of the existing solution (S_0) in the x dimension. How far it is plotted to the right of S_0 depends on how different the new technology is from the existing technology. ii. Do new tactics (instructions) need to be delivered to the user for them to implement this solution? In other words, does the user have to behave differently with respect to existing or new technology to accomplish the desired task? If so, new tactics cross the control volume boundary, and the concept is plotted above the existing solution (S_0) in the y dimension. How far above depends on how different it is from existing tactics.

It is important to note that, in this paper, the control volume is defined by what is delivered to the end user not what is delivered to the manufacturer. This is helpful in clearing up confusion about what information or physical goods are crossing the boundary.

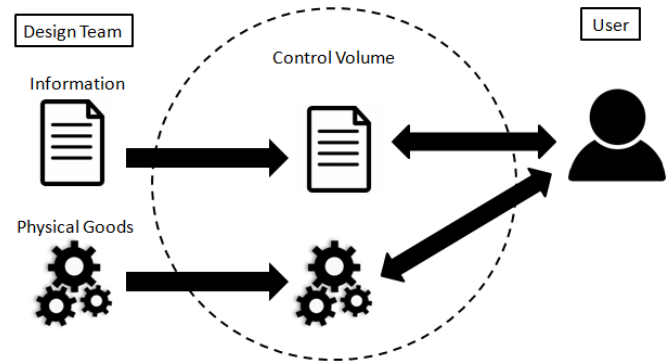


FIGURE 2. Control Volumes in Solution Delivery: all aspects of a given solution must be passed through the boundary by the design team (at a cost) to become accessible by the user (also at a cost)

Three Different Perspectives on TEC/TAC Plots

Up to this point in the paper, we have simply considered the TEC/TAC plot from the perspective of change in technology and change in tactics beyond an existing solution. We have considered that perspective to be the general interpretation of the TEC/TAC plot.

There are, however, at least two other ways to use TEC/TAC plots in a meaningful way during the design process; using them (i) to characterize the anticipated development costs for each concept, and (ii) to characterize the anticipated costs for users to acquire and learn to use the concept under consideration. In brief, three different TEC/TAC plot types are considered in this paper:

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

The first of these types has been the focus of the paper up to this point. The second type aims to illustrate the feasibility of concepts from the design teams perspective in terms of actually being able to develop the concept, and the third type considers feasibility of each concept from the users perspective in terms of a user being able to acquire and learn to use the technology efficiently.

Importantly, each of these perspectives benefits from using the principle of control volumes. For design team centric plots, teams consider how much it will cost to develop each concept, which in the context of control volumes means how much will it cost (in terms of time, money, and skill) to transition technology across the control volume boundary. And for the user centric plots, how much will it cost (in terms of time, money, and skill) to acquire and learn to use the new technology within the control volume.

By considering team- and user-centric TEC/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.

A total of 7 specific TEC/TAC plots have now been introduced. They are:

- The general (relative difference) TEC/TAC plot
- The financial cost to develop TEC/TAC plot
- The time to develop TEC/TAC plot
- The skill required to develop TEC/TAC plot
- The financial cost for users to acquire or learn to use the new technology TEC/TAC plot
- The time for users to acquire or learn to use the new technology TEC/TAC plot
- The skill for users to acquire or learn to use the new technology TEC/TAC plot

It is not necessary that all of these plot types be considered to evaluate the effectiveness of the ideation process, but these and others may be considered if the team deems it valuable to do so. The plots will now be described in more detail to help teams better understand the relative value of each.

Relative Difference Plot (General TEC/TAC Plot).

The value of the general TEC/TAC plot is its simplicity. The plot can be used generically and relatively, without defining a specific measure for change in technology and change 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 plot it on a TEC/TAC plot. Concepts can be added to the plot easily, and the meaning of each concepts location within the plot grows as more concepts are added. This simple plot helps teams identify where in the design space additional exploration is needed.

Challenges associated with the general TEC/TAC plot are that the upper and lower limits are more difficult to define than the limits of TEC/TAC plots characterizing cost and time. Additionally, when considered alone, the general TEC/TAC plot does not capture all relevant information. For example, concept feasibility due to team or user-centric factors is not specified, so some concepts may be infeasible, even those very close to S_0 , due to factors represented in the team or user centric TEC/TAC plots. In this case, a simple demarcation cannot be drawn to separate feasible and infeasible concepts as it relates to important team and user considerations. However, when used in conjunction with team and user centric plots, infeasible concepts relative to all perspectives can be removed from the general TEC/TAC plot, leaving it a useful summary of all plots, as shown in Fig. 3. Note that S_0 is plotted at the origin.

When establishing upper limits on change in technology and change 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. The exact shape of this upper budget will vary based on how independently the team can work on tactics and technology development. Establishing this limit requires significant understanding of the market preferences and trends.

When establishing lower limits on change in technology and change in tactics, the client who commissions or funds the development is likely to have expectations regarding a minimum level of development (change or differentiation) beyond existing solutions. Establishing these lower limits helps the team avoid spending too much time on concepts containing only marginally incremental improvements. A recent study

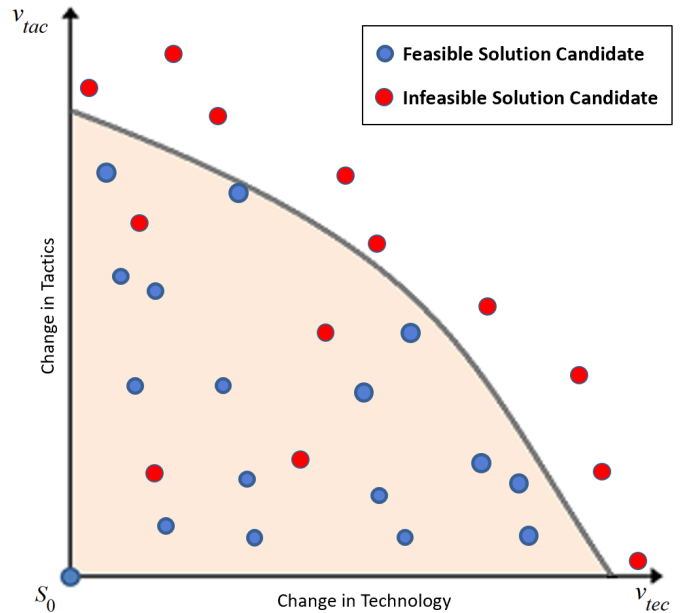


FIGURE 3. The Relative Difference Plot, with an outer boundary marking the point where changes in the concepts become too extreme, though some infeasible concepts still exist inside the boundary based on other criteria

by Goodson et al. discusses recent attempts by students and faculty to establish and use such limits [17].

The Design Team Centric TEC/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. 4. 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 $(Tactics\ spend) + (Technology\ spend) = \text{Max budget}$, as shown in Fig. 5 below.

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 TEC/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.

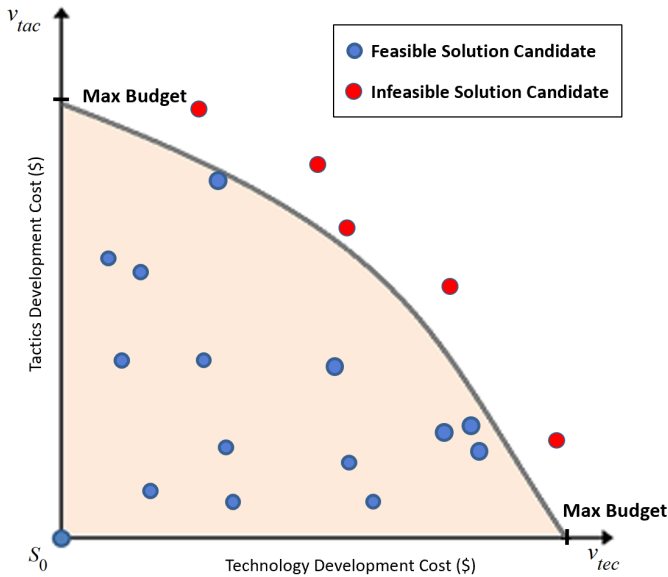


FIGURE 4. The Design Team Centric-Financial Cost Plot. Upper limits based on point where concepts become too costly for the design team to pursue

We recognize that it is more difficult to establish the limits of skill as it relates to a TEC/TAC plot, than it is to establish limits for quantities such as financial cost and time. Nevertheless we believe it is valuable for a team to consider their skills when evaluating concept sets that result from ideation, even if that evaluation is more qualitative or anecdotal than the evaluation of financial cost and time.

The User Centric TEC/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 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 and 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 users time, money and skill
- Principle 4: It is essential for development teams to consider the design space from the consumer's perspective [18] [19] [20]

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 users 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

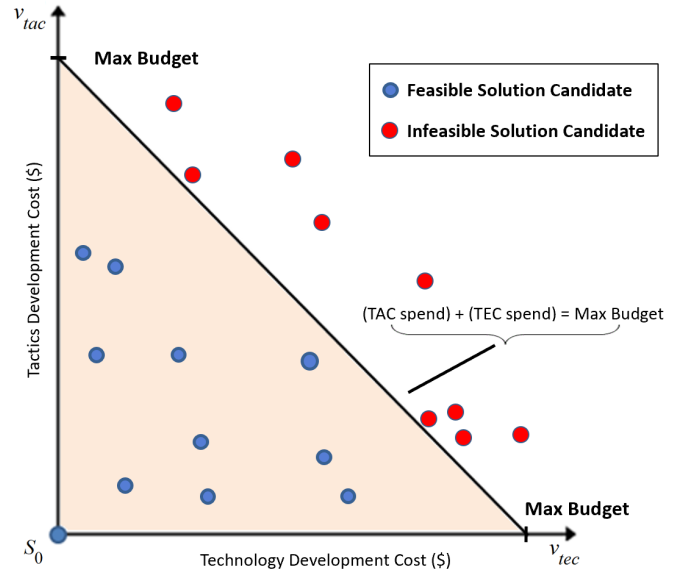


FIGURE 5. The Linear Limit Case. High cost of developing more complex Tactics means less money available for Technology development

for users to become proficient at using the new technology. And 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 to their environment; is the user expected to have skill in a particular field of knowledge such as machine maintenance or deploying a missile? When a team plots concepts on a TEC/TAC plot relative to the skill required of the users, it helps the team understand if they are asking too much of users. Setting the limits of user centric plots requires knowing the user, including their skills and resources.

There is one additional TEC/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. 6.

The benefit added plot illustrates the perceived benefit of technology innovation, and the perceived benefit of tactics innovation to the user. 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. We mention this plot here to emphasize that by only examining the costs to the user and not the benefit it is impossible to estimate which concepts will be valued by the user and which will not. In evaluating the concept set, the team should determine if it has created a sufficient number of concepts, of sufficient variety.

PLACING CONCEPTS ON TEC/TAC PLOTS AND USING THEM FOR EXPLORATION

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

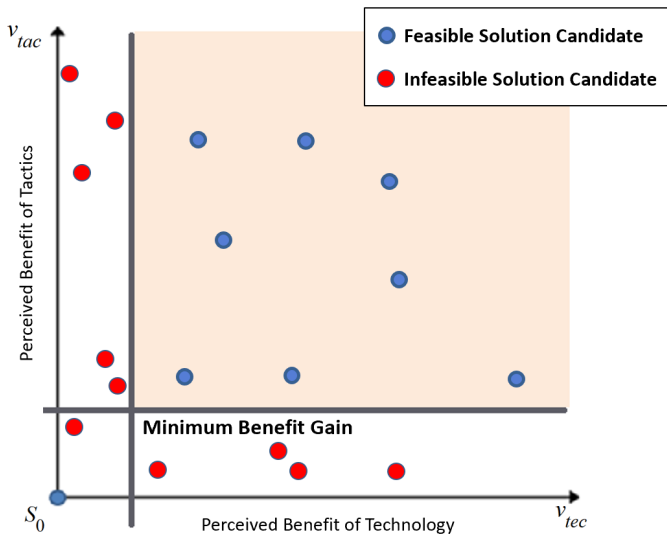


FIGURE 6. Design Team Centric Benefit-Added Plot. Projects that provide low benefits to the design team are marked as infeasible (note these are lower bounds). No upper bound has been found

- be used for the evaluation. The options are (i) relative difference perspective, (ii) design team perspective, and (iii) user perspective.
- 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 is associated with S_0 , and what tactics are associated with S_0 .
 - Choose whether S_0 will be located at the origin (0,0) or another point in the design space.
 - Establish TEC/TAC plot limits, if there are any. These limits are likely to be discovered through interactions with project stakeholders.
 - Evaluate each concept relative to S_0 and the TEC/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 TEC/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 7 TEC/TAC plots.
 - 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.
 - 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.
 - Use the evaluation results of (8) to decide if additional ideation is needed, and where in the design space improved quantity, variety, novelty, or quality are needed.

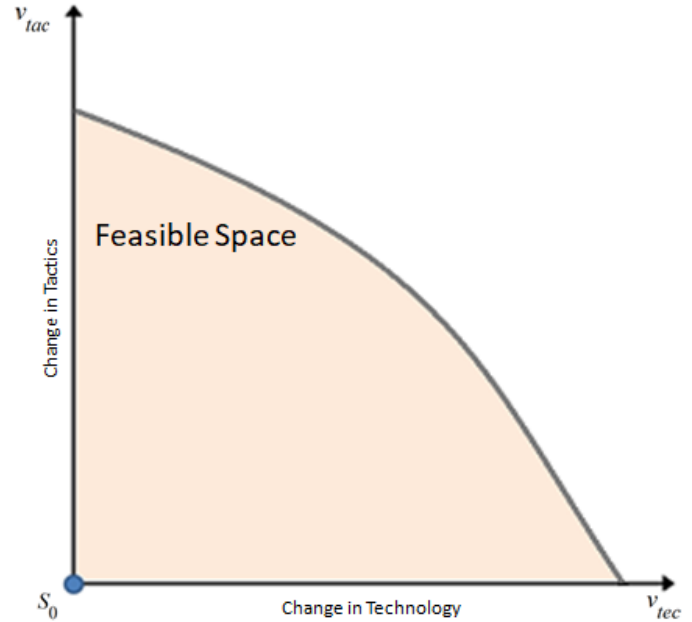


FIGURE 7. The Feasible Design Space on a TEC/TAC Plot. The actual placement and shape of the upper bound will depend on the basis of the plot

- Repeat steps 1-9 until the results of the ideation process are satisfactory.

In using the process described above, the team explores the design space, in that it discovers the size and content of the feasible design space.

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 more clear understanding of the feasible boundaries begin to emerge.

To illustrate this, consider the feasible design space shown in Fig. 7.

Notice the presence of S_0 and the feasible boundary (shown as a curve) 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. 8.

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

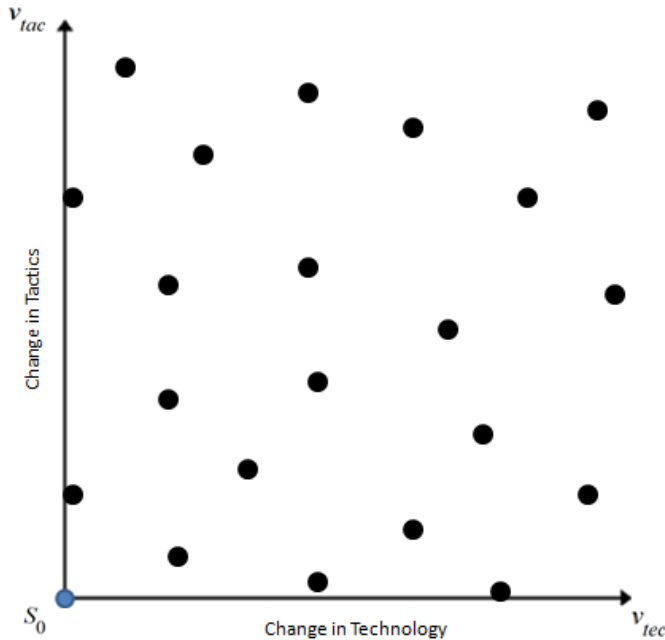


FIGURE 8. A Sample Candidate Set. Note that in this representation, the set appears to fill the entire design space

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 teams 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. 9, 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.

EMPIRICAL FINDINGS

To test the implications of the TEC/TAC plot, the basic principles of the plot were presented to capstone students at the United States Air Force Academy, and the teams were encouraged to incorporate the concept into their design ideation processes. Figure 10 shows the results of an ideation session by one of the teams. This design team was challenged to develop technologies for detecting the presence of certain sensors and prevent the sensor from detecting the user.

With the TEC/TAC plot as a guide, the team effectively filled less concentrated areas of the plot to cover the available space. Figure 10 illustrates the potential for this plot to alter the lens through which the design team sees their concepts. Take, for example, the concept Shoot

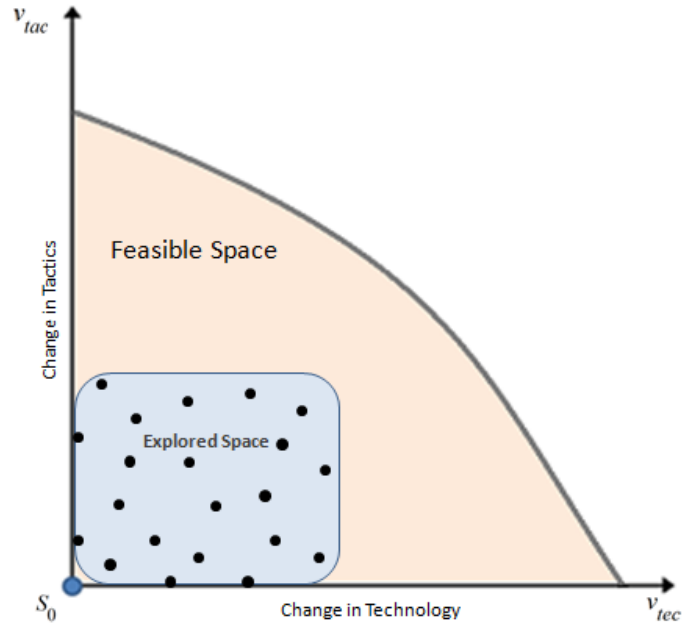


FIGURE 9. The Explored Design Space, which in this case only fills a portion of the entire design space. Discovery of the actual upper bound on the space reveals empty space we can explore

it (in the upper left-hand corner). Despite its obvious simplicity, this concept was plotted very high on the tactics axis. Perhaps the design team considered the impact of this concept on established movement patterns of the end-user. They may have considered the high level of skill an end-user would need to acquire in order to successfully locate and shoot a small sensor in a (potentially) hostile situation. In short, the design team is deliberately considering their users and the desirability and feasibility of the tactics they would be expected to adopt.

After reaching the candidate set in Fig. 10, the team began to consider their concept set. Earlier it was noted that bounds are difficult to establish on the general plot because of the challenge of defining the amount of change that is acceptable to the user. In this early test, the team had the freedom to determine the upper limits. In this case, the upper limit (designated by a green dotted line in Fig. 10) does not denote upper limits on the change, but rather an elimination of several high-change concepts which all were determined infeasible for various reasons.

Having completed an initial elimination, the team then arrived at the concept set illustrated in Fig. 11 (note the scope of the plot has been narrowed to below the upper bounds, and that several of the points within those bounds were also determined infeasible for separate reasons. They then took the examination a step into convergent examination, restricting the set to the most promising concepts, which further reduced the set to Fig. 12.

Though this paper is focused on the uses of TEC/TAC in divergent thinking and ideation, this experiment also shows the promising applications of the plot to convergent methods as well. In fact, in a survey of 21 of the students involved in this investigation, 17 of those students

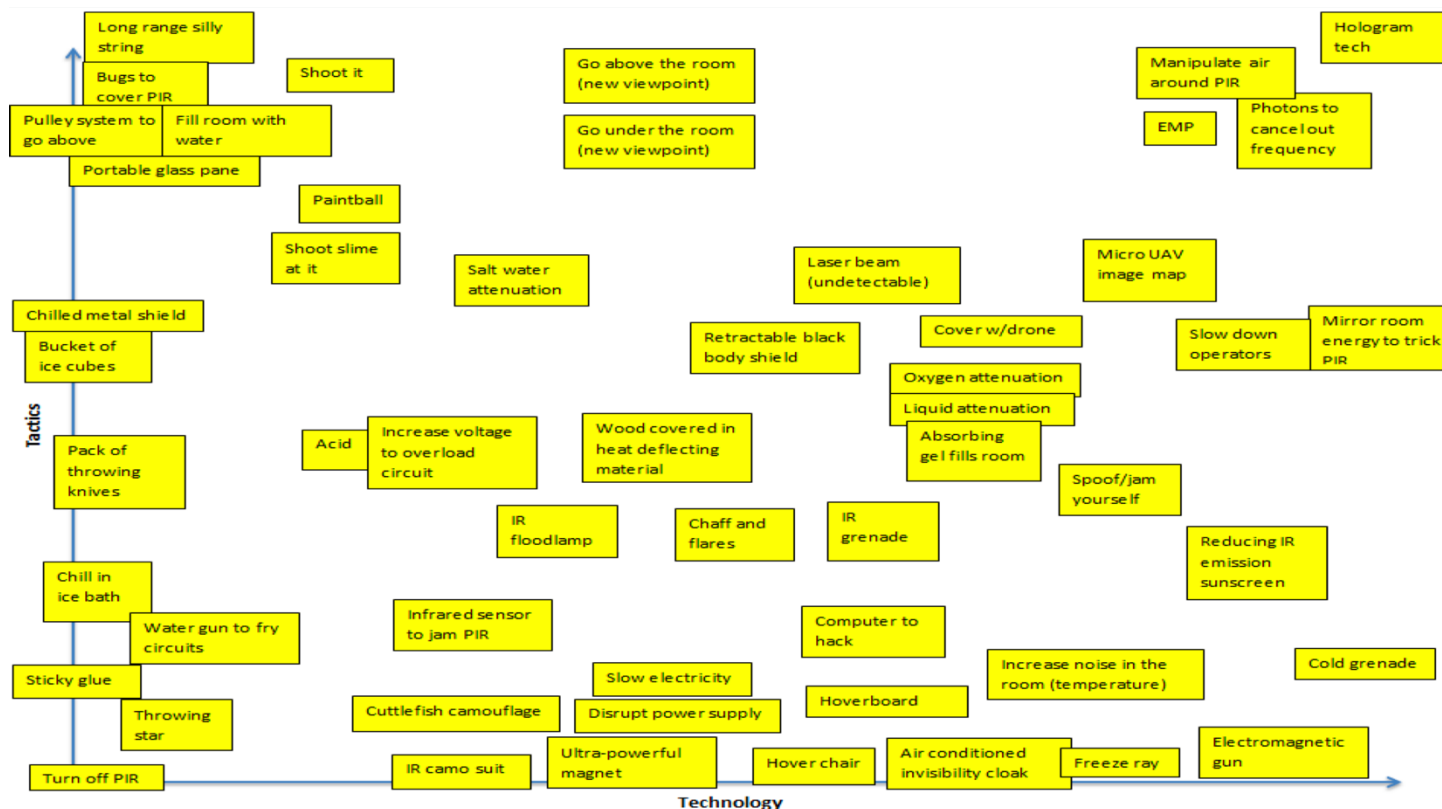


FIGURE 10. Filled TEC/TAC Plot. The team has attempted to fill the blank areas on the plot, and has included many infeasible concepts to push limits on the explored design space

cited aiding in down-selecting their concepts as a primary benefit of the plot.

Further research is exploring the applications of TEC/TAC to convergent processes. In this case, this design team was able to utilize the plot to grow their concept set until the feasible design space was mapped, and then use the limits to assist in converging toward the best solution. This initial test drive demonstrates the potential value of the TEC/TAC plot as a design tool throughout the entire design process.

CONCLUSION

In this paper, we have explored the merits of exploring the feasible design space as a 2D vector space. We introduced the concepts of tactics and technology as axes for that space, and established the mapping of solution concepts within the TEC/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 TEC/TAC plot helps design teams to avoid the pitfall of under-examining the design space during ideation, especially when it comes to

examining the tactics dimension. Likewise, viewing the sequence of plots, as we have done, provides a straight-forward means for the design teams client(s) to evaluate the thoroughness of the teams ideation. It 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, their client, 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 far more likely to find and produce a superior final result. The merits of TEC/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.

ACKNOWLEDGMENT

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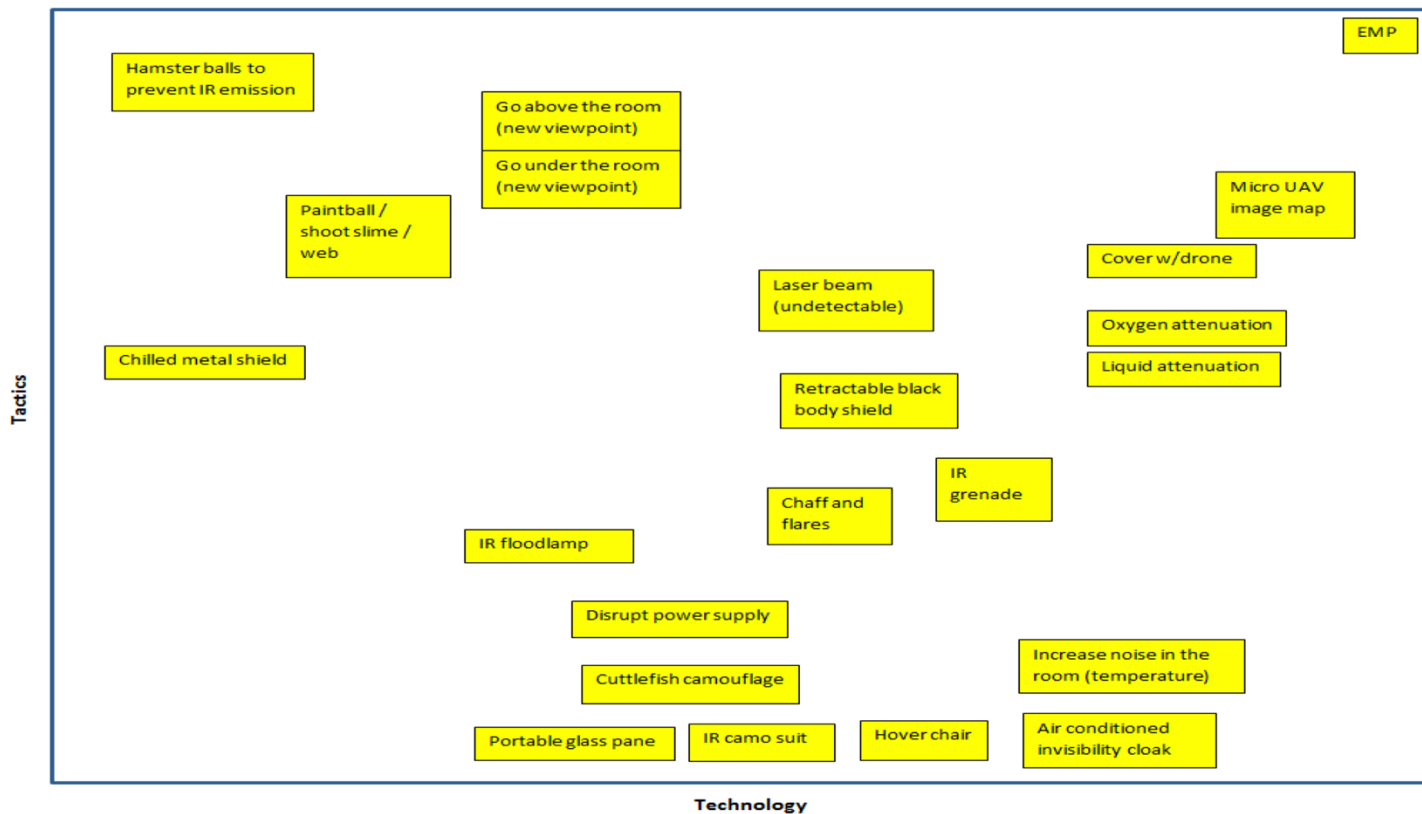


FIGURE 11. Infeasible Concepts Removed. Note that "EMP" is now the top-rightmost concept. The students were able to establish upper limits above this point

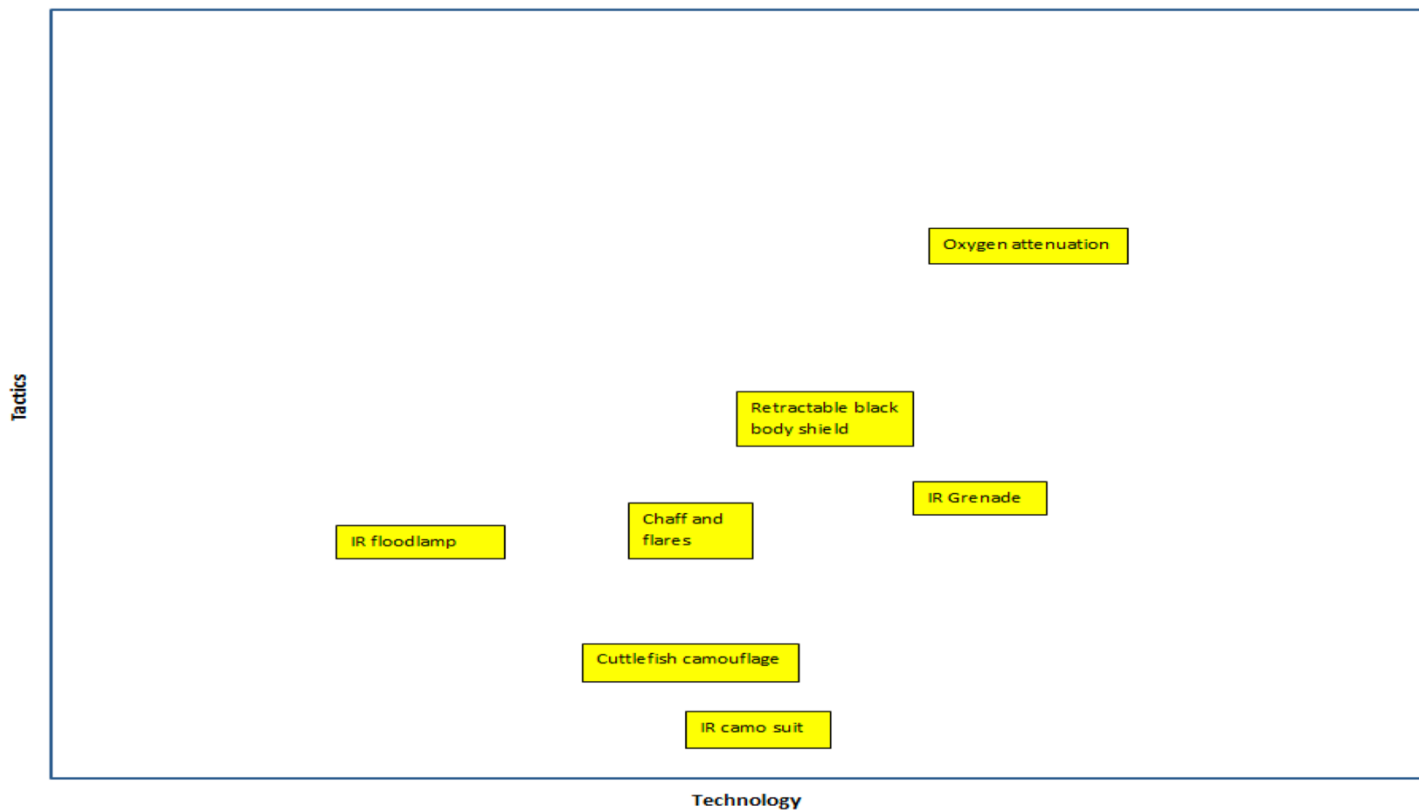


FIGURE 12. Most Promising Concepts Selected. The team's understanding of the performance of each of the concepts in accomplishing the mission allowed the top-performing concepts to be selected

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**DO CAPSTONE STUDENTS REALLY UNDERSTAND THE NEEDS OF THE CUSTOMER?:
OBSERVATIONS ON STUDENTS' BLIND SPOTS LEFT BY EARLY PROGRAM
CURRICULUM**

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ABSTRACT

Student capstone teams have varying degrees of success in meeting the expectations of their project sponsors. Keeping sponsors happy is important to these programs in order to ensure continued support from these industry representatives, so finding ways to improve project outcomes is critical. In order to find blind spots that students may have been left with after their first 6-7 weeks of instruction, we conducted structured interviews with students in capstone programs at Brigham Young University and the US Air Force Academy. These interviews were then transcribed, coded, and analyzed for themes that may have been well understood or misunderstood by students. We found that a significant number of students had not understood concepts such as a design being more than a prototype, that sponsors have expectations for the tradeoffs between product cost and performance, or that they need to be thinking about how their designs might be deployed. It was also interesting to note that most students also reported feeling confident in their understanding despite their apparent lack thereof, indicating that these could represent major blind spots for students. We propose that developing methods for teaching these principles early on will help students see more clearly what their end goals need to be, and thus help them be more successful in delivering desirable designs.

Keywords: Capstone, Project Descriptions, Sponsor Expectations, Customer Needs, Design Deliverables

1. INTRODUCTION

A joint research team was formed between the United States Air Force Academy (USAFA) and Brigham Young University (BYU) engineering design capstone programs in order to find ways to help instructors better mentor students and also to explore new ways of thinking about the design process that could prove valuable to designers everywhere.

As part of this project, the team conducted interviews with students in the universities' capstone programs during the 2018-2019 scholastic year in order to try to gauge how well students understand what their sponsors expect of them, especially with regard to the final project outcomes.

The two capstone programs are distinct, with very different backgrounds and each having its own educational objectives and methods for achieving those objectives. A brief summary of the two programs is given here.

1.1 Brigham Young University Capstone Program

The Capstone program at Brigham Young University is a two-semester senior design class required for all students in Computer Engineering, Electrical Engineering, Manufacturing Engineering, and Mechanical Engineering. Students are placed in interdisciplinary teams and asked to develop products that meet the needs of real customers. Most students work on design challenges provided by external sponsors; a few teams work on engineering competitions such as the Shell Eco-marathon and Baja SAE. BYU Capstone has been in operation since 1989 and has completed over 800 projects from nearly 300 different

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sponsors and served over 4600 students. Enrollment in the 2018-19 academic year has included 350 students working on 46 projects.

The BYU Capstone program was developed to meet industrial needs for graduating students [1]. In recent years it has focused on the importance of developing desirable and transferable product designs [2]. The course focuses on inviting students to seek for design outcomes, rather than focusing on design tools. Design tools are viewed as a means to an end. Students are challenged to thoughtfully select tools that optimally help them meet the design challenges they face in an optimal manner. Students are required to advance the design of their product through four stages of product development: Opportunity Development, Concept Development, Subsystem Engineering, and System Refinement. Students are also expected to create artifacts that define the design and its evaluation; the evolution of the design is reflected by the artifacts.

In the BYU Capstone program, students work in interdisciplinary teams that typically have 5 to 8 students. Students are placed on teams according to their interest in and skills related to specific design challenges. Teams are expected to develop market requirements and performance measures for the product to be developed. They then create a concept with a high likelihood of meeting the market requirements. During Subsystem Engineering, teams focus on designing, building, and testing individual subsystems that will meet the system requirements. During System Refinement, teams formally integrate the subsystems into a final system that hopefully meets the intended requirements. The final deliverable teams create is a design and testing package that will allow a production system to create and test the quality of the product that the team has designed.

1.2 US Air Force Academy Capstone Program

The Capstone Design program within the United States Air Force Academy's (USAFA) Department of Engineering Mechanics annually serves roughly 50-80 students distributed among 6-10 projects. The program employs a multi-step design process, which has been created specifically to facilitate maximum innovation. It includes a number of distinct phases including, but not limited to: 1) Project definition and background research, 2) Customer needs and requirements analysis, 3) Functional description, 4) Ideation, 5) Concept selection, 6) Analysis and modeling, 7) Risk assessment and mitigation, 8) Prototyping and 9) Testing [3]. This process has been developed gradually through experimentation and scholarly design method research [4-11]. The process emphasizes the ideation, or concept generation, stage in the design process and numerous patents have been awarded as a result.

Typically, the year-long design experience groups 4-6 senior undergraduate mechanical and systems engineering students with a mentoring faculty member and, occasionally, a graduate student who is an expert in the area of "innovative design". The collaborative team works to solve a real-world problem provided by a sponsoring organization that (ideally) desires a fresh

approach to the problem and they are seeking to develop solutions characterized by disruptive innovation. Students spend significant time developing a wide variety of innovative new concepts to solve the problem; implementing a suite of techniques that enhance creativity in the concept generation (ideation) process. In addition, the collaborative effort results in proposing enhanced design techniques and processes. For example, past research efforts resulted in two novel design methods: 1) a process for developing prototyping strategies [9-13] and 2) ideation techniques based on biological analogies [14-15]. The sponsor organization research partners take keen interest in the design methodology research; oftentimes adopting these techniques into their own programs.

2. MATERIALS AND METHODS

Structured interviews were conducted with 29 student volunteers—17 seniors in the USAFA capstone program and 12 seniors in the BYU capstone program. At the time of the interviews, both the BYU and AFA students had received roughly 6 weeks of instruction. The students came from 15 different project teams, and each had received varying degrees of face-to-face time with their project sponsors.

Interviews were one-on-one with each student and conducted by researchers with no ties to the student's program or grades in order to encourage students to be open and honest when giving their responses. They took place outside of class time and took about 20 minutes each. Every interviewee was compensated for their time with \$10.

2.1 Interview Questions

The interview questions were carefully crafted and intended to be read verbatim by the interviewers, though interviewers could give or ask for clarification when needed. Students were briefed on the nature of the interview including the fact that no one with any ties to their Capstone grades would have access to any identifiable information. The interviews were scripted as follows:

2.1.1 Brief Introductory Questions

- 1.) Can you tell me a little about yourself?
- 2.) Will you please confirm for the record that you were briefed on the nature of this interview?
- 3.) Will you please confirm that you consent to be anonymously recorded?
- 4.) Can you please state your alpha-numeric identifier?
- 5.) What is the problem your team has been tasked to solve?
- 6.) Is there an existing solution to this problem?

2.1.2 Questions About Expectations

- 7.) The problem your team has been presented with is (interviewer restates the interviewee response from question 5 in his own words for clarity). Could you explain to me what level of market readiness or deployment readiness you think your sponsor expects your solution to have at the end of the year? By

market readiness we mean how close your project will be to release onto the market.

8.) What do you think about using existing products in a new way to solve the problem you've been presented with? How much have you and your sponsor considered this as an option?

9.) Can you tell me what level of product functionality your sponsor expects to see at the final demonstration?

10.) I'm going to ask you two questions about design deliverables. I want to make sure you understand that design deliverables are all of the things you'll hand over or send to your sponsor at the end of the project. Can you tell me about what your sponsor would *love* to see as the final design deliverables resulting from your work on this project? Can you tell me about what your sponsor would be *willing to accept* as the final design deliverables resulting from your work on the project?

11.) Can you tell me about what your sponsor expects you to deliver as far as procedures for implementing your solution go when your team has finished your work on the project? We mean procedures for the user to engage in to utilize your product.

12.) What can you tell me about how your sponsor would like you to handle the tradeoffs between reducing cost and improving performance? Will they accept a reduction in performance at all? Will they accept an increase in cost at all?

2.1.2 Confidence Questions/Closing Questions

13.) We've talked a lot about your sponsor's expectations. How confident are you in the answers you've given and why?

14.) How much has your team thought about these sponsor expectations?

15.) How well do you feel you understand your sponsor's expectations for the final deliverables?

16.) Is there anything else you'd like to say?

2.2 Methods of Analysis

Once the interviews were completed, the audio recordings were transcribed in order to enable the information to be coded and analyzed. The data was first analyzed using the method of open coding, the process by which we went through and looked for themes, some of which were unexpected and surprising to the researchers. As we would start to notice these themes, we would create a "node" at which we would begin to code information related to that theme. We then used an axial coding method to start to consider how these codes/nodes were related, how they might intersect or overlap [16-17].

Once we determined that our core variable for analysis would be the seeming validity of the students' responses based off whether they seemed to be inferring, we were able to perform the rest of the coding using the selective coding method, where we focused on coding for information validity and how it might intersect with other major themes we wished to explore [18].

2.2.1 Codes Used in Analysis

Some of the codes that we examined and which we will discuss in our results and discussion include:

- 1.) Inferring
- 2.) Design Deliverables

- 3.) Design Deliverables Sponsors Would Love
- 4.) Design Deliverables Sponsors are Willing to Accept
- 5.) Misunderstanding
- 6.) Naming only a Prototype as their Design Deliverables
- 7.) Naming Performance Measures as their Design Deliverables
- 8.) Cost/Performance Tradeoffs
- 9.) Confusing Project Budget with Product Cost
- 10.) Expectations Regarding Market Readiness
- 11.) Expectations Regarding Product Functionality
- 12.) Technology Readiness Level (This included all the data in codes 10 and 11)
- 13.) Tactics Readiness Level
- 14.) Student has not Considered Tactics
- 15.) High Confidence
- 16.) Why High Confidence
- 17.) Sponsor Expectations (This included all the data in codes 2, 8, 12, and 13)

3. RESULTS AND DISCUSSION

During the coding and analysis, we largely clustered the discussion topics into common themes (such as the ones discussed in the subheadings 3.1-3.4 below) and then evaluated each response for the level of actual sponsor-communicated information therein. When individuals responded using phrases such as "well, I think..." or "I guess..." or "I would expect..." we coded this information as "inferring," since the speech indicates that the students weren't telling us what they knew their sponsors expected, but what they thought or guessed. Responses where students used phrases like "they want..." or "they've said..." or "they expect..." were coded as "information from sponsor," since they seem to indicate that the source of the information was the sponsor and not the student's best guesses. If a response didn't use either of these clear delineations, it was left uncoded. With this arrangement, we were able to examine the students' responses to see whether their sponsors and instructors had clearly communicated about some of these important expectations, or if the students were working on their projects without a clear understanding of the expectations on the desired results.

This analysis was performed by "crossing" the codes to find their intersection, which basically meant taking a pair of nodes and observing all of the references in the data where both nodes were simultaneously present. For example, crossing "Design Deliverables" with "Inferring" would yield all of the references where a student was both talking about design deliverables and inferring what he was saying. We have largely chosen to use the number of students with data appearing in these intersections of codes as our method for analyzing and presenting the data, since we want to know how many students do or don't have a solid understanding of these topics.

3.1 Design Deliverables

As described above in section 2.1.2, after defining design deliverables as "all the things that [students] hand over or send

to their sponsor at the end of the year,” we asked students to tell us about what their sponsors would *love* for them to deliver and what they would be *willing to accept* as the deliverables. As students are working to create something for their sponsor, it seems reasonable to believe that it would be critical for students to know just what it is that their sponsors want them to deliver. The students seemed to understand that they need to create something that could meet certain performance measures, but their programs and their sponsors failed to help them consider what they will actually need to create to please their sponsor, or at least meet their minimum expectations. In the discussions with the students about design deliverables, 12 of the 29 students were tagged as inferring when asked about what their sponsor would love, 13 when asked what their sponsor would be willing to accept, and 18 total students were making inferences regarding design deliverables during the overall discussion of those two questions. As shown in Table 1 below, this left 11 of the 29 students who did not speak as though they were inferring regarding their design deliverables from their sponsors. The table below can be read by adding the numbers in a row or column to get the total number or percent of students making or not making an inference, or by looking in individual boxes for the values of intersections of those inference states. All the boxes add to 29 students, or 100%.

TABLE 1: INFERENCE REGARDING DESIGN DELIVERABLES

		Students that inferred about what their sponsor would love	
		Yes	No
Students that inferred about what sponsor would accept	Yes	7 (24.1%)	6 (20.7%)
	No	5 (17.2%)	11 (38.0%)

It is interesting to note that even after giving our clarifying definition of design deliverables we also coded 18 students as describing their performance measures or a prototype that would meet said performance measures as their design deliverable, indicating a lack of understanding of what design deliverables are. As shown in Table 2, of the 18 that seemed to lack this understanding, 9 were included in the 18 that were making inferences about the design deliverables their sponsor expects, and 9 were not. That leaves just 2 of the 29 students as having a clear idea of what their sponsor expects them to deliver and having a clear comprehension that a design is embodied by and communicated with much more than a prototype that can meet a set of performance measures.

TABLE 2: LACK OF UNDERSTANDING OF DESIGN DELIVERABLES CROSSED WITH INFERENCE REGARDING DESIGN DELIVERABLES

		Students that lacked an understanding of what design deliverables are	
		Yes	No
Students that inferred about design deliverables	Yes	9 (31.0%)	9 (31.0%)
	No	9 (31.0%)	2 (7.0%)

3.2 Cost/Performance Tradeoffs

With the exception of a few competition teams, most of the teams are working for corporate sponsors. These corporate sponsors give a budget to the students to carry out their project, but beyond worrying about the cost of the project, these sponsors have a market that they are targeting that has its own cost requirements. Sponsors know whether they want to go for a premium product that might cost more but will also outperform their competition, or if they'd be better off trying to create a product that's cheaper than current solutions. These two levers can have a huge influence what part of the market the design team needs to be targeting and if a design team doesn't know who they are designing for, they're left to hope that they'll create a product that will meet the needs of the appropriate market segment [19].

We asked students how their sponsors would like them to handle the tradeoffs between cost and performance, whether they would accept an increase in cost from current solutions, and whether they would accept a decrease in performance compared to those same solutions. Of the students interviewed, 17 were tagged as making inferences regarding their sponsors expectations regarding these tradeoffs, and on top of this, there were 14 students that seemed to fail to grasp the concept that their sponsor had expectations for the final product cost and not just their team's budget, 4 of which weren't coded as using inferring speech. In the end there were only 8 students that weren't making inferences about cost/performance expectations and that also had a clear understanding of the difference between their project budget and the cost of the product resulting from their work.

TABLE 3: LACK OF UNDERSTANDING OF PRODUCT COST/PROJECT BUDGET CROSSED WITH COST/PERFORMANCE INFERENCE

		Students that lacked an understanding of product cost and project budget	
		Yes	No
Students that inferred about cost vs. performance tradeoffs	Yes	10 (34.5%)	7 (24.1%)
	No	4 (13.8%)	8 (27.6%)

3.3 Technology Readiness Level

Products under development have to go through a process where they move from being vague concepts to being refined products that can be sold on the market. The position of a product on that spectrum is described here as its technology readiness level. Project sponsors could be expecting the results of the capstone project to be anywhere from a list of theoretically feasible concepts all the way up to a fully functioning design ready for production. With the technology readiness scale being so wide, designers can easily fail to deliver what their sponsor expects if these things aren't communicated.

We assessed the students' understanding of their sponsors' expected technology readiness level by asking them questions about what level of product functionality their sponsor expects at the end of the project, and what level of market readiness their designs needed to attain by that time. These responses were lumped together into a code we called the "Technology Readiness Level," and we found that it intersected with inferring for 17 of the 29 students. This shows that the expectations surrounding the technology readiness level is another major concept where instructors and sponsors have failed to communicate with students enough to give them clear ideas about where their design needs to end up.

3.4 Tactics Readiness Level

We also wanted to investigate teaching deficiencies with helping students to understand that they needed to be thinking about how users would interact with the product. We wanted to see whether they understood that they will likely need to communicate the intended user experience and instructions for using their product with their sponsor. We deemed this the "tactics readiness level," since different sponsors expect different levels of development for the user experience/interactions with the product. We asked students what their sponsor expects them to deliver as far as procedures for a user go, and 18 were found to be inferring in their responses. We also tagged 10 individuals that told us plainly that they hadn't considered tactics at all, 4 of which hadn't been tagged as inferring. That left us with a total of 7 out of 29 individuals that had both considered the user procedures and didn't seem to be inferring their sponsors expectations regarding those user procedures.

TABLE 4: LACK OF CONSIDERATION OF TACTICS CROSSED WITH INFERENCES MADE REGARDING TACTICS

		Students that admitted that they haven't considered tactics (procedures) at all	
		Yes	No
Students that inferred about tactics	Yes	6 (20.7%)	12 (41.4%)
	No	4 (13.8%)	7 (24.1%)

3.5 Confidence

We asked the students how confident they felt about their understanding of the sponsors' expectations as discussed in the interview. We thought it would be valuable to see if they would identify areas they knew they needed more guidance on. Interestingly, while several students did point out specific areas regarding sponsor expectations where they personally had realized there were gaps in their knowledge, most (24 of the 29) indicated a high level of confidence with speech like "I'm very confident" or "I'd say I'm 80-90% confident," often-times citing extensive conversations with their sponsors as the reason for their confidence.

We coded for a combination of all the major sponsor expectation themes, and crossed it with our code for inferring, and discovered that every one of the 29 students had been tagged as inferring something about their sponsor expectations. As depicted in Table 5, 4 of the 24 students that indicated high confidence pointed out specific areas they were unsure about, but that left 20 of the 29 students indicating that they felt highly confident that they understood their sponsors expectations for Design Deliverables, Cost/Performance Tradeoffs, Technology Readiness Levels, and Tactical Readiness Level despite having inferred information and/or lacked understanding about one or more of those expectations.

With all the previously cited observations regarding the student's inferences and their lack of understanding of what some of these ideas even mean, these high levels of confidence seem to indicate that these topics represent real blind spots for many of the students. The students have a whole set of sponsor expectations apart from the design performance measures that would help them to really please their sponsors and the market, but many of these students haven't been made to understand that these expectations exist, and they think that they understand everything their sponsors want.

TABLE 5: HIGH CONFIDENCE CLAIMS CROSSED WITH STUDENTS WHO DISCUSSED SPECIFIC DOUBTS

		Students that claimed a high level of confidence	
		Yes	No
Students that discussed specific doubts	Yes	4 (13.8%)	5 (17.2%)
	No	20 (69.0%)	0 (0%)

3.6 Discussion

This study we have performed has been an exploratory investigation into the alignment of expectations between sponsors and sponsored design teams. We performed this work with the intention of identifying procedures and best practices for more thorough investigation in the coming years. We hope to be able to gather data from a more statistically significant group of students so that we can prove the value of whatever tools we develop for aligning expectations, and so that we can determine similarities and differences between the BYU and AFA programs. We also hope to gather data from sponsors as well, so

that we can determine much more accurately whether or not their expectations are being communicated and aligned.

While this observational study hasn't included any data or work to show that including these topics among the early discussions about getting started on a design project will produce improved outcomes, we are making the conjecture that it will. We believe that having these expectations clearly communicated from the beginning of a design project will help design teams deliver desirable results to their sponsors. We invite individuals responsible for design teams of all sorts to investigate whether their teams understand the project outcomes discussed in this paper, in order to make sure that they have a vision of where they are going while they are working. Without having this vision in mind, designers will work and expend resources pursuing a path, but until they communicate regarding these end goals with their sponsors, they won't know if they're going in the right direction as efficiently and effectively as possible.

For instructors, it may also be valuable to consider that students were struggling with the concepts of design deliverables and product cost vs project budget. These are major concepts that students work with in design, and it might be valuable to evaluate how they are being taught and see if they shouldn't also be explained early on with some of these other concepts regarding sponsor expectations.

4. CONCLUSION

Capstone programs like the two involved in this study may be leaving students with blind spots regarding important sponsor expectations for things like final design deliverables, cost/performance tradeoffs, technology readiness levels, and tactics readiness levels. Program coordinators and sponsors may benefit from investigating the effectiveness of their early program curriculum in communicating about these expectations.

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AN APPROACH FOR REPRESENTING AND EVALUATING USER TACTICS IN EARLY STAGE PRODUCT DEVELOPMENT

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ABSTRACT

Frequent and effective design evaluation is foundational to the success of any product development effort. Products that will be used, installed, or otherwise handled by humans would benefit from both an evaluation of the product itself (the physical embodiment of the technology, termed technology), and the steps a user should take to use that technology (termed tactics). Current methods for the evaluation of tactics are scattered across multiple research areas, and are often inaccessible to engineers who have no prior experience with them. Furthermore, the existing tactics evaluation methods often focus mostly on the use of a product and do not simultaneously consider technological performance. In this paper we present a method for the simultaneous evaluation of tactics and technology during the conceptual design stage. To achieve this, we propose three contributions; an approach for representing tactics concepts, a set of criteria for tactics evaluations, and a means for presenting the results of the technology/tactics evaluation to facilitate team ideation.

Keywords— Conceptual Design Evaluation, Tactics Evaluation,

Human-Centered Design, Human Factors, Ergonomics.

1 INTRODUCTION

When developing a product that will be used by humans, at least two questions should be considered: *What is the product?*, and *how is it to be used?* The latter of these is of particular interest to us in this paper, and we will refer to it as tactics. The former, we will refer to as technology.

The goal of product development is to evolve ideas into fully detailed solutions that will delight the customer [1,2]. Both technology performance (e.g. Horsepower, battery life, etc.) and tactics performance (e.g. Ease of use, safety, etc.) are of high importance in creating delightful products [2]. Therefore, it is valuable to explicitly consider both technology and tactics during product development [3]. Both the tactics design and the technology design undergo evolution throughout the design process. For instance, a technology might evolve through various states of increasing detail, such as from a vague idea to a verbal description, to a visual description (a sketch), to a prototype, to a 3D model, and so on [4]. In this paper we focus on the conceptual design stage, where the tactics and technology exist at relatively low levels of detail, and a set of concepts for evaluation exists.

To be clear, we define tactics as the steps a person takes to use a product to achieve an objective. While a person can take a variety of different steps to use or attempt to use a product, in this paper we are concerned specifically with the user steps the development team *intends*

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the users to take.

The evaluation of tactics has been examined in many fields such as human factors, human centered design, user experience, and others. From the literature, we can observe at least three ways to handle the evaluation of tactics:

- (A) No tactics evaluation is carried out at all [5]
- (B) Tactics are evaluated generally without specifics, while the product is evaluated as a whole. For example, a simple usability criteria is added to an evaluation matrix such as a Pugh Matrix [6], or concept screening and scoring matrices [7].
- (C) Tactics are evaluated in a highly detailed and specific way, often by someone trained in the art. Such a specialized evaluation means that the evaluation generally does not simultaneously evaluate technology. These are kept separate, either in time, or carried out by separate members of the design team (e.g. Checklists [8], heuristics [8,9])

Each of these three approaches has notable drawbacks. Of course, not evaluating tactics can lead to less usable and useful products [5]. The absence of a detailed and specific evaluation can lead to an inadequate concept evaluation [10, 11]. Finally, the detailed evaluation of tactics in isolation of a technology evaluation can obscure overall concept quality, and diminish the evaluation's effectiveness since a major purpose of concept evaluation is to identify strengths and weaknesses so that choices can be made to improve, combine, or eliminate concepts [6].

In this paper, we propose a method of overcoming these drawbacks that is intended to help development teams more effectively create high quality technology and tactics simultaneously. The proposed method carries out a deliberate semi-detailed, semi-specific tactics evaluation within the same time period and by the same people as the technology evaluation. In creating such a method, three questions arise that are at the root of the main contributions this paper. They are:

1. How should a tactics concept be represented, and at what level of detail? While many agree that an annotated sketch is a satisfactorily matured form of a technology concept in early design [6], it is less clear what form a tactics concept should take. This uncertainty could easily lead to less useful concept evaluations.
2. What criteria should the tactic be evaluated against? The answer to this question is at the core of the proposed method, since it attempts to strike a balance between the (B) non-specific and (C) highly-specialized, evaluation approaches described above.
3. How can the evaluation results be presented to facilitate combination and improvement of concepts? The answer to this question is not trivial; should the results be presented as a number? as a plot? as a diagram? or as words?

In response to the first question, we propose that a tactic concept be represented in a written form that captures three details: i) Information about the person carrying out the tactic, ii) information about the environment in which the tactic will be carried out, and iii) the steps that will be carried out. We propose the steps be detailed by way of a modified task analysis [8].

In response to the second question, we propose that tactics be evaluated based on the following criteria:

- Functional Performance
- Human Factors

- Damage/loss to product from use
- Time required to use
- Cost required to use
- Safety of use
- Environmental impacts of use

Finally, in response to the third question, we propose that technology/tactics spider plots be used as a means for visualizing the evaluation results. Such plots will allow the quality of the tactics and the quality of the technology for each concept to be quickly understood.

In the following sections we will first give a brief review of the literature related to the representation of tactics concepts, the evaluation criteria for tactics, and the presentation of results. After this, theoretical developments will be presented and finally an example of an application of the method is provided.

2 LITERATURE SURVEY

In this section we review the literature as it relates to the development of the proposed method. We specifically review the state of the art in: 1) representations of tactics, 2) tactics evaluation criteria, and 3) the means for presenting results of evaluations.

2.1 Representations of tactics

Noting that human working memory can retain somewhere between 3-7 chunks (units of information) [12, 13], a representation for tactics should not only help ensure that the design contains enough details such that an evaluation will be useful, but also should exist in a form which allows the designer to review it and recall its characteristics relatively quickly while carrying out the evaluation. With this preface, we review the current means for tactics representation.

Bodystorming [14] and cognitive walkthroughs [15] both provide different approaches to tactics representation. In Bodystorming, designers carry out the steps needed to interact with a product, and in place of a product use a prop or simply their imagination. Thus the subject of evaluation is the user's actual movements. A limitation of this representation of tactics is that it is not easily shared with or evaluated by dispersed teams, since its stored form (video), though information-rich, can be time-intensive to review or give feedback on.

In cognitive walkthroughs, the designer imagines the use of the product by talking aloud. The subject of the evaluation in this case is the audible words describing the tactic. Just as in bodystorming, this representation of the tactic is beneficial because the design is no longer in the stage of a vague idea. However, reviewing the verbal dictations of many concepts while carrying out an evaluation may be prohibitively expensive.

Storyboards represent tactics by a series of drawings or photos which provide chronological snapshots of a product's use [16]. While this representation can be easily used later, it is higher-level and not as information-rich as a bodystorming. Further it may not be easily constructed during ideation.

A task analysis is a tactics representation from the field of human factors. To create a task analysis, the designer begins at a task and decomposes it into a series of steps, which take the form of a hierarchical list [8, 12, 17].

One difficulty associated with task analysis is determining how far to decompose a task. Some ergonomists decompose the task until a useful point of detail is reached, while others determine a stopping point by using a $P \cdot C$ criterion, where P is the probability of failure at that task, and C is the consequences of that failure [8]. Note that this is not usually carried out by a formal calculation, but rather a mental guideline for the ergonomist [8]. With or without a $P \cdot C$ criterion, it can be difficult for those who do not have experience with task analyses to know how far to decompose the task. This can ultimately result in an excessively detailed list, which is difficult for a novice in task analysis to use.

Despite these difficulties, the task analysis does represent a series of steps in a way that is relatively easy for the designer to review, and is relatively inexpensive to create. A task analysis alone, however, is inadequate to describe a tactic concept prior to evaluation. It is clear, for instance, that the difficulty of a series of steps would be different depending upon the characteristics of the human carrying them out. The inclusion of these details within the tactics representation is therefore necessary in order to carry out a tactics performance evaluation.

In sum, the lack of necessary information and other shortcomings make the existing representations of user tactics sub-optimal for representing a tactics concept for semi-detailed evaluation.

2.2 Tactics Evaluation Criteria

In reviewing the tactics evaluation criteria used in the literature, we first recognize that evaluation criteria are not always stated explicitly in the published evaluation methods. Methods such as scenarios [18], storyboards [16], bodystorming [14], and cognitive walkthroughs [15] all represent the tactic in a way that is believed to make weaknesses apparent to the development team. Evaluations made using these representations are not necessarily made on specific criteria – rather the product's use is evaluated against the designer's mental model for a usable product [14].

Other methods do, however, evaluate a tactics concept against specific criteria. In order to review these criteria, consider the *Tactics Evaluation Criteria Decomposition Tree*, referred to hereafter as *the tree*, in figure 1. The decomposition suggests that the most abstracted, general criterion for evaluating a tactic concept is whether or not it is a delight to use. One layer down in this decomposition includes criteria such as *Easy to use* and *Simple*.

Many methods exist that use criteria at the second level of the tree. One example of a method at this level is the System Usability Scale (SUS) [19]. The SUS is a widely accepted ten-item user survey for determining the usability of products and services. Two points in the survey are: "I found the system unnecessarily complex." and "I thought the system was easy to use." Criteria at this level in the tree present difficulties to teams carrying out evaluations in the conceptual design stage. For example, Pugh observed that the use of ambiguous criteria in the Pugh matrix can lead to a less productive evaluation, since these criteria can be interpreted very differently by development team members [6].

Methods exist that use criteria at lower levels of the tree, but they too have limitations when applying them to the purposes in this paper. Human factors and ergonomics has examined closely what makes a product easy to use. For instance, the effects of spatial compatibility and number of alternatives on the ease of action selection have been examined [12](See figure 1). Other decompositions have been carried out in this field, such as studying what makes a movement physically difficult

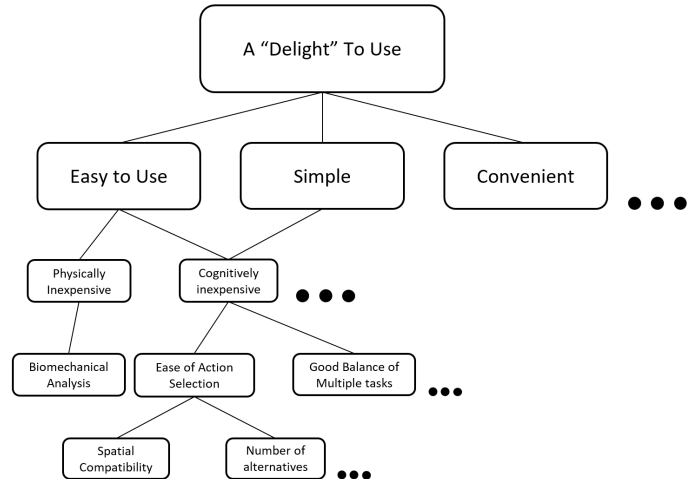


FIGURE 1. The *Tactics Evaluation Criteria Decomposition Tree*. Methods for tactics performance evaluation exist at every level of this tree.

for a human, as in biomechanical analysis [12, 20, 21]. A problem with using criteria deep in the tree is that they are less accessible to a design engineer, who would need to invest significant time to learn and to use them.

Having understood criteria near the top of the tree and those deep in the decomposition, it is logical to conclude that a set of criteria exists between these two extremes that contains unambiguous criteria and that contains accessible criteria to be quickly learned and used by development teams. Exactly what this set of criteria might be is not clear from the literature.

2.3 Presentation of Results

Many evaluation methods for the conceptual design stage represent their results as a matrix. The Pugh matrix [6] presents results as cells of +, -, or S symbols to denote better, worse, or same as reference, respectively. Another version of the evaluation matrix fills cells with a number between one and five, a 3 denoting same as reference, a 1 denoting much worse, a 2 denoting slightly worse, and so on [4].

As discussed earlier, although bodystorming, storyboards, and experience prototyping focus mainly on representing the tactic, an informal evaluation is often carried out based on these representations. These methods do not specify how the results of the informal evaluations are to be presented, but it may be that the results are presented in a manner similar to the simple recording of observations on Post-its, as in Cognitive walkthroughs [15].

An advantage of presenting results in the form of a matrix is that it is an organized form in which data is captured on every concept for every criterion. In other presentation methods, data may not be recorded for certain concepts or with respect to certain criteria. Ultimately this organization can make it easier for the design team to quickly see strengths and weaknesses for many concepts.

A disadvantage of the matrix is that it can contain a significant amount of data, such that digesting the data can require notable effort

Tactics Concept Name:	<i>Pull sliding door and lever</i>
Actor	<i>An able-bodied warehouse worker of typical stature and strength.</i>
Environment	<i>A temporary warehouse for receiving and distributing aid supplies. Warehouse is located in a middle-eastern conflict zone</i>
User Actions	• <i>Grasp handle of garage door</i> • <i>Pull door to open position, keeping body behind the door in the process</i> • <i>Pull lever to drop external barrier</i> • <i>Attend to vehicle as normal</i>

FIGURE 2. A tactics concept for a product can be represented in a written form with descriptions of the actor, environment, and sequence of steps.

from the design team. Our proposed presentation approach reduces this effort in hopes of facilitating the creation of new ideas.

3 THEORETICAL DEVELOPMENTS

This section provides a detailed description of our proposed approach to represent a tactics concept, our proposed criteria for evaluating tactics concepts, and our proposed approach to present the concept evaluation results, including the results of both tactics and technology evaluation.

3.1 Representing a Tactics Concept

We propose that a tactic can be adequately described in the conceptual design stage by a simple written description including the following three things, which are illustrated in Fig. 2:

- The Actor:** The actor is one or more people who carry out the tactic. A brief description of the actor is sufficient, when it is focused on actor characteristics that affect the actor's ability to carry out the tactic. For example, the actor is an experienced able-bodied warehouse worker of typical stature and strength.
- The Environment:** The environment is the location(s) where the tactic will take place. A brief description is sufficient when it is focused on the characteristics of the environment that affect that actor's ability to carry out the tactic (This may include weather, noise, hazards, etc.). For example, the environment is a temporary ware-

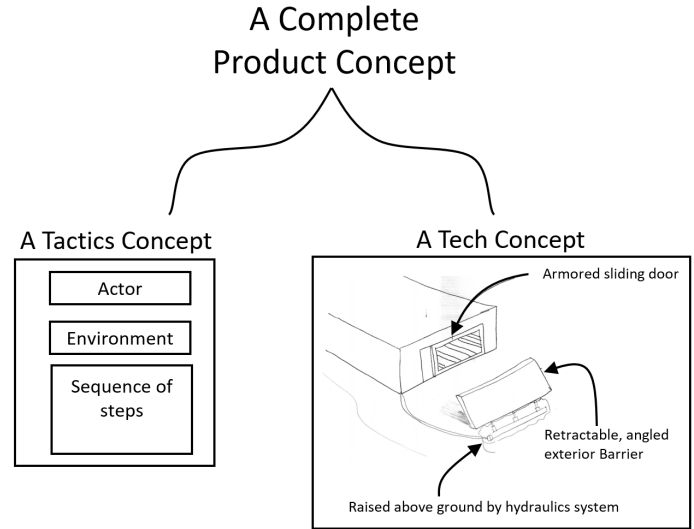


FIGURE 3. A complete product concept contains a form for both tactics and technology which contains enough detail for an evaluation to be carried out.

house for receiving and distributing aid supplies to Afgans in a military conflict zone.

The Sequence of Steps: The sequence of steps is simply a list of what the actor would do to carry out the tactic, as shown in Fig. 2.

One other important piece of information included in the tactics representation is the name of the tactics concept, given to the concept defined by the actor, environment, and steps. This simply facilitates organization and discussion later in the design process.

The sequence of steps is the most substantial part of representing a tactics concept. A *task analysis* [8] is an effective means for representing the sequence of steps during conceptual design because it can be created and edited quickly, information is captured and is not subject to loss, and information can be reviewed relatively quickly during an evaluation.

As described in Section 2, the challenge of task analysis is knowing when to stop decomposing the task. We propose that the designer decompose tasks until the tasks describe whole body movements, part acquisition, and part placement. These three items are inspired by the work of Boothroyd and Dewhurst [22], where they present time predictions based on two categories of actions: 1) Part acquisition and orientation and 2) Part insertion. We have found that this guideline helps avoid confusion over how far to decompose a tactic, and allows for more uniform creation of tactics concepts.

This form of a tactics concept, a written description of the actor, environment, and steps, addresses all of the weaknesses identified in existing tactics concept representations. Specifically, it can be created relatively quickly, it contains the basic information needed to carry out an evaluation, and it can be reviewed and shared relatively quickly.

This simple representation for a tactics concept, along with the representation for the technology concept, make up a complete product concept (Fig. 3). It is anticipated that during the ideation process the full product concept is created.

3.2 Tactics Evaluation Criteria

Tactics may be evaluated based on numerous criteria, ranging from a single general criterion to very specialized sets of criteria, as described in Sec. 1. We recommend that for development teams wishing to consider both tactics and technology during concept evaluation, a semi-detailed tactics evaluation be completed.

We present the recommended list of criteria⁶ below, followed by a description of why these items are recommended.

- **Functional Performance:** Extent to which the tactic-technology combination carries out the primary function described in the design problem.
- **Human Factors:** User comfort while using the product. Includes cognitive and physical aspects.
- **Damage/loss to product from use:** The probability of product loss or damage as a result of the use (including wear).
- **Time required to use:** Time needed for the user to carry out the tactic with the technology.
- **Cost required to use:** Cost to the user needed to carry out the tactic (Ex: Fuel for a car)
- **Safety of use:** Probability and severity of safety risks that arise as a result of product use.
- **Environmental impacts of use:** Possible negative environmental impacts from the use of the product.

This list of evaluation criteria aims to address the weaknesses found in the criteria discussed in the literature survey, namely, that criteria can be either ambiguous or time-consuming to learn and to use. Another important need this set of criteria seeks to meet is that the set adequately cover the tree as opposed to covering a small subset of branches.

The functional performance may at first appear to be out of place amongst tactics criteria. We believe, however, that for any tactics-technology combination that does not fulfill the overall intended function of the product, the tactics of that concept cannot be considered high performing regardless of the other positive aspects of its use.

This set of criteria is one that could practically be placed in an evaluation matrix to guide a design team's evaluation of a concept's tactics, thus setting up the opportunity to evaluate both tactics performance and technology performance together.

3.2.1 Justification for Including the Recommended Criteria In this section, we describe the process by which we arrived at the recommended criteria for tactics evaluation. To apply to a large range of products, we turned to the classical mechanical design literature [2, 6, 23]. We began with Ullman's general requirements list, seen in figure 5, then cross examined Pahl and Beitz's list and Pugh's list to find additions. Importantly, we categorize the resulting list as designed for the evaluation of a product concept as a whole, both the technology and the tactics (as in approach (B) of Sec. 1).

The next step was to identify which of these requirements apply to tactics. Our method was to filter out, in two stages, those requirements that related more to technology, ultimately leaving the requirements that related most to tactics.

The first filter was applied by asking the following question: Suppose you are given all information about the physical makeup of the product (e.g. Drawing package, CAD renderings, materials, etc), and you are aware of your company's manufacturing capabilities but know nothing else about the product. Could you evaluate the product's performance relative to a requirement in this category? Product distribution, appearance, physical properties, and materials are all examples of requirements that were filtered out in the first round, meaning they were not deemed to be primarily about tactics.

Next, requirements were consolidated logically. For instance, it is logical that the same principles that make something easy to clean and repair are those which make something easy to handle and use. Therefore, reparability and cleanability were absorbed into human factors.

After consolidation (see appendix for details), the last filter – one whose focus was practicality – was applied. It was asked: Which of these criteria would be least helpful to consider during early stage ideation?

3.2.2 Further decomposition of Criteria The final criteria found after the filtering process are helpful in that they cover many of the performance aspects that relate to a product's use. Ultimately, the design team must decide which criteria are most relevant to their particular design project. In this section we provide the design team with more criteria to consider by decomposing the initial criteria one step further. We expect that for certain design projects, these more specific criteria will be useful.

We propose that "human factors" can be broken up into two further categories: 1) Physically inexpensive and 2) Cognitively inexpensive.

For environmental impact of use, we propose a decomposition into two further elements: 1) Environmental impact of typical use, and 2) Environmental impact of atypical use.

For loss and damage, two sub-elements are proposed: 1) Loss and damage from typical use (As in the case of failure of parts from normal use) and 2) Loss and damage from atypical use (As in the case of failure of parts from worst-case and other uses)

To be clear, the fully decomposed list now contains 10 items:

1. Functional Performance
2. Physically Inexpensive
3. Cognitively Inexpensive
4. Damage/loss from typical use
5. Damage/loss from atypical use
6. Time to use
7. Cost to use
8. Safety of use
9. Environmental impacts of typical use
10. Environmental impacts of atypical use

3.3 Presentation of Evaluation Results

Having identified criteria for tactics performance evaluation, we recommend that each criterion be evaluated for each concept, for example, by using a concept scoring matrix with a 5 point scale [7].

The technological performance criteria that will populate the matrix must also be identified. We propose that the design team select three to ten key performance measures [4] – Performance measures that have

⁶Although costs associated with training users are an important factor for many products, this aspect does not appear in this list because it was not specifically found in the literature consulted during the list creation.

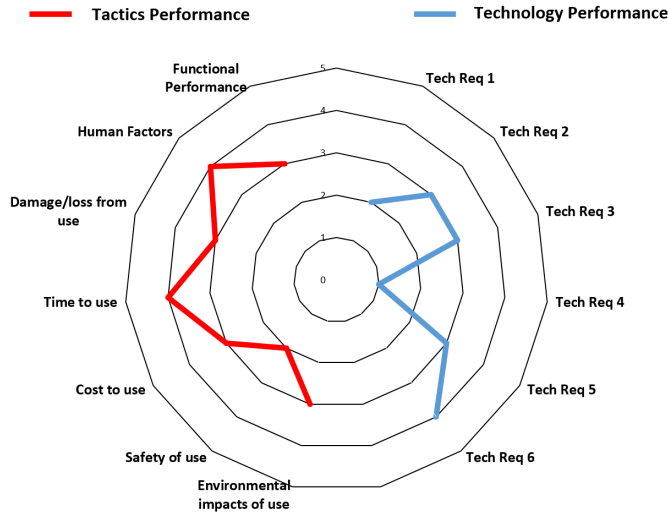


FIGURE 4. A spider plot displaying the tactics and technology performance evaluation of a concept.

a strong effect on the perceived quality of the product – for the technology, and evaluate the technology concept based on them using the same scoring matrix.

At this point, the scoring matrix contains both tactics performance and technological performance criteria, and an evaluation can be carried out and the results displayed in a spider plot, as in Fig. 4) Spider plots make it easier for the design team to identify strengths and weaknesses of concepts relative to tactics and technology, allowing them to imagine new concepts that improve upon the existing performance.

3.4 Description of Full Evaluation Method

This section's aim is to take the pieces described earlier and demonstrate how they would be used to do an evaluation of a tactics concept.

Suppose that a development team has generated a set of concepts, and that those concepts contain technologies that have evolved to the point of a sketch, and tactics which are currently still in the form of a vague idea. We do not suggest that this state of evolution is the most common or the best state of evolution for a set of ideas. Instead, we begin at this point purely to illustrate the creation of the proposed written form for tactics concepts.

In order to evaluate the tactic, the designer must first narrow the scope of the tactic to one appropriate for the desired analysis. A user can carry out many different activities with a product; They purchase it at the store, unbox it, stow it, retrieve it, use it, clean it, and more. The full scope of the activities a user engages in with the product is illustrated well Otto and Wood's Activity Diagram [24]. With awareness of the extent of possible activities, the first step is to choose one or more activities to analyze.

Having chosen an activity, the development team begins representing the tactics concept by stating the actor and environment. As part of specifying the environment, it can be useful at this point to specify the initial relative positions of the product and human for the activity or

Types of engineering Specifications	
Functional performance	Life-cycle concerns (continued)
Flow of energy	Testability
Flow of information	Reparability
Flow of materials	Cleanability
Operational steps	Installability
Human factors	Retirement
Appearance	Resource concerns
Force and motion control	Time
Ease of controlling and sensing state	Cost
Physical requirements	Capital
Physical properties	Unit
Available spatial envelope	Equipment
Reliability	Standards
Mean time between failures	Environment
Safety (Hazard assessment)	Manufacturing/assembly requirements
Life-cycle concerns	Materials
Distribution (shipping)	Quantity
Maintainability	Company Capabilities
Diagnosability	

FIGURE 5. A list of types of engineering specifications as found in Ullman's *The Mechanical Design Process* [2]

activities being analyzed. Then, the steps for carrying out the tactic are stated. This is done with a simple task analysis.

This process is then carried out for each tactics concept in the concept set. With this completed, each concept now has a representation of tactics and technology which have evolved past the state of a vague idea, and can now be evaluated based on the recommended evaluation criteria.

Together the technology performance criteria and the tactics criteria are used to evaluate all concepts in a concept scoring matrix. Spider plots are then created to visualize the evaluation results. A subsequent discussion can be carried out in which the development team carefully considers the strengths and weaknesses of each concept, and both the tactics and the technology can be considered as design variables to enable the improvement and combination of concepts.

4 EXAMPLE

As an example of this method's use, we will consider the design of a new type of impact driver hand tool [4, 25]. This design problem was selected for this paper because it clearly illustrates novel tactics concepts. Specifically, the goals of the design are to 1) Reduce arm fatigue for those who use the impact driver for long periods of time, such as outdoor deck fabricators, drywall hangers, or general construction workers, 2) increase time between battery charges, and 3) maintain the mobility of a cordless impact driver.

We will demonstrate the proposed method using three concepts (Shown in Figure 6) generated as solutions to this design problem. Concepts 1 and 3 both remove weight from the drill by placing the battery closer to the person's center of mass. Energy flows from the batteries through a cord that connects to electrical contacts in a glove. Electrical contacts would then be placed on the handle of the impact driver. Concept 2 approaches the problem differently, and instead gives the user the option of how much weight (and how much battery life) to take on for a given job. The user could then use a smaller battery for a smaller job, or opt for more weight if time is more valuable. Concept 1 will be called

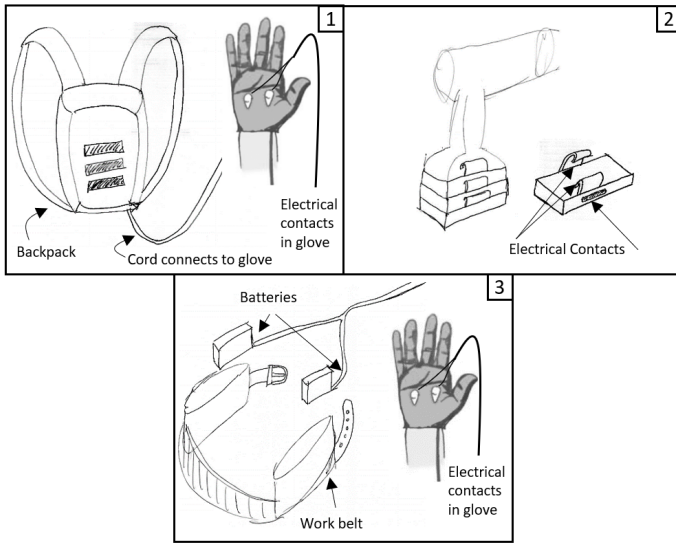


FIGURE 6. Three concepts for an improved impact driver.

“Backpack”, Concept 2 will be called “Battery Stack”, and Concept 3 will be called “Belt”.

We begin by creating a user activity diagram. It’s worth noting that it could be useful to have created the user activity diagram before generating ideas, and to have used it to guide ideation. However because evaluation, not generation is the main focus of this paper, we omit this step here. The user activity diagram is shown in figure 7.

We now select one or more activities of interest to evaluate. In this example we will evaluate the *Use Drill* activity. Next, the representations for the tactics for each concept are created. First, the actor is a general construction worker, of average stature and typical skill. Second, the environment is inside a semi-completed house, putting up drywall. The initial position for the human is near a table; the initial position for the tool is on the table. Third, the task analysis is created for each concept.

The task analysis for the backpack concept was the following, with other task analyses given in the appendix.

- Grasp the glove
- Insert hand into glove
- Grasp Backpack
- Place backpack on shoulders
- Grasp drill
- Drill for 8 hours
- Grasp the glove
- Remove glove
- Place glove on table
- Grasp backpack
- Remove backpack
- Place backpack on table

The task analysis gives the development team a deeper understanding for what each tactic entails as they write out each step and envision the process of product use. Whereas before, the tactic existed only as a

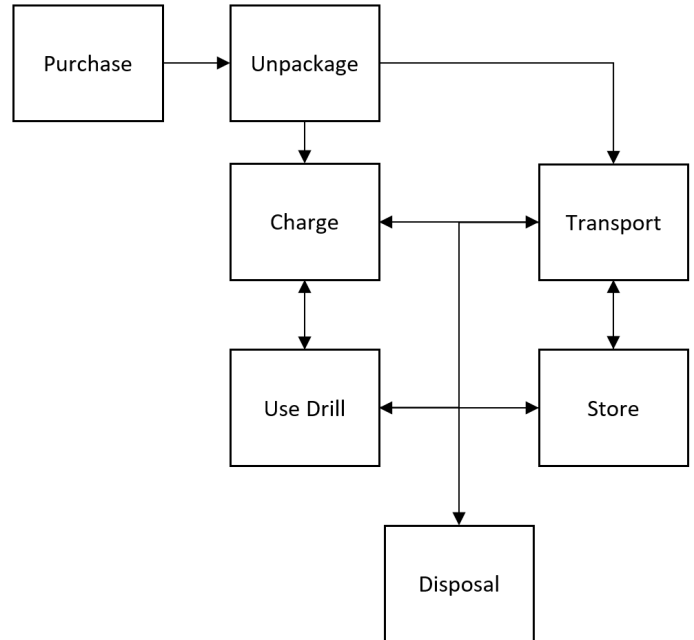


FIGURE 7. An activity diagram for the drill concepts.

vague idea, it now has a written form and can be communicated to others as well as referenced during the following evaluation. The next step is to create the scoring matrix. We will demonstrate using the original tactics performance criteria, without the further decomposition. A normal impact drill with an assumed 4 hour battery life (for this use case) was used as the reference concept. The key performance measures for the technology were that the drill 1) achieve a high torque, 2) be compact, 3) achieve a fast speed, 4) be manufacturable and 5) be aesthetically pleasing. The matrix can be seen in Fig. 9.

The following is a discussion of the justification for the rating and the insights from this rating. The High Speed and High Torque ratings for these concepts were all the same, simply because no significant change was made to the drill assembly. This should signal to the team that more variety could be pursued in this part of the design space. All concepts were rated as more compact than the normal drill, because all ideas propose a smaller drill housing than the original. Battery stack was given the highest rating in compact design because it removes volume from the drill housing and does not add it elsewhere. The manufacturability also varied among the concepts, with battery stack receiving the highest rating. Aesthetically, the battery stack received the highest rating as its appearance is familiar but also somewhat novel. The battery life ratings were assigned based on the estimated battery size each concept would accommodate; accordingly, the backpack received the highest rating. Functional performance was about the same for each concept as each concept was equally capable of fulfilling the primary purpose of the design problem, to drill.

The human factors (HF) ratings differed among the three concepts. The battery stack concept received a higher rating for HF because of the reduced fatigue in the user’s arm, as he has less weight extended out from the body. The Backpack and Belt concepts both received lower

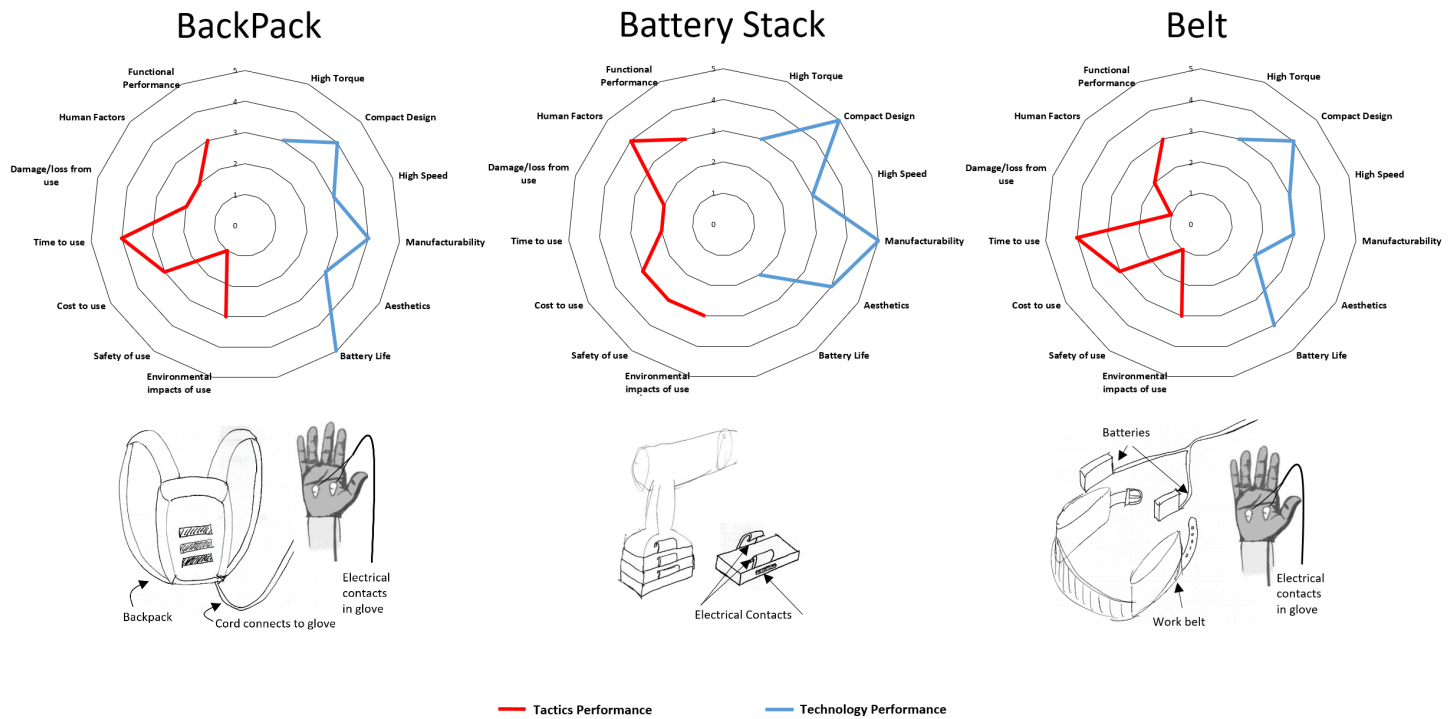


FIGURE 8. A spider plot for all three concepts considered.

HF ratings because of the difficulty of ensuring that the contacts on the glove align with those on the drill handle. The belt concept received slightly lower HF ratings than the backpack because of the increased trouble of finding a place for the batteries.

Damage/loss was an insightful criteria to consider. Putting ourselves in the place of a general construction worker, it becomes clear that everything will be subject to harsh conditions. All concepts with gloves received lower ratings than the normal drill as it can be guessed that the glove could easily be mistreated, the cord yanked, and more. The battery stack concept also received low ratings because the batteries would be loose in a workbelt and possibly come into contact with conductive materials.

When considering time, the battery stack concept was given slightly lower ratings as it required the most battery changes. The other concepts received slightly higher ratings than a traditional drill for fewer battery changes. Evaluating the tactics concept for safety was also insightful. It became clear that if the user grasped something conductive, he would form a complete circuit and pass electricity through that object, shorting out the battery pack. Cost was about the same for all concepts as this is only the cost to use the product. Environmental impacts of use were also rated as the same, as no one concept's use impacts the environment more than the others.

Fig. 8 presents the accompanying spider plot for this evaluation matrix. All criteria, whether deemed to be pertaining to technological performance or to tactics performance, were included as axes in the plot. Several observations can be made from this presentation of the concept performance. First, that the backpack and belt concepts are very simi-

lar in their performance, which indicates a possible need to expand the variety of the concept set, or to be more critical in the evaluation process. Also, it is apparent that no concept has reached a rating of 5. This naturally provides the design team with a stimulus for the next generation session: Think of a concept that would reach a level 5 in any of these criteria. Beyond this, it is apparent that while many of the concepts are an improvement beyond the standard drill, they falter in many other ways. The design team can now ideate based on the weaknesses of these concepts and seek to create improved concepts which no longer have these weaknesses.

This example illustrates that the use of the proposed method shows promise in its ability to bring about positive outcomes for design teams, including the identification of potential hazards, inefficiencies, and vulnerabilities of the technology relative to certain use cases.

5 CONCLUSION

In this paper we have proposed 1) a means for representing tactics concepts, 2) a set of criteria for their evaluation, and 3) a means for presenting the results of the evaluation to a development team for further design work. The contributions in this paper, while small in and of themselves, together offer a practical method to simultaneously evaluate a concept's tactics and technology which ultimately facilitates the design team's creation of improved concepts by changing the tactics, the technology, or both. To be more specific, this paper presented a tactics concept representation approach that is simple and akin to an annotated handsketch, which is typically used to represent technology.

	Technology						Tactics						
	High Torque	Compact Design	High Speed	Manufacturability	Aesthetics	Battery Life	Functional Performance	Human Factors	Damage/loss from use	Time to use	Cost to use	Safety of use	Environmental impacts of use
Normal Drill	3	3	3	3	3	3	3	3	3	3	3	3	3
Backpack	3	4	3	4	3	5	3	2	2	4	3	1	3
Battery Stack	3	5	3	5	4	2	3	4	2	2	3	3	3
Belt	3	4	3	3	2	4	3	2	1	4	3	1	3

FIGURE 9. A Concept scoring matrix which carries out both a focused evaluation of tactics and an evaluation of technology.

It also presented tactics evaluation criteria that originated from, but are more detailed than requirements found in classical mechanical design literature. Finally the paper presents a simple way to visualize both the strength of a concepts tactics as well as the strength of its technology, side-by-side. Such a side-by-side plot makes it clear which concepts have strong tactics and technology.

Combined, these simple contributions facilitate the simultaneous development of strong tactics for strong technology – something that is otherwise easily lost using traditional design methods.

ACKNOWLEDGMENT

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Appendix

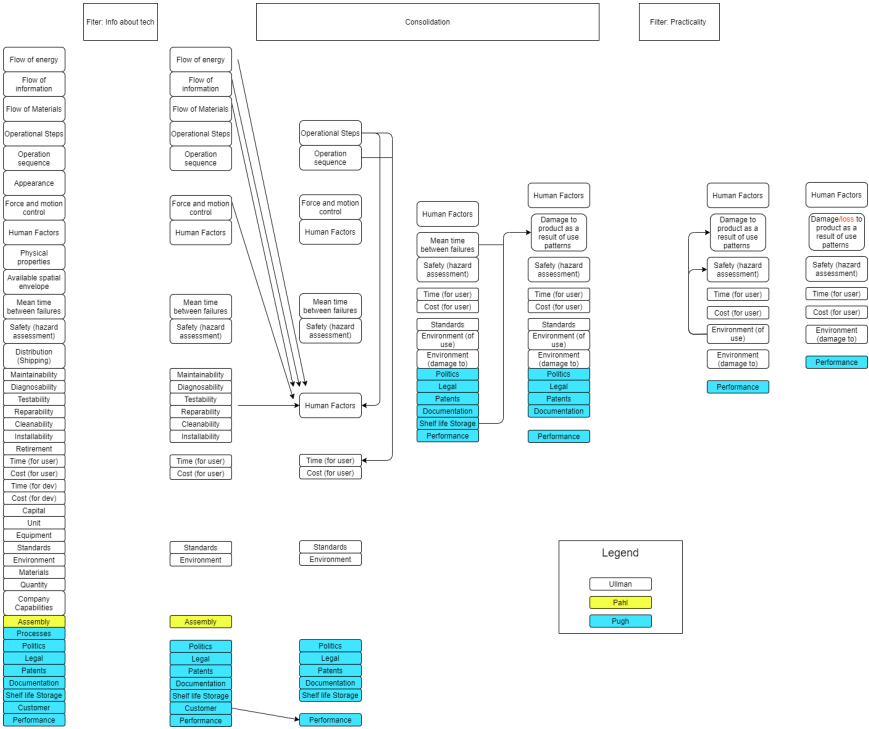


FIGURE 10. Filtering process from origin of criteria

- Backpack**
1. Grasp the glove
 2. Insert hand into glove
 3. Grasp backpack
 4. Place backpack on shoulders
 5. Grasp drill
 6. Drill for 8 hours
 7. Grasp the glove
 8. Remove glove
 9. Place glove on table
 10. Grasp backpack
 11. Remove backpack
 12. Place backpack on table
 13. Place drill on table
- Dual**
1. Grasp the glove
 2. Insert hand into glove
 3. Grasp batteries
 4. Place one into left pocket of toolbelt
 5. Place second into right pocket of tool belt
 6. Grasp drill
 7. Drill for 8 hours
 8. Grasp left battery
 9. Remove left battery
 10. Grasp right battery
 11. Remove right battery
 12. Place batteries on table
 13. Grasp glove
 14. Remove glove
 15. Place glove on table
 16. Place drill on table
- Modular**
1. Grasp drill (With one battery attached)
 2. Drill for 2 hours
 3. Grasp battery
 4. Remove battery
 5. Place battery on table
 6. Grasp new battery
 7. Insert battery
 8. Drill for 2 hours
 9. Grasp battery
 10. Remove battery
 11. Place battery on table
 12. Grasp new battery
 13. Insert battery
 14. Drill for 2 hours
 15. Grasp battery
 16. Remove battery
 17. Place battery on table
 18. Grasp new battery
 19. Insert battery
 20. Drill for 2 hours
 21. Place drill on table

FIGURE 11. Task analyses for each concept

A Formal Consideration of User Tactics During Product Evaluation in Early-Stage Product Development

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Abstract

Frequent and effective design evaluation is foundational to the success of any product development effort. Products used, installed, or otherwise handled by humans would benefit from an evaluation of the product while formally considering both the physical embodiment of the technology, termed technology, and the steps a user should take to use that technology, termed tactics. Formal and simultaneous evaluations of both technology and tactics are not widespread in the product design literature. Although informal evaluation methods have advantages, formal methods are also known to be effective. In this paper we propose a formal method for evaluating tactics and technology simultaneously. Unlike the published literature, this evaluation involves explicitly defined tactics in the form of a written description of the actor, environment, and series of steps. It also involves the use of stage-appropriate, explicitly defined tactics-dependent criteria, which include criteria from a broad range of impact categories, such as impacts on the user, environment, project, and technology.

Keywords— Conceptual Design Evaluation, Tactics Evaluation, Human-Centered Design, Human Factors, Ergonomics.

1 INTRODUCTION

When developing a product that will be used by humans, at least two questions should be considered: *What is the product?*, and *how is it to be used?*. The consideration of both the hardware design and the design of the product's use has been explored in many research fields, and among those fields there exist many different terms to represent the notion of product use. Here, for simplicity's sake, we will refer to the product's use as *tactics*. And we further specify for clarity that tactics are the steps a person takes to use a product to achieve an objective (Owens provides a detailed



Figure 1: In this paper, *product* refers to the complete solution to the design problem and therefore involves both tactics and technology.

comparison of tactics with other notions in the literature [1]). While a person can take a variety of different steps to use or attempt to use a product, in this paper we are concerned specifically with the steps the development team *intends* the product users to take.

The goal of product development is to evolve ideas into fully detailed manufacturable solutions that will delight the customer [2, 3]. Both technology and tactics are of high importance in creating delightful products [3, 4]. Therefore, it is valuable to explicitly consider both technology and tactics during product development [5, 6]. Both the tactics design and the technology design undergo evolution throughout the development process. For instance, a technology might evolve through various states of increasing detail, such as from a vague idea to a verbal description, to a visual description (a sketch), to a prototype, to a 3D model, and so on [7]. Tactics also evolve but there is less consensus in the literature and in practice of how to illustrate the evolution of tactics.

In this paper we focus on the conceptual design stage, where the tactics and technology exist at relatively low levels of detail, and a set of concepts for evaluation exists. According to Ullman [3], an evaluation is an assessment of a *Subject of Evaluation (SOE)* against one or more criteria. Otto further indicates that a *formal* concept evaluation involves an explicitly defined SOE and explicitly defined criteria [8].

Nevertheless, informal evaluations are common in product development. An informal evaluation is one where either the SOE or the criteria or both are not explicitly defined. An example of this is role plays, where the SOE is the acted-out tactic (explicitly defined) but the criteria are often not explicitly defined, and instead the goal is described as “to gain insights” [9]. The insights arise as participants compare the acted-out tactic with the implicit criteria they have in their minds.

In product development, a common SOE is the current state of the product. Hereafter, a *product* refers to the complete solution to the design problem, which includes both tactics and technology (see Fig. 1). *Product Concept* as it is used here refers to the product in a conceptual stage, and therefore is composed of the tactics concept and the technology concept.

While there are advantages to using informal evaluation methods, formal methods can also be effective [10]. In this paper we focus on a formal method for evaluating tactics and technology simultaneously. In order for such a simultaneous evaluation of both tactics and technology to be also formal, it must contain two explicitly defined SOE’s – the tactics concept and the technology concept – and two explicitly defined sets of criteria – one to evaluate the tactics and another to evaluate the technology.

We use the term *tactics representation* to refer to the SOE for the tactics concept, and the term

tactics-dependent criteria to refer to the criteria that can be used to evaluate a tactics concept. It is clear that a product concept’s performance in a certain criterion may be dependent on the tactics concept, the technology concept, or both. For example, a product concept’s *manufacturability* is solely dependent on the technology concept, while its *ease of use* is dependent on both the technology and tactics concept.

We have so far established that a formal and simultaneous evaluation of tactics and technology concepts at least involves a representation of the tactics concept, a representation of the technology concept, tactics-dependent criteria and technology-dependent criteria. We have said little as to what traits might be found in high quality tactics-dependent criteria or tactics representations. We can identify at least three goals to this end:

- Goal 1: That tactics representations contain information about the actor, environment, and series of steps. It is critical to know information about each of these items in order to evaluate the quality of a tactic concept [11]. For example, the age/experience of the actor can impact the tactic’s feasibility/desirability, as can the expected weather conditions at the place of use. Essential are the steps, which are the actions the user will complete.
- Goal 2: That tactics-dependent criteria contain stage-appropriate detail. Some methods in the literature use criteria that are ambiguous (e.g., “human desirability” [12]). This is a potential problem as Pugh observed that the use of ambiguous criteria can be interpreted differently by development team members [10]. However, too much detail would be inappropriate for the conceptual stage of product development [13].
- Goal 3: That tactics-dependent criteria represent a broad range of impact categories. Some methods only focus on impacts on the user, such as *usability*. This is an incomplete evaluation as the tactics design can also have other impacts, such as impacts on the project, environment, and technology. For example, the tactics design for a car could impact the comfort of the driver, the level of pollution produced by the driver’s style of operating the car, the engineering development time, and/or the reliability of the car.

As shown in Table 1, there are many methods in the literature related to the evaluation of tactics and technology concepts, but none that meets all three goals listed above. Note their inclusion or exclusion of explicit SOE, criteria, or their fulfillment of the three goals listed above.

Table 1: C

omparison of existing methods for evaluating tactics and technology during conceptual design from the literature. Note, solid circles indicate *the presence of*, empty circles represent *the absence of*, while half circles indicate *somewhat present*.

Method Name	Explicit representation of concept for:		Explicit criteria for evaluation of:		Has information on actor, environment and steps for tactic (Goal 1)	Has tactics criteria with stage appropriate detail (Goal 2)	Has tactics criteria from a broad range of impact categories (Goal 3)
	Tec	Tac	Tec	Tac			
Decision-matrix [7, 3]	●	○	●	●	○	●	○
Task Analysis [14]	○	●	○	○	○	○	○
Storyboards [15]	●	●	○	○	◐	○	○
Role Plays [16]	●	●	○	○	●	○	○
Bodystorming [9]	●	●	○	○	●	○	○
Scenarios [11]	●	●	○	○	●	○	○
Empathic Walkthroughs [17]	●	●	○	○	●	○	○
Cognitive Walkthroughs [18]	●	●	○	●	●	○	○
Journey Maps [19]	●	●	○	○	●	○	○
Service Engineering [20]	◐	●	●	●	●	●	○
Service Blueprints [21, 12]	○	●	○	●	○	●	○
Extended Service Blueprint [22]	○	●	●	●	○	●	○
Bertoni, 2019 [23]	●	●	●	●	○	●	●
Maussang, 2009 [24]	◐	●	●	●	◐	●	○
Proposed Method	●	●	●	●	●	●	●

To summarize the findings presented in Table 1, the challenges of the methods found in the literature for tactics evaluation are that some methods are informal, but those which might be considered formal either 1) focus only on a subset of the criteria, 2) have ambiguous criteria and/or 3) the tactics representations are missing key information which is necessary in an evaluation. In short, there is a lack of methods in the literature for the formal and simultaneous evaluation of both concept technology and tactics in conceptual design.

The objective of this paper is to build on appropriate methods in the literature to create a method for simultaneously and formally evaluating technology and tactics during the early stages of product development, which meets all three goals previously iterated.

To achieve this objective, two main questions must first be answered:

1. How can a tactics concept be represented?
2. What stage-appropriate criteria can be used to evaluate the tactics concept?

A method for the formal and simultaneous evaluation of tactics and technology can then be created by combining the tactics representation and tactics-dependent criteria with a representation of the technology concept and technology-dependent criteria. An important, but more straightforward, part of a formal evaluation method is the presentation of evaluation results to team members to facilitate further ideation. In this paper we choose to present the results using common radar charts.

The remainder of this paper is organized as follows: In Section 2 we provide a brief review of the literature related to the representation of tactics concepts, and tactics-dependent criteria. In Section 3, theoretical developments and the proposed method are presented and in Section 4 a demonstration of the method’s use in a design project is provided.

2 LITERATURE SURVEY

In this section we review the literature as it relates to the development of the proposed method. We specifically review the state of the art in: 1) representations of tactics, and 2) tactics-dependent criteria.

2.1 Representations of Tactics

As shown in Table 1, various methods exist for representing tactics concepts. Each is described in more detail in this section.

Bodystorming [9] and empathic walkthroughs [17] both provide different approaches to tactics representation. In bodystorming, designers carry out the steps needed to interact with a product, and in place of a product use a prop or simply their imagination. Thus the tactics representation is the user’s actual movements. A limitation of this representation of tactics is that it is not easily stored by, shared with, or evaluated by dispersed teams, since its stored form (video), though information-rich, can be time-intensive to review or give feedback on [25].

In empathic walkthroughs, the designer imagines the use of the product by talking aloud. The subject of the evaluation in this case is the audible words describing the tactic. Just as in bodystorming, this representation of the tactic is beneficial because the design is no longer in the stage of a vague idea. However, reviewing the verbal dictations of many concepts while carrying out an evaluation can be prohibitively expensive [26].

Storyboards represent tactics by a series of drawings or photos which provide chronological snapshots of a product's use [15]. While this representation can be easily used later, it is less detailed and not typically as information-rich as bodystorming. Further it may not be quickly constructed during ideation [27].

Contextual inquiry [28] and co-creation workshops [29] are examples of methods which allow the tactic to be represented not by the designer, but by the user themselves. In contextual inquiry, the design team observes the user as they carry out the current tactic in their workplace. Co-creation workshops allow the design team to see the actual user act out the tactics concepts. User participation provides obvious benefits, but also requires significant resources which make these representations ill-suited for use in impromptu ideation that often is needed throughout the product development process.

A journeymap [19] describes actions in various phases of product use, plus the user goals, emotions and mindsets which can explain those actions. Although the described series of actions represent the tactical design well, the high level of detail present related to user motivations and emotions make such a method difficult to use quickly when representing many concepts.

Two service design methods are service engineering and blueprints [30]. The service engineering method [31] proposes that a service is an activity, where an activity is a series of actions performed by the people involved. The method [20] involves considering deeply the characteristics of the user and the series of steps the user takes in interacting with the product service system (PSS). The steps take the form of a sequential list of written steps. The characteristics of the environment however are not formally defined.

Shostack, a Marketing researcher, presented the blueprint as a way to represent a service during the service design process [21]. A blueprint represents steps using a flow chart with execution times to represent the service, and provides a means for denoting when a step is performed by the consumer rather than the service provider. Others have also made use of the blueprint in developing PSS [32]. While the blueprint represents the user steps and distinguishes between steps taken by different actors, it does not detail the actor skills/knowledge nor the environmental characteristics.

A task analysis is a tactics representation from the field of human factors [14]. It fills at least two functions: It helps the ergonomist discover the steps currently taken to complete a task, and it presents the list of steps for future reference. To create a task analysis, the designer begins with a task and decomposes it into a series of steps, which take the form of an ordered list [14, 33, 34].

One difficulty associated with task analysis is determining how far to decompose a task. Some ergonomists decompose the task until a useful point of detail is reached, while others determine a stopping point by using a $P \times C$ criterion, where P is the probability of failure at that task, and C is the consequences of that failure [14]. Note however that this is not usually carried out by a formal calculation, but rather a mental guideline for the ergonomist [14]. With or without a $P \times C$

criterion, it can be difficult for those who do not have experience with task analyses to know how far to decompose the task. This can ultimately result in an excessively detailed list, which is difficult for a novice in task analysis to use.

When representing the technology and tactics concepts, we believe it is important that a similar level of detail should be used when describing each. It could be problematic for example to represent the technology in high detail and the tactics in minimal detail, or vice-versa [35].

Despite these difficulties, the task analysis does represent a series of steps in a way that is relatively easy for the designer to review, and is relatively inexpensive to create, share and get feedback on. A task analysis alone, however, is inadequate to describe a tactic concept prior to evaluation. It is clear, for instance, that the difficulty of a series of steps would be different depending upon the characteristics of the human carrying them out, or depending upon the environment within which the tasks would be carried out. Because a task analysis does not include these details, a task analysis alone is an insufficient SOE to use for tactics when the goal is to evaluate the tactics design.

We see that while each of the existing tactics representation methods have their own strengths, they also have drawbacks that make their application to the conceptual design stage problematic. Noted drawbacks include ease of creation, ease of transferability, time to review, and amount/type of information captured.

As a final note, the literature indicates a potential connection between the notion of formally defining user tactics and capturing design rationale [36, 37]. An intended user tactic may be the rationale behind a particular technology concepts, for example, the placement of knob or other user interface to promote a particular tactic. In this way, a formal representation of user tactics, in a way captures design rationale.

2.2 Tactics-Dependent Criteria

As noted in Table 1, evaluation criteria are not always stated explicitly in the published evaluation methods. Existing methods such as scenarios [11], storyboards [15], bodystorming [9], and cognitive walkthroughs [17] all represent the tactic in a way that is believed to make weaknesses apparent to the development team. Evaluations made using these techniques are not necessarily made on explicitly stated tactics-dependent criteria; rather the product’s use is evaluated against the designer’s mental model for a usable product.

This can be problematic because it relies on the design team having expertise in the intended use-case, and/or being able to empathize effectively with stakeholders. Technology based evaluations don’t rely on the design team having these traits, instead they rely on explicit criteria derived from customers.

Other methods do, however, evaluate the product against specific tactics-dependent criteria [38, 33, 39, 40, 41, 42]. In order to review these criteria, consider the *Tactics-Dependent Criteria Decomposition Tree*, referred to hereafter as *the criteria tree*, in Figure 2. The decomposition suggests that the most abstracted and general tactics-dependent criterion is whether or not a product is a delight to use. One layer down in this decomposition includes criteria such as *Easy to use* and *Simple*, and so on.

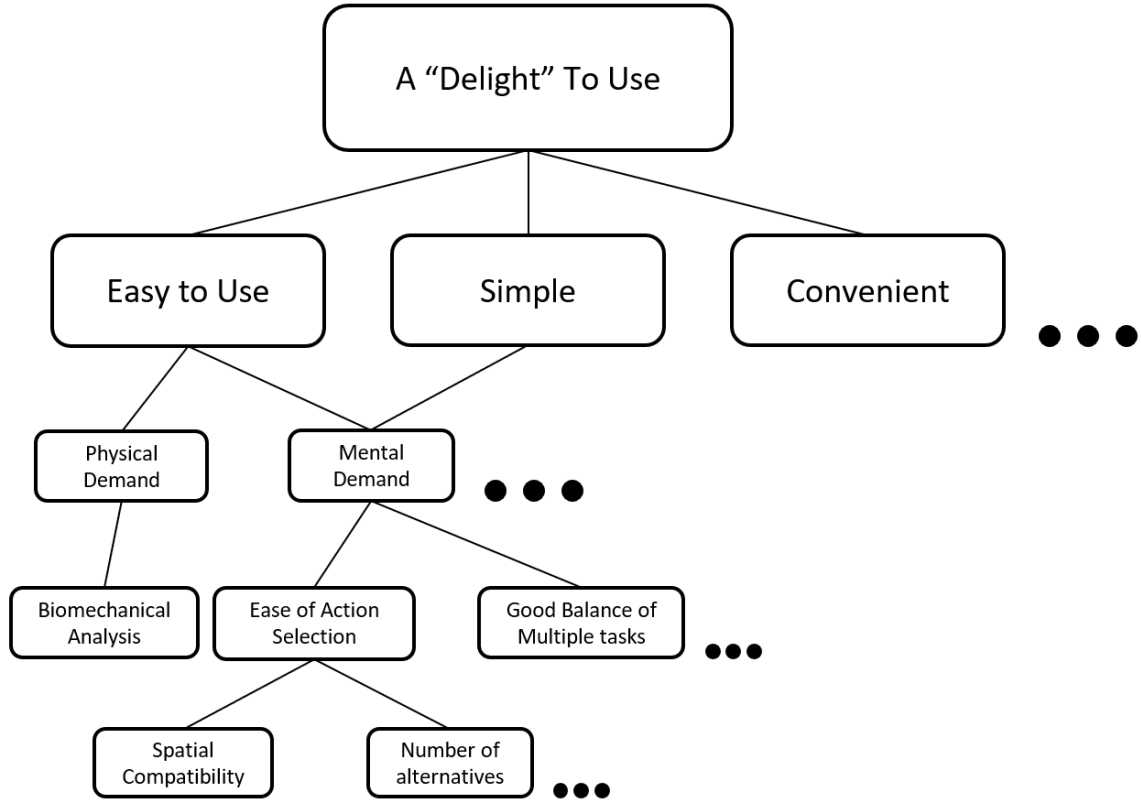


Figure 2: The *Tactics-Dependent Criteria Decomposition Tree*. Methods exist at every level in the tree that utilize tactics-dependent criteria to evaluate products.

Many methods exist that use criteria at the second level of the criteria tree. One example of a method at this level is the System Usability Scale (SUS)[38]. The SUS is a widely accepted ten-item user survey for determining the usability of products and services. Two points in the survey are: “I found the system unnecessarily complex.” and “I thought the system was easy to use.” Criteria at this level in the tree present difficulties to teams carrying out evaluations in the conceptual design stage because there is no physical technology for potential users to evaluate. Further, Pugh observed that the use of ambiguous criteria in the Pugh matrix can lead to a less productive evaluation, since these criteria can be interpreted very differently by development team members [10].

Other methods exist that use criteria at lower levels of the criteria tree, but they too have limitations when applying them to conceptual design. Human factors and ergonomics has examined closely what makes a product easy to use. For instance, the effects of spatial compatibility and number of alternatives on the ease of action selection have been examined [33] (see Fig. 2). Other decompositions have been carried out in this field, such as studying what makes a movement

physically difficult for a human, as in biomechanical analysis [33, 39, 40]. A problem with using criteria deep in the criteria tree is that they require more information and therefore are inappropriate to use in the conceptual stage when relatively little information about the design exists.

Stage-appropriate criteria do exist and are often situated in the middle portion of the criteria tree. Mental demand, physical demand [41], psychological stress load [42] and cost of operation [43] for example, are criteria that are quickly understood and are also more specific than the criteria higher in the tree. The difficulty with these mid-level criteria is simply that they are scattered across multiple areas of research, making engineers less likely to be aware of and use them because of the associated acquisition cost.

In summary, many tactics-dependent criteria exist and are currently used by practitioners to evaluate products, however they are not readily applicable by design engineers in the conceptual stage. This is because criteria lower in the tree require more information than is available in the conceptual design stage, criteria higher in the tree tend to be ambiguous, and criteria in the middle portion of the tree are scattered across many areas of research and practice.

3 THEORETICAL DEVELOPMENTS

This section provides a detailed description of our proposed approach to represent a tactics concept, our proposed criteria for considering tactics during concept evaluation, and a basic, but adequate, approach to present the concept evaluation results to teams.

3.1 Representing a Tactics Concept

We propose that a tactic can be adequately described in the conceptual design stage by a simple written description including the following three things, which are illustrated in Fig. 3:

The Actor: The actor is one or more people who carry out the tactic. A brief description of the actor is sufficient, when it is focused on actor characteristics that affect the actor’s ability to carry out the tactic. This is a key component missing from the task analysis discussed in Sec. 2. As shown in Fig. 3, the description can be simple. For example, the actor is an experienced able-bodied warehouse worker of typical stature and strength.

The Environment: The environment is the location(s) where the tactic will take place. A brief description is sufficient when it is focused on the characteristics of the environment that affect that actor’s ability to carry out the tactic, or the technology’s ability to perform (this may include weather, noise, hazards, etc.). This element is also absent from the task analysis in Sec. 2. For example, the environment is a temporary warehouse for receiving and distributing aid supplies to Afghans in a military conflict zone.

The Sequence of Steps: The sequence of steps is simply a list of what the actor would do to carry out the tactic, as shown in Fig. 3.

One other piece of information included in the tactics representation is the name of the tactics concept. This simply facilitates organization and discussion later in the design process.

Tactics Concept Name:	<i>Pull sliding door and lever</i>
Actor <i>An able-bodied warehouse worker of typical stature and strength.</i> Environment <i>A temporary warehouse for receiving and distributing aid supplies. Warehouse is located in a middle-eastern conflict zone</i> User Actions • <i>Grasp handle of garage door</i> • <i>Pull door to open position, keeping body behind the door in the process</i> • <i>Pull lever to drop external barrier</i> • <i>Attend to vehicle as normal</i>	

Figure 3: A tactics concept for a product can be represented in a written form with descriptions of the actor, environment, and sequence of steps.

The sequence of steps is the most substantial part of representing a tactics concept. A *task analysis* [14] is an effective means for representing a sequence of steps during conceptual design because it can be created and edited quickly, information is captured and is not subject to loss, and information can be reviewed relatively quickly during an evaluation.

As described in Section 2, one challenge of task analysis is knowing when to stop decomposing the task. We propose that the designer decompose tasks until the tasks describe whole body movements and part placement. These two items are inspired by the work of Boothroyd and Dewhurst [44], where they present time predictions based on two categories of actions: 1) part acquisition and orientation and 2) part insertion. We have found that this guideline helps avoid confusion over how far to decompose a tactic, and allows for more uniform creation of tactics concepts. This guideline also has the quality of guarding against the over-decomposition of tasks which is also a function of the $P \times C$ criterion. The task would never be decomposed so far such that P , the probability of failure is nearly zero (e.g., Human looks at the handle. Extend human

arm towards handle.). By basing decomposition on whole body movement and part placement, such over decomposition is avoided and since whole body movements and part placement are easily comprehensible guidelines, they are more accessible to novices at task analysis.

Boothroyd and Dewhurst’s categories are used here because they are effective in describing user interactions of a physical nature. Although other types of user interaction exist, we do not make them a focus of this paper. While the Boothroyd and Dewhurst approach is certainly relevant in the detailed design stages of product development, the principles behind the method can be applied in the conceptual stage. This is evident since some tactics-representation methods which are used in the conceptual stage (e.g. Empathic Walkthroughs [17]) represent the steps the user would take to use a product on a level of detail similar to Boothroyd’s approach. As an example of the use of these categories, the task analysis for opening a door would be: Walk to the door (major body movement), open the door (part placement).

It should be noted that this form of a tactics concept is meant to be used when the concept set contains fewer than 20 concepts. If the set were much larger, a significant amount of time would be required to create tactics representations for each concept.

This form of a tactics concept – a written description of the actor, environment, and steps – does entail certain drawbacks. For example, it is not as information-rich as other representation methods such as bodystorming, and although the proposed decomposition guideline reduces confusion, it can still be difficult to know how far to decompose an action. Despite these drawbacks, this form of a tactics concept addresses many of the weaknesses identified in existing tactics concept representations which are important in conceptual design. Specifically, it can be created relatively quickly, it can be reviewed and shared relatively quickly, and unlike task analysis alone, this method articulates who the actor is and the environment, which facilitates meaningful evaluation.

3.2 Tactics-Dependent Criteria

We recommend that for development teams wishing to formally consider tactics during product concept evaluation, the set of stage-appropriate tactics-dependent criteria in Table 2 should be considered by the team as a requirements checklist [13]. The list serves to alert engineers of potentially useful criteria that the team can consider as they choose final tactics-dependent criteria for their specific project.

To help teams with the process of choosing criteria from Table 2, we provide the following guidelines:

- Choose criteria that different product concepts will perform differently in. For example, *manpower* would not be a helpful criterion to use if all of the proposed concepts in a set use only 1 person to carry out the tactics.
- Choose criteria that are important given the specifics of the project. Each design problem is different and so necessitates the prioritization of certain criteria over others.

The first guideline is given based on the rationale that it is not effective to use a criterion which does not highlight any differences in concept performance since a main purpose of an evaluation

Table 2: A list of tactics-dependent criteria. The performance of a product in a criterion on this list is sometimes dependent upon the tactics design. Therefore, it is wise to consider tactics when evaluating a product relative to these criteria.

Units	Criterion	Description
Impact on project		
Time	Time to reach milestones	Key project deadlines
\$	Cost for development	Financial cost to design the product.
\$	Target product Cost	Intended market price for product
\$/Time	Rate of return on investment	Expected financial performance considering revenues and expenses
\$, time	Resources for developing user documentation	Resources required to develop documentation necessary for user to be capable of carrying out product steps.
\$ spent on fines	Degree of intellectual property infringement	Resources spent on patent and intellectual property infringements. E.g. new use patents.
Impact on user		
n/a	Boredom and monotony	User boredom and monotony while using the product
\$	Cost of operation	The financial cost to the user to operate.
\$	Opportunity Cost	The financial cost of forgone opportunities.
n/a	Human comfort	Human comfort while using the product
n/a	User acceptance	User acceptance of the sequence of steps necessary to use the product. Historical, cultural, and other factors may impact acceptance.
n/a	Favorable working environment for human performance	Characteristics of the service environment that support successful human performance. E.g. Light, temperature, etc.
n/a	Fatigue and physical stress	Human fatigue and physical stress
n/a	Ease of use	Ease of using a product.
Time	Losses of time	Losses of user time during product use.
#/time	Frequency of errors	Rate of human errors. May be specified to be error rate for errors with a specific degree of consequence severity.
Time	User training necessary	Time user must spend in receiving training necessary to carry out product steps.
#	Manpower	The number of people required to use a product.
n/a	Personnel	The aptitudes, experiences, and other human characteristics necessary to achieve optimal system performance
n/a	Mental demand	Extent of mental and perceptual activity required. (e.g. thinking, deciding, calculating, remembering, looking, searching etc.). Level of concentration and complexity.
n/a	Physical demand	Extent of physical activity required (e.g. pushing, pulling, turning, controlling, activating, etc.).
n/a	Temporal demand	Pressure due to the rate at which the tasks occurred. (E.g. Slow or fanatic). Frequency of spare time and occurrence of interruptions or activity overlap.
n/a	Human performance	Extent to which the human successfully carried out the main goal of the task.
n/a	Psychological stress load	Level of stress due to confusion, frustration, insecurity, discouragement, or anxiety.
$Prob_{\text{hazard}}$	Safety (Hazard assessment)	Probability of hazards to human safety that arise from product use. May be specified to be probability of hazards with a specific degree of severity.
Impact on technology		
Time	Life in service	Service life of technology.
Time	Time to unacceptable wear	Wear on technological components.
Time	Mean time to failures	Mean time to technological failures.
\$	Cost of equipment losses	Losses of technology due to human use.
Various	Functional Performance	Functional performance of the technology.
Various	Key performance targets	Key performance targets of the technology.
Impact on environment		
m_{CO_2}/m_{fuel} , m_{NO}/m_{fuel} , etc.	Environmental impact resulting from use	Impact on environment as a result of product use. (e.g. Pollutants, noise, production of waste, use of natural resources)

of concepts is to comprehend the strengths and weaknesses among the set. The second guideline is supported in Pahl’s work [13]. The criteria in Table 2 aim to address the challenges associated with the criteria discussed in the literature survey, namely, that criteria can either be ambiguous or require more information than is available during conceptual design.

3.2.1 Methodology for Creating and Using Table 2

The approach for deriving the list of tactics-dependent criteria in Table 2 can be summarized in three major steps. First, potential tactics-dependent criteria were gathered from the literature into a master list. Second, the list was consolidated by removing redundancies. Third, the tactics-dependent criteria were identified from the consolidated list. In what follows, each of the three processes will be described, one at a time. Finally, guidelines are provided for teams who wish to determine dependencies of criteria for their specific project.

Gathering Criteria into Master List Criteria were gathered in two ways. First, tactics-dependent criteria at a middle level of detail in the Criteria Tree (see Sec. 2) were sought out and added to the master list. Second, sets of general product criteria from the mechanical design literature were added. This was done because such sets of requirements tend towards comprehensiveness, which is helpful in ensuring that the list of tactics-dependent criteria cover the breadth of ways that tactics can affect the results of a product evaluation.

Stage-appropriate tactics-dependent criteria from three methods — NASA TLX [41], SWAT [42], and MANPRINT [45] — and one requirements set [46] in the field of human factors were added to the list. Criteria lists from the field of product service system design were also considered [47, 23, 48, 49].

Four lists of general product criteria were used from the mechanical design literature [3, 10, 43, 13]. Ullman [3], Pahl [13], and Dieter [43] used headings to organize requirements. While general phrases were used as headings, on occasion authors used more specific phrases as headings such that the headings themselves could be considered semi-detailed criteria. Two headings were deemed to be specific enough to be considered criteria: functional performance [3] and key project deadlines [43]. The initial list of compiled criteria, excluding the 25 headings, contained 157 items.

Consolidating the Master list The first step in consolidating the master list was to ascertain meanings behind the criteria by examining each source. This not only enabled the elimination of redundant entries, but also led to a clear understanding of the criteria for future analysis. As an example of this consolidation step, Pugh’s criterion *environment* is similar in meaning to Dieter’s *service environment*, and both were consolidated into the same criterion, *effect of service environment on product performance*.

Four criteria were omitted from further analysis: *Soldier survivability* [45], *product name* [43], *customer* [10] and *competition* [10]. *Customer* and *competition* suggest that the design team understand the competition and the customer in creating requirements. These were omitted because they suggest a process for gathering requirements, and are not criteria for product evaluation. *Soldier*

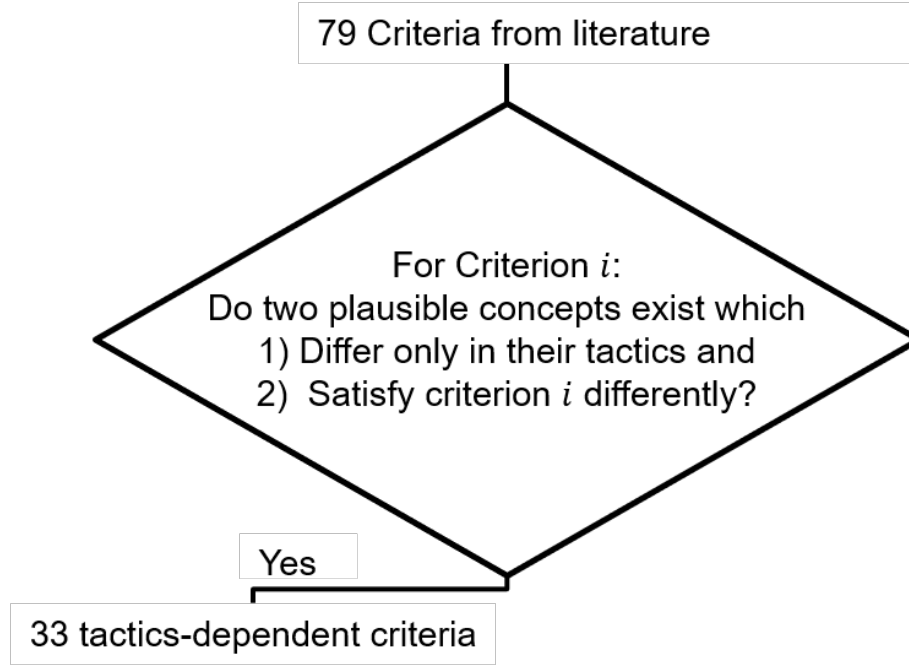


Figure 4: Process used to determine if an evaluation criterion is dependent on tactics.

survivability was omitted because of its multifaceted nature, and *product name* because of the lack of importance in conceptual design.

At the end of this step, 79 criteria remained. See Appendix B in [1] for this full list of criteria. The resulting list was considered to be a suitable starting set of criteria from which tactics-dependent criteria could be identified.

Identifying Tactic-dependent Criteria from the Consolidated List The basis behind the approach for identifying tactics-dependent criteria is depicted in Fig. 4 and can be summarized in the following principle:

If two products exist that 1) differ only in their tactics and 2) satisfy criterion i differently, then the satisfaction of criterion i is dependent upon the tactics.

Following this principle, we can test if a criterion is dependent upon the tactics by determining if two plausible product concepts exist that 1) satisfy the criterion differently, and 2) have different tactics but the same technology. As will be seen later, it is instructive to also identify technology-dependent criteria, and a similar test can be carried out to determine those criteria.

In summary, tactics-dependent criteria and technology-dependent criteria can be identified by carrying out the following tests:

Tactics test: Determine if two plausible product concepts exist that 1) satisfy criterion i differently, and 2) have different tactics but the same technology

Technology test: Determine if two plausible product concepts exist that 1) satisfy criterion i differently, and 2) have different technology but the same tactics

The list in Table 2 are tactics-dependent criteria that resulted from the tactics test. See Appendices D and E in [1] for the product concepts used to justify the inclusion of each criterion and the reasoning used. The results of the technology test were that almost all criteria are technology-dependent criteria. Only two criteria were found to not be dependent upon the technology: *Manpower* and *personnel*. *Manpower* is the number of people needed to carry out a tactic, and *personnel* is the aptitudes, experiences, and other human characteristics necessary to achieve optimal system performance. Because these criteria relate to the actor, which is a characteristic of the tactic, a concept where the tactics remained the same and the performance in the criterion changed was not found. Therefore, all criteria in Table 2 except *manpower* and *personnel* were classified as being both tactics-dependent and technology-dependent. *Manpower* and *personnel* were classified as only being tactics-dependent.

Using an affinity diagramming approach [50], the list was then organized into similar groups, and headings were given to each group. The following four headings resulted from this process: Impact on the project, impact on the user, impact on the technology, and impact on the environment, where environment here refers to the earth’s environment.

3.2.2 Team Guidelines for Project-Specific Criteria Classification

Clearly, more criteria may be classified as tactics-dependent or technology-dependent than have been given here. In addition, some criteria presented here as dependent may be independent when applied to projects with certain characteristics.

Therefore, while the list in Table 2 functions well as an initial checklist, it may be helpful for design teams to add to or subtract from this list after considering the details of their specific design project. To do this, we recommend that design teams simply carry out the tactics and technology tests themselves in order to classify criteria as tactics and/or technology-dependent. These tests require the team to find two plausible concepts with certain characteristics (see Sec. 3.2.1). We provide the following guidelines to help teams with the process of finding two plausible concepts:

- Clearly state the design objective that the two product concepts must achieve. The objective should be achievable by both product concepts.
- Try to find product concepts whose tactics and technology differ significantly for the tactics and technology tests, respectively. For example, for the tactics test, seek significant changes in the user actions. For the technology test, seek significant geometry or material changes.
- Find concepts that could plausibly be generated by a design team during an ideation session. It is therefore not necessary that each concept be free of flaws or be fully defined.

These guidelines represent the lessons learned while carrying out the process described in Sec. 3.2.1. During that process, it was apparent that without clearly stating the design objective, it was easy to unintentionally generate two concepts that do not achieve the same objective and are therefore two fundamentally different ideas which violated the requirements of the tests listed in Sec. 3.2.1. It was also apparent that another pitfall was making a very minor change to technology or tactic, for example, changing a screw. While this technically satisfies the requirements of the tests, it does not satisfy the purpose of the test. The last pitfall was that one might be tempted to require high quality ideas when in practice, ideas are not required to be high quality in an ideation session.

To summarize, there are at least two ways to use the list in Table 2. First, teams can use the list directly by simply accepting the presented classifications of criteria as being tactics-dependent or both tactics and technology-dependent. Second, teams can use the list in Table 2 as a starting point and classify the criteria themselves in light of the details of their specific project. The first approach has the benefit of being faster, but it may be that certain criteria are imperfectly classified for their particular project. The second approach is slower, but has the advantage of more accurate classifications. The advantages of having criteria classified is discussed in the next section.

3.2.3 Criteria Organization

After the design team has chosen tactics-dependent criteria, we recommend that design teams organize their chosen set of evaluation criteria into three possible classes: Criteria that are only dependent on tactics, criteria that are only dependent on technology, and criteria that are dependent on both tactics and technology.

Such an organization is helpful in several ways. First, it reminds engineers when tactics may impact a certain criterion. This signals to the team that evaluating without an evolved form of the tactics as part of the SOE may lead to a less accurate evaluation. Second, it gives engineers a starting point for the idea generation process that often follows an evaluation. For example, if it is desirable to improve a product’s performance in a particular criterion, which is dependent upon both tactics and technology, then the performance can be improved by changing the tactics, the technology, or both. A third way this classification is helpful is it can save time during evaluations. Traditionally, teams often review the product concept being evaluated before making a judgement about its performance in a certain criterion. By knowing the criterion’s dependencies, the team can skip reviewing any concept that does not impact its performance.

3.3 Description of Full Evaluation Method

This section’s aim is to combine the previously described elements and demonstrate how they would be used in a method for the formal and simultaneous evaluation of tactics and technology concepts. The illustration of this overall method is found in Fig. 5.

Suppose that a development team has generated a set of product concepts, and that those concepts contain technologies that have evolved to the point of a sketch, and tactics which are only vaguely defined. We do not suggest that this state of evolution is the most common or the best

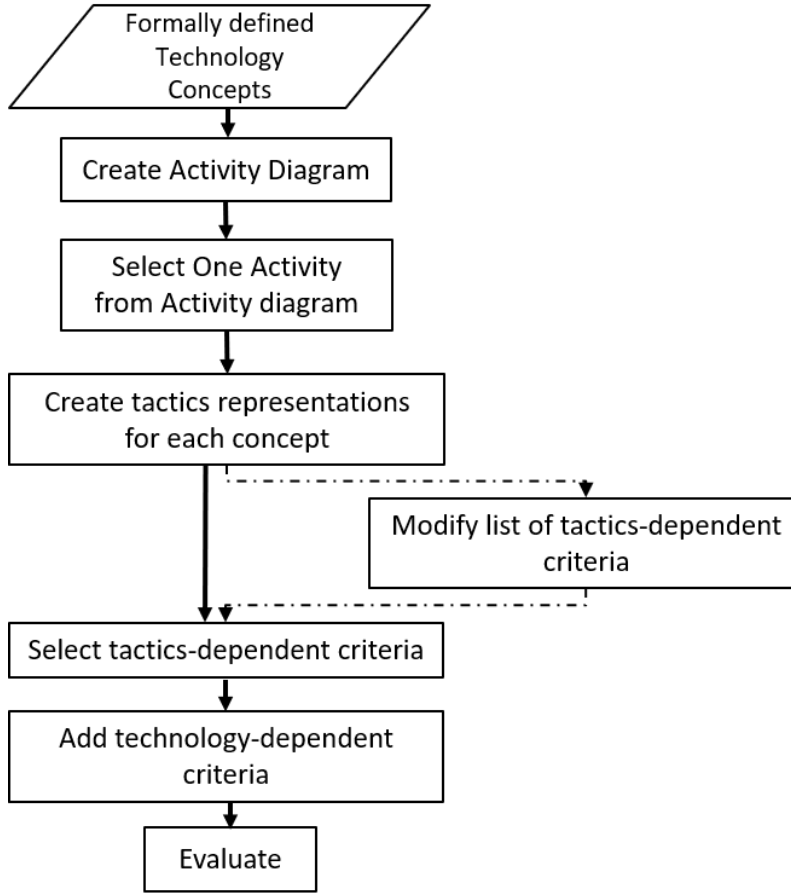


Figure 5: The overall evaluation method using the tools proposed in this paper. Note that although in this paper it is assumed the team begins with technology concepts, this is not the only valid starting point.

state of evolution for a set of ideas. Instead, we begin at this point purely to illustrate the creation of the proposed written form for tactics concepts.

In order to consider the tactics during evaluation, the designer must first narrow the scope of the tactic to one appropriate for the desired evaluation. A user can carry out many different activities with a product; they purchase it at the store, unbox it, stow it, retrieve it, use it, clean it, and more. The full scope of the activities a user engages in with the product is illustrated well by Otto and Wood’s Activity Diagram [51]. With awareness of the extent of possible activities, the first step is to choose one or more activities to analyze.

Having chosen an activity, the development team begins representing the tactics concept by stating the actor and environment. As part of specifying the environment, it can be useful at this

point to specify the initial relative positions of the product and human for the activity or activities being analyzed. For example, the battery-powered drill is in a protective case inside the bottom drawer of the tool chest, and the user is in front of the tool chest. Then, the steps for carrying out the tactic are stated in the form of a list of user actions.

With this completed for each product concept, each product concept now has a representation of tactics and technology that contains enough detail such that an evaluation can be carried out, and tactics-dependent criteria can be chosen from the list in Table 2. As an option, the team may choose to modify this list using the guidelines in Section 3.2.2.

After adding in any other technology-dependent criteria that the team sees fit, the criteria are then used to evaluate all product concepts for example, in a concept scoring matrix. A subsequent discussion can then be carried out in which the development team carefully considers the strengths and weaknesses of each product concept, and both the tactics and the technology can be considered as design variables to enable the improvement and combination of concepts.

4 DEMONSTRATION

As a demonstration of the method, we present the results of a team of undergraduate engineers who are designing a machine that can create broom bristles from two liter plastic bottles (see Fig. 6), and is meant to be used in Amazon region of Brazil as a sustainable means for producing household brooms. Prior to carrying out the method, the team had created many technology concepts in the form of annotated sketches but had not yet considered tactics deliberately during product concept evaluation. The first sub-section that follows will present how the team used the method during conceptual design. The second will discuss the more and less effective ways the team used the components of the method, and the third will discuss what the team could do next with the results of the method.

4.1 Results From Team’s Use of Method

First, the team created a user activity diagram (defined in Sec. 3.3) for the bristle machine (see Fig. 7). After selecting the *use machine to produce bristles* activity, the team created tactics representations for each technology concept in the set (see Fig. 8).

The list of user actions gave the development team a deeper understanding for what each tactic entailed as they wrote out each step and envisioned the process of product use. Whereas before the tactics were only implicitly defined, the tactic now had a written form and could be communicated to others as well as referenced during the following evaluation.

The next step was for the team to select tactics-dependent criteria to use during product concept evaluation. After following the guidelines for criteria selection in Section 3.2, the team chose nine criteria from Table 2, and these criteria are labeled as 1 through 9 in Table 3. Seven other technology-dependent evaluation criteria were of interest to the team, and these are labeled as 10 through 16 in Table 3.



Figure 6: A broom whose bristles are made from 2L plastic bottles.

In this case, the criteria were classified in light of project-specific details as described in Section 3.2.2. The classifications found are given in Table 3. Note that in this case, all of the classifications from Table 2 remained the same. As an example of when this might not have been the case, consider a concept set in which all concepts include an automated cutting system. In this case, the "Bristle size" criterion would be only technology dependent, whereas in the current concept set concepts exist where the bristle size is dependent upon the user tactics (E.g. product concept 10 in Fig. 8). In addition, bristle size was determined to be tactics-dependent. This was due to product concept 10, in which the user must cut each bristle to size individually.

With both technology and tactics concepts as part of the SOE, and tactics-dependent criteria being used for the evaluation, the team was ready to proceed with a product concept evaluation that considered tactics.

Note that there are many methods for carrying out the next step of the evaluation. Some heuristic methods are commonly used in conceptual design, such as the concept scoring matrix or Pugh's matrix. Other methods like VIKOR and TOPSIS [52] take a numerical approach for identifying the best alternatives. If desired, criteria can be weighted subjectively as in traditional decision matrix methods [7], or their weightings could be informed by a numerical approach like DEMATEL [52]. All of these are valid ways to continue the evaluation. In this demonstration we choose to use a concept scoring matrix without criteria weights and evaluate each product concept on a 5 point scale, using a baseline product (See Appendix C in [1] for baseline concept) as reference. When using a 5 point scale, a 3 represents "same as baseline", while 4 and 5 represent better and much better than baseline, respectively [53]

After scores were assigned for each product concept and for each criterion, these scores were used to create radar charts of the evaluation information. In this case, only two categories of criteria were present in the plots: Technology-dependent criteria and both tactics and technology-dependent

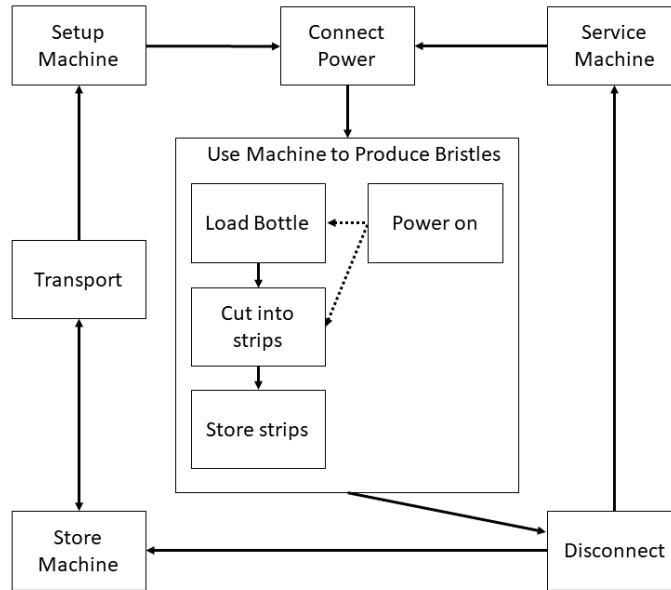


Figure 7: An activity diagram for a machine which converts two liter bottles into broom bristles.

criteria (see Fig. 8). This is because the team had no criteria that were only tactics-dependent.

This demonstration has thus far illustrated how the method works when used on an actual design project by engineers who were previously unfamiliar with the research. In the next section, the results of the team will be discussed in relation to how they illustrate more and less effective ways of applying them.

4.2 More and Less Effective Use of the Method

Poor use of the *actor* component of the tactics representation is illustrated in product concept 7, where "Machine operator" was the written description of the actor. Clearly, this description provides minimal additional detail beyond the word actor itself. Better use of the *actor* component can be seen in product concept 10: "A worker with great understanding of using a machine with sharp edges and patience." This description provides specific characteristics about the user that affect his/her ability to use the product; in this case, one of the characteristics provided is experience handling a machine with sharp edges.

#	Criterion	Tac	Tec
1	Safety	✓	✓
2	Time to reach milestone	✓	✓
3	Human comfort	✓	✓
4	Ease of use	✓	✓
5	User training necessary	✓	✓
6	Physical demand	✓	✓
7	Temporal demand	✓	✓
8	Boredom and monotony	✓	✓
9	Time to unacceptable wear	✓	✓
10	Bristle size	✓	✓
11	Machine is powered by washing machine motor or similar		✓
12	Machine is functional in Brazil		✓
13	Convenience of finished bristle storage		✓
14	Cost of machine		✓
15	Machine size		✓
16	Production speed		✓

Table 3: Evaluation criteria chosen for the broom bristle project. *Tac* and *tec* denote tactics-dependency and technology dependency, respectively.

	Technology Concept	Tactics Concept	Radar Chart
Product Concept 7		Actor: Machine Operator Environment: House in Amazon User Actions: - Place bottle wall in between trench walls - Spin bottle pushing edge past blade to start cut - Pull thread around roller and towards paddle - Tie thread to paddle - Start motor - Remove bottle top from trench - Load new bottle and repeat - Once finished remove paddle and cut bristles	
Product Concept 9		Actor: Regular person with basic knowledge about machine Environment: A simple warehouse that might not be completely prepared for different weather conditions, especially rain. It will be located in the Amazon, where it is difficult to find parts or replacements. User Actions: - Load bottle in machine - Adjust wheels/pole to be able to fit the diameter of the bottle - Adjust blade height/place bottle in trench with desired depth - Rotate the bottle and cut it through the trench - Pull ribbon and pass it through the straightener - Tie ribbon to the paddle - Turn on machine - Load new bottle - Cut it and tie it to previous ribbon - Once finished remove paddle and cut bristles	
Product Concept 10		Actor: A worker with great understanding of using a machine with sharp edges and patience Environment: A simple warehouse that might not be completely prepared for different weather conditions, especially rain. It will be located in the Amazon, where it is difficult to find parts or replacements User Actions: - Load bottle in lower pole - Move pole to adjust according to bottle diameter - Adjust blade height - Cut bottle through blade - Pull ribbon - Pass the ribbon through rollers - Turn on motor - Use guillotine to cut bristles - Store bristles in bucket - When bottle is done, remove bottle top - Load new bottle and repeat	
Product Concept 11		Actor: A regular person with basic training in how to use the machine Environment: A simple warehouse that might not be completely prepared for different weather conditions, especially rain. It will be located in the Amazon, where it is difficult to find parts or replacements User Actions: - Load bottle into pole - Spin bottle and cut it with the blade - Pull ribbon towards rollers - Push ribbon from the other side of the rollers into straightener - Wrap around straightener and pass through rollers - Turn on machine - Store bristles in a bucket	

Figure 8: Product concepts for a machine that ²² turns 2L plastic bottles into broom bristles. Each product concept has an associated Technology and Tactics concept, as well as a radar chart.

Poor use of the *environment* component can be seen in product concept 7: "House in Amazon." This description leaves many questions unanswered which may impact the nature of the user interaction with the product. Better use of *environment* is given in product concept 9, "A simple warehouse that might not be completely prepared for different weather conditions, especially rain. It will be located in the Amazon, where it is difficult to find parts or replacements." With more specifics defined about the environment, it is more likely that the design team will have a common understanding of the environment so that a more uniform evaluation can be carried out.

Poor use of the *user actions* list is demonstrated in concept 11, where the use of the technology is described, but only for using one bottle to create bristles. This is problematic as the actual use of the technology will involve creating bristles from many bottles, one after another. Therefore, only a portion of the actual tactic has been described with this representation, which may leave the engineer with an inaccurate understanding of what the tactic is before proceeding with the evaluation. Better use of the *user actions* is demonstrated in product concept 7, where the simple statement "load new bottle and repeat" demonstrates that the engineer was cognizant of the range of user actions needed to use the product.

Another illustration of the more and less effective uses of the user actions is evident in the decomposition of tasks. As an example of poor decomposition, consider the user action "store bristles in bucket." This action doesn't specify what the user must do to store the bristles. For example, do the bristles simply drop into the bucket, and the user must collect and order the bristles? Or does the user bundle the bristles and drop them into the bucket already ordered? This is unclear. Many examples can be found in the tactics concepts of better uses of the user actions. For example "wrap around straightener and pass through rollers" in product concept 11 gives a clear picture of what the user must do.

4.3 Future Steps for the Team

As a next step, the team should now view the presented results found in the radar charts in Figure 8 to identify strengths and weaknesses that will inform the combination, improvement, and elimination of concepts.

For example, it is immediately clear that product concept 11 may be a promising candidate for future consideration as it performs better than the baseline concept in many criteria. However, it appears to have notable weaknesses in the *cost of the machine*, *functionality in Brazil*, and the *time to unacceptable wear* criteria. As an approach to improvement of concept 11, the team could use the tactics and technology dependencies to guide their ideation. For example, to improve in the *functions in Brazil* and *cost of machine* criteria, the team can note that these criteria are solely dependent on the technology and can therefore focus on technology improvements. In the case of the *time to unacceptable wear* criterion, it is dependent on both the tactics and the technology, and the team can therefore try to imagine a way to improve the product concept in this criterion by only changing the tactics. For example, if the product may wear more quickly because of the user using the blade adjustment mechanism roughly, it is possible that the team can create documentation to instruct the user in proper handling. The team could also guide ideation by trying to imagine a

way to improve the product by changing only the technology, or by changing both the tactics and technology.

5 CONCLUDING REMARKS

In this paper we have proposed 1) a means for formally representing tactics concepts, 2) a set of tactics-dependent criteria that can be used to evaluate products while considering tactics in conceptual design and 3) a method which makes use of 1) and 2) to formally and simultaneously evaluate tactics and technology in conceptual design. The contributions in this paper together offer a practical method to simultaneously consider a product concept's tactics and technology which ultimately can facilitate the design team's creation of improved concepts by changing the tactics, the technology, or both.

To be more specific, this paper presented a tactics concept representation that can be quickly created and reviewed, is transferable, and contains descriptions necessary to make an evaluation that considers tactics. It also presented a list of stage-appropriate tactics-dependent criteria from a broad range of impact categories that originated from the literature but have not previously been presented in a compiled, ordered form that is ready for use by engineers. The proposed method meets all the goals identified in Table 1 unlike the existing methods from the literature.

We believe that designers who apply the proposed method, in full or in part, will benefit from the examples in section 4 to improve their ability to create tactics representations with sufficient detail and to effectively consider tactics during product concept evaluation. Further, we believe that using Table 2 as a checklist will broaden the thinking of a typical engineering team about tactical requirements, and that by separating evaluation criteria into groups based on their dependence on tactics or technology will help engineers be mindful of the role of tactics in determining a concept's success. Finally, we believe that teams who are rigorous about the evaluation of both the technology and tactics during the conceptual stage of design are likely to develop better, more desirable products.

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