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ADVANCES IN TRANSFORMATIONAL DESIGN: CORRELATING CONTEXT EVALUATION TO QUALITY FEASIBILITY AND NOVELTY

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ABSTRACT

In response to the call for multi-functional products, we have developed several relevant ideation techniques. These techniques are tailored for design of *transformers- devices with multiple functional states*. In this paper, we present significant advancements in transformational design. Primarily, we introduce a method to enhance quality, novelty, and feasibility (QNF) of design solutions. The method is used to classify design problem context and suggest pursuit of one of the two following device archetypes, transformer or *monomorph- devices with a single functional state*. The Indicators method is associated with a significantly increased probability of producing a design problem solution with higher QNF than a control (standard) design method. The claim that this method is accurate, its results are repeatable, and usage thereof enhances QNF is supported by a network of experiments and analyses. Statistical analysis is used to establish the accuracy, precision and repeatability of the method. Industry-standard qualitative methods, including inter-rater reliability analysis, demonstrate that usage of the Indicators method enhances design concept QNF. Concurrent minor analyses highlight the novelty of transformable designs; and some positive psychological effects of using the method. Additionally, the contextual (archetype) indicators have shown implicit promise as a core element for future research into ideation methods.

1 INTRODUCTION

Designers and engineers are called to develop products that can address customer needs in an environment of rapid change and development. Correspondingly, the research community is called to develop methods and techniques that empower the engineer to analyze design context in a refined manner that matches this dynamic environment. These tools must provide reliable insight regarding the best approach to each particular design problem. Although many concept ideation and customer needs analysis techniques are extant, there are fewer methodologies which provide systematic selection of the appropriate subset of these to apply.

1.1 MOTIVATION

The approach explored in this paper is to examine the influence of one concrete or not intuition-based, method for the selection of concept ideation methods. Such ‘selection’ methodologies are employed during early phases of design problem research and provide the designer with a guided, systematic design process that has been individuated to the given problem.

One such method is the Indicators method, which is examined herein. The result of this method is to provide a tailored subset of concept ideation methods and assist the designer in relating the concept selection process in a systematic way to design context. It provides a means to select between the transformational and monomorph ideation methodologies tracks.

Transformational design methodologies *enhance the creative ideation of transformable design solutions* [1]. As implicated, these methods are utilized to develop transformer device concepts, *devices with multiple physical configurations (or states) that enable enhancement or multiplicity of function* (e.g. a clamshell cell phone) [1].

As a counterpart, standard or monomorph design methodologies are *typical concept ideation techniques, resulting in the development of monomorph designs.* A monomorph is a device *with one single functional state or configuration* (e.g. a single speed bicycle).

The Indicators method was proposed in previous research [26, 27]. Iterative experimentation has shown that there are certain context clues which indicate that a given design problem will be best suited by one or the other of the basic archetypes- transformer or monomorph. In this paper we further explore the way in which utilizing such indications, for the selection of concept ideation methods, affects the QNF of the final design solution.

1.2 HYPOTHESIS

Usage of the Indicators method facilitates development of design solution concepts with higher quality, novelty, and feasibility than would result from undirected application of ideation methodologies to the same problem, Figure 1.

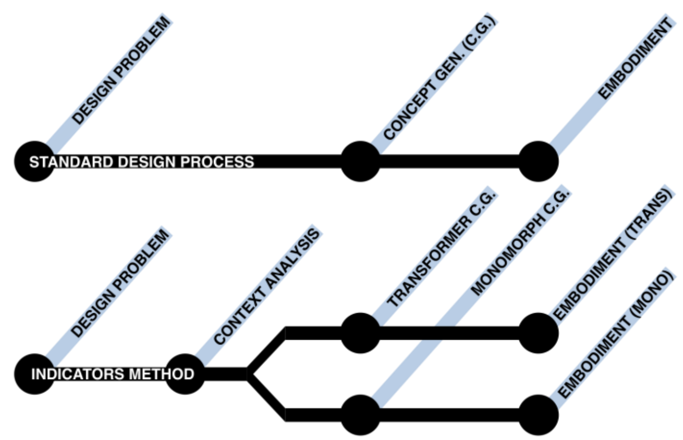

Figure 1: Comparison of the global design process with and without use of the Indicators method

2 BACKGROUNDS

Several methodologies for developing transformers have been developed previously. These methods are employed when context indicators for transformation are present (as determined by the Indicators method).

2.1 TRANSFORMATION PRINCIPLES

The seminal work on transformers design methodology, at the University of Texas at Austin, included an outline of three transformational principles or *generalized directives to bring about a certain type of mechanical transformation*. When embodied, a principle singly brings about transformation. One of the three indicators is depicted in Figure 2. A facilitator is in turn *a design architecture that helps or aids in creating mechanical transformation*. Transformation facilitators do not singly create transformation [1]. The principles and facilitators assist in cataloguing existing embodiments and generating new transformers. After studying thousands of transforming products in the electromechanical space, the set of three transformation principles and twenty facilitators appears to span the entire space [1, 9], Table 1.

Table 1: Transformation Principles and Facilitators

PRINCIPLES
Expand/Collapse
Expose/Cover
Fuse/Divide
FACILITATORS
Share Core Structure
Utilize Composite
Conform with Structural Interfaces
Enclose
Fan
Flip
Fold
Share Functions
Furcate
Utilize Generic Connections
Inflate
Interchange Working Organ
Utilize Flexible Material
Modularize
Nest
Roll/Wrap/Coil
Segment
Share Power Transmission
Shell
Telescope

Example Conceptualization of Principle

Figure 2: Transformation principle- *Expose/Cover*, seen in a rollerblade to shoe transformer

2.1.1 TRANSFORMATION CARDS

One transformers ideation tool is the Transformation Card set. The method for employing these cards is quite simple; laminated cards containing colorful examples and clear definitions of the transformation principles and facilitators are laid out on a table (perhaps during a sketch brainstorming session or similar) to provide analogical inspiration. An example Transformation Card can be seen in Figure 3. The method has been shown to quantifiably increase creativity in terms of quantity and novelty [9].

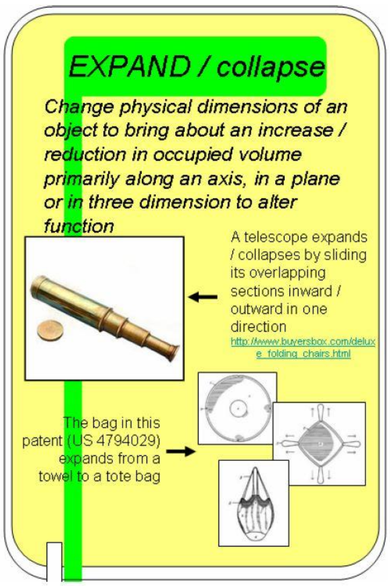

Figure 3: An example Transformation Card- for the transformation principle *Expand/Collapse* [6]

2.1.2 AUGMENTED TRANSFORMERS MIND-MAPPING

In Augmented Mind-mapping method, the elemental design problem is written centrally on a large sheet. However, instead of immediately spawning links to child elements, containing solution concepts (as is standard)- the transformation principles are added to the page as the first generation of child elements. Solutions are added as child elements under each principle. These solutions utilize the parent principle [4], e.g. Figure 4.

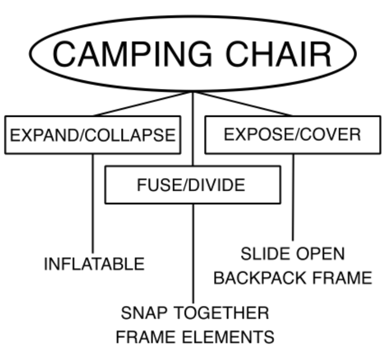

Figure 4: Example modified mind-map that demonstrates the constitutional elements

2.2 CONTEXT INDICATORS METHOD

The Indicators method, as mentioned above is a precursor to design ideation. This method is implemented at the phase when the designer has established the customer needs and design requirements. The indicators method is a qualitative-to-quantitative procedure that ultimately provides one of two simple instructions: "pursue the ideation of a transformable concept", or "pursue the ideation of a monomorphic concept". Figure 1 provides a high-level comparison between the Indicators method and standard design process[1].

To use this method the designer makes a sequence of qualitative evaluations on a Likert scale[2]- one for each of the four transformation indicators (TI) and five monomorph indicators (MI). For each indicator the designer responds to the prompt "How well does this indicator describe key characteristics of the given design problem?" and records a Likert value e.g. "How strongly would you agree that devices in the usage context/environment *share functionality* (a TI indicator) to those required of the to-be-designed object?" (a strong indication could lead to the example in Figure 2)

2.2.1 INDICATORS

There are four indicators for transformation and five indicators for monomorphic design[3], Table 1. The indicators were previously introduced [26, 27] and have been iteratively refined. Research to develop the indicators, is summarized in phase 1 and 2 of Figure 6. This involved the iteration and synthesis of dozens of design experiments which have been detailed in previous publications [26, 27].

Table 1: List of Indicators

TRANSFORMATION INDICATORS
Shared Function – *two similar products share use context and function*
Adhere to a Variable – *input variable to a device is dynamic*
Storage – *storage space is at a premium*
Adhere to Sequence – *multiple devices are needed for one process*
MONOMORPH INDICATORS
Vital Function – *a single function cannot be compromised*
Low Cost – *cost of complex features (i.e. transformation) is unacceptable*
Parallel Multi-Function – *all functions must be available simultaneously*
Ease of Use – *there is no time or ability to learn complex use procedure*
A-Periodic Use – *function is required without time to prepare/change state*

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[1] Application of the Indicators method does not retract any element of the standard design process.

[2] The Likert scale is a numerical agreement/disagreement spectrum. Typically, the Likert agreement scale has six options. These range, in whole numbers from zero- *complete disagreement*, to five- *complete agreement*.

[3] Because of this, the aggregated score is normalized to avoid imbalance; which can be seen in Equations 1 and 2.

The final representation mechanism chosen for the indicators is a set of laminated plastic cards. A complete copy of the Indicators Cards set is provided in Appendix A, while an example can be seen in Figure 5.

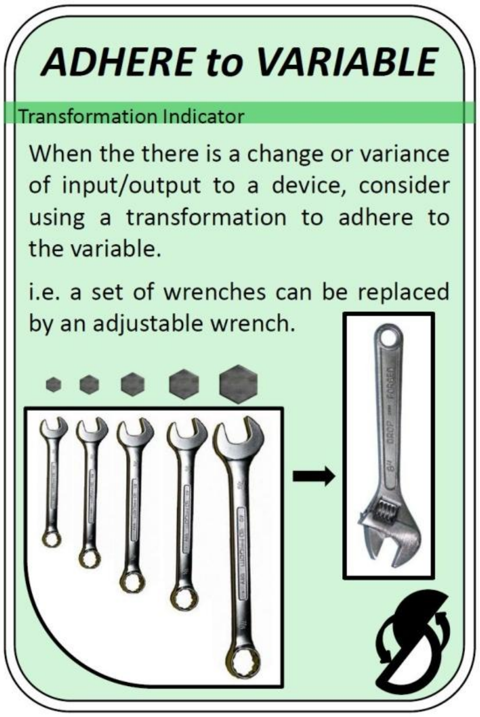

Figure 5: Example Transformation Indicator Card

2.2.2 CALCULATING INDICATION

There may be a mixture of indications for transformer or monomorph solutions in every design problem. The value of the Indicators method is to systematically evaluate all of the relevant factors and reduce the consideration into a single suggestion.

The binary instruction of this method is determined by first computing the normalized total indication value for TI and MI- the mathematical processes for calculating the indication magnitudes, $\overline{TI}$ and $\overline{MI}$, are respectively given in Equations 1 and 2:

$$\overline{TI} = \frac{\sum_{i=1}^{N_{TI}} TI_i}{Val_{\max} N_{TI}} \tag{1}$$

$$\overline{MI} = \frac{\sum_{i=1}^{N_{MI}} MI_i}{Val_{\max} N_{MI}} \tag{2}$$

where Equations 1, and 2: TI_i, MI_i are, respectively, the point value assigned by the respondent for the ith indicator of that archetype. Val_{max}, is complete agreement on the Likert scale (in this case, 5). N_{TI}, and N_{MI} are the number of transformation indictors and monomorph indicators, respectively (4 and 5). TI and MI are the normalized (0 to 1 range) indication values..

Finally, compare the values and pursue that with the larger normalized indication magnitude[4]. To 'pursue an archetype' means to include the transformers design methods, Sections 2.1.1 and 2.1.2, if a transformer is indicated; and to perform standard ideation methods if a monomorph is indicated. Additionally, the designer is encouraged to guide the design process towards the respective archetype when generating final concepts.

3 RESEARCH

The research goal of this paper is to evaluate the effect of the Indicators method on the quality, novelty, and feasibility of final design concepts. This influence is evaluated using several methods described below, and outlined in Figure 6.

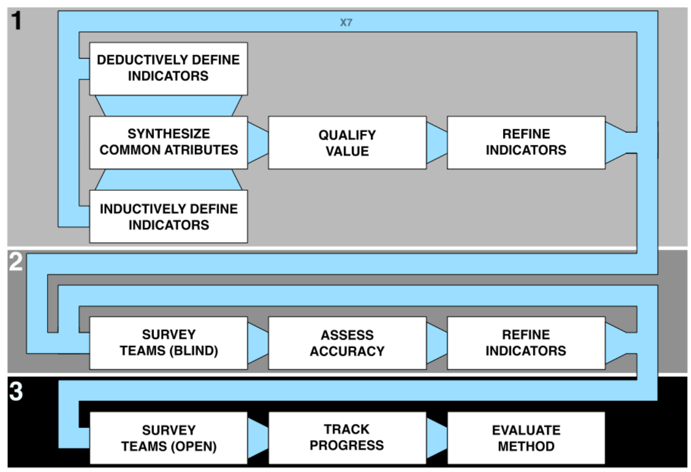

Figure 6: Research methodology flowchart – with research phases annotated

3.1 RESEARCH QUESTIONS

The objectives of this paper are to explore the relationships between usage of the Indicators method, and the quality, feasibility, and novelty of the final solution. Therefore the following research questions have been proposed:

1. *Are the context indicators complete, their determination process repeatable, and is their prediction of the desired archetype correct?*
2. *Can employing the Indicators method encourage more quality, feasibility and novelty in design solutions?*
3. *What are the correlations of interest between this method and other aspects of successful design-robustness to design requirement changes, etc.?*

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[4] The sensitivity of this analysis is .1; differences less than this should be iteratively recalculated until a consensus is reached on a greater differential. If no consensus can be reached, divide the design problem into subproblems and apply the method to each. Again, iterate to consensus on a relevant difference. Then, accordingly, pursue transformation or monomorph ideation methods for the physical systems of the design that relate to each subproblem (to the extent such is conceptually feasible).

3.2 EXPERIMENTAL PROCEDURE

There have been three phases of this project, some of which have been initiated in previous publications by the authors. The completion of all of these phases (see Figure 6), has resulted in answers to all three research questions:

1. *Identification and refinement of the indicators* [26].
2. *Assessment of indicator predictive accuracy (are they relevant?)* [27].
3. *Evaluation of the effects of implementing the Indicators method on QNF* [explored in this paper].

Several mechanisms were employed in the conduction of this research, including: surveys, interviews, design documentation, and various analytical methods.

3.2.1 PHASE 1: IDENTIFICATION

For the first phase, Figure 6.1, a paired inductive and deductive study was used. In the deductive analysis, indicators were proposed based on the experience of the authors and then tested via case studies, i.e. evaluating whether the indicators appeared in the design problems of previously completed projects which resulted in the corresponding archetype [26].

In the inductive study a broad database of products was gathered and analyzed using techniques such as the functional model, activity diagram and black box model. These are each methods for abstracting the characteristics of a design at various levels [6]. Then common attributes were identified. This approach was iterated until the results stabilized, i.e. no new indicators appeared after continued analysis. This method of search-until-exhaustion has been previously established for developing a classification system [1].

3.2.1 PHASE 2: ACCURACY

For the accuracy assessment phase, several studies were conducted with design teams at the United States Air Force Academy, in the engineering mechanics department.

In the first study of phase 2 (control group), final concept design results were collected from a previous year for which the indication had not been assessed, so that the students were not influenced by the indicators method. For the control study, the students simply completed their design problem using standard procedures[5]

For the second study of phase 2, Figure 6.2, capstone design teams compared their design problems to the indicators-looking for similarities. This process occurred during the first several weeks of the design process, before teams began ideation. The teams were not informed of the purpose of the method or given the formula for determining indication. The design decisions of the teams would be influenced by the knowledge of the indicators, as compared to control, but not by the indication itself. Accordingly, teams were introduced to the transformation brainstorming techniques; but, again, not to their individual team's archetype indication. All teams were encouraged, but not required, to use the transformers methods. In private, the researchers calculated the indication for each team. The

3.2.3 PHASE 3: ASSESSMENT

For the third phase, Figure 6.3, teams received exposure to the indicators and the corresponding archetype indication. Additional data was collected during this phase. A series of surveys was deployed to gain qualitative insight to several psychological influences of the method. Students self-reported the design requirements for their project, and their reaction (positive or negative) to the method. This additional survey was collected three times. Final design concepts and Pugh charts were collected and analyzed at the end of the design process. Note that this set of design problems was the same as in phases 1 and 2 i.e. the same problems were solved thrice.

3.2.4 SUPPLEMENTARY PROCEDURES

An auxiliary experiment was also conducted in which forty individuals independently applied the Indicators method to a common design problem. These responses contributed to analysis of the method's reliability.

4 DATA COLLECTION

Over several research years, one hundred and forty five senior engineering mechanics students have applied this method to their capstone design course project. This set included twenty-one unique teams (seven teams per year). The indication analysis was always performed independently by the individual; however in the phase 3, Figure 6.3, group discussion and consensus was encouraged after initial analysis. This approach allowed for cross-comparison of team and individual designers behavior.

The primary data for this study comes from several years of research. Detailed descriptions of the methods for determining the indicators and evaluating the relevance (accuracy) can be found in references [26, 27]; however the aggregative analysis has been explicitly described in this paper as well as the detailed procedure for data collection from phase 3.

4.1 CONTEXT AND SELECTION

As detailed in the experimental procedure, the second phase and third phases included permitting teams to read the indicators and determine how well they each matched their given design problem. Additionally, the final archetype selection at the end of the semester was also recorded (archetype was determined as described in 5.1).

4.2 VARIANCE OF INDICATION

A separate experiment was also run with independently operating designers to determine if they would produce the same archetype indication for a given example problem. A class of forty students and several faculty members was presented an

[5] Students *were* introduced to the transformational methods – this ensures that any increase in QNF is due to the Indicators method. It is necessary to isolate these influences as previous research has shown that the transformers methods *do* already enhance QNF [1, 6].

example design problem entitled, “develop a writing utensil for zero-gravity”, and the indicators. The designers walked through each of the indicators to determine the suggested archetype, given this problem.

4.3 ADDITIONAL DATA COLLECTION

Several additional variables were recorded during the experiments. During the third phase, in which the entire method was performed and each individual student received indication feedback, the students provided a list of the design requirements for their project. Each individual provided this list of design requirements several times. The survey was collected during the initial indication screening, midway through analytical modeling and during prototyping.

4.3.1 SELF-PERCEIVED INFLUENCE OF THE METHOD

The survey also included self-assessment questions. The students provided feedback regarding their opinion of the methodologies. An example from these questions is “Do you feel that the Indicators methodology had a significant impact on your design process?” This last survey was introduced to informally evaluate the psychological impact of the method. Responses were of the standard Likert scale used in this paper.

4.3.1 PARTICIPANT RUN OBSERVATION STUDY

Two under-graduate researchers at the Air Force Academy (Patel, A., and Robbens, J.) performed a series of qualitative analyses. They were participants in the design project and peers to the other designers. The ‘peer’ status between these researchers and the other designers provided an import terminal for information that students may have been reticent to reveal to researchers with graduates and professors.

Seven people were interviewed across four unique design teams (including projects on: micro-air vehicles, robotics, unmanned reconnaissance, and energy harvesting). The undergraduate researchers utilized voice recorded interviews, and surveys to collect quotes and opinion polls. They also sat in on brainstorming sessions for subjective observation.

5 ANALYSIS

Three independent team sets were analyzed for the primary data collection of this experiment. Each set consisted of seven teams and each team of five to seven designers. The several analytical methods used herein for determining the QNF influence of the Indicators method rely heavily on this well-controlled series of independent test trials, Table 2.

Table 2: Experimental Conditions Matrix

PHASE	**1**	**2**		**3**
(STUDY)		1	2	
INFORMATION GIVEN				
INDICATORS	*no*	*no*	*yes*	*yes*
FEEDBACK	*no*	*no*	*no*	*yes*
DATA COLLECTED				
FINAL CONCEPT	*yes*	*yes*	*yes*	*yes*
REACTION	*no*	*no*	*no*	*yes*

5.1 ARCHETYPE CATEGORIZATION

When the final design concepts were collected, they were classified as either transformer or monomorph. An experienced design research determined this based on the definitions of transformer and monomorph, i.e. if the device had multiple, and distinct functional states; and, there was a significant physical re-arrangement of the device between states (as achieved by one the the three principles in Table 1), it was classified ‘transformer’. Two independent researchers performed this classification. One was the primary author, a PhD researcher specializing in the area of design methods research, and the other an engineering mechanics design methodology professor (Jensen, D. PhD). There were no instances of disagreement regarding archetype classification.

5.2 DESIGN REQUIREMENT CHANGES

As a preliminary for further research into the relation between dynamic design- *design in which the customer needs change after the design process has begun*, the researchers also recorded the functional requirements (as self-reported by the students) at three points in the projects: early customer needs gathering, design specification, and prototyping. For each team, the alteration or addition of function was recorded. Students typically reported requirements as a sentence. These requirements were reduced to verb-noun pairs, by the author, to simplify comparison between the three survey iterations, i.e. this eliminates semantic noise. The goal of this analysis is to correlate team member’s awareness of the dynamic nature of design and other recorded variables

5.3 QUALITY NOVELTY AND FEASIBILITY

For this particular experiment the quality, novelty, and feasibility[6] of the final design concepts were determined using an established qualitative-to-quantitative method [34]. These attributes are broken into several subdimensions (metrics) and an experienced designer determines the design’s strength for that subdimension.

A Likert scale is used for evaluation of each subdimension value. The results were cognitively anchored by providing indicative responses for each subdimension (meaningful descriptions of each numerical response). For example, the “Efficiency of resource deployment” subdimension ‘0’ value is labeled with, “resource input completely dwarfs resource output”, and the ‘1’ value with “input is less than output”. Similar descriptions are linked to each Likert value on each subdimension. Table 3 provides a list of the topic headings under which the detailed questions were placed[7].

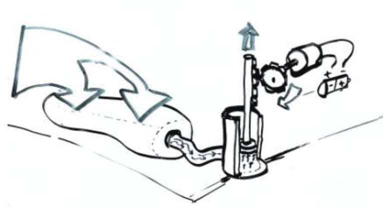
[6] Variety is a standard third metric to evaluate design concept ideation methodologies. However, feasibility is a more direct measure of final design value- the only design evaluated herein. The goal of a *selection* method, such as the Indicators method, is to enhance the final concept value by choosing selectively among many ideation methods; which, may each individually result in an equal variety of solutions, on average.

[7] The complete intake form is available by request, from the primary author.

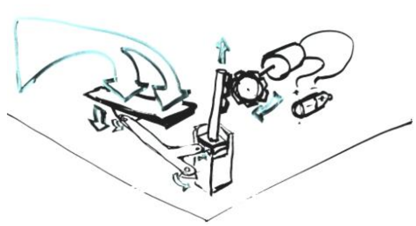
Table 3: Subdimension Metrics (categories) for QNF

QUALITY
Completion of design requirements
Efficiency of resource deployment
Portability
Initial difficulty to build/assemble
Standard difficulty to access function
FEASIBILITY
Number of operators required for use
Production cost
Manufacturability
Ease of use
Feasibility of principle
NOVELTY
S-curve location (commonness)
Conflict mitigation (cleverness)
User interest (like-ability)
Maturity of technology
Comparative capability (to previous)

The analysts determined the detailed QNF values for each subdimension of each final design concept from all of the experimental phases. Analysts were provided with final concept sketches, a description of the design problem, and details regarding the operating principle of each specific concept. Two example design concepts sketches, for passive energy harvesting on a bridge from motor vehicles, are depicted in Figure 7 (arrows indicate kinetic activity, +/- signs current).



Pneumatic Bladder – PE to linear ME, to rotational ME to EE



Pressure plate – linear ME to rotational ME to liner ME to rot ME to EE

Figure 7: Two energy harvesting solutions using various mechanical (ME), pneumatic (PE), and electrical (EE) energy conversions

5.4 INTER-RATER RELIABILITY OF QNF VALUES

To reduce noise in the QNF value determination, qualitative bias is reduced in several ways. Firstly, the analysts are experienced designers. Also, several experts independently perform the same analysis and the results are compared. This is achieved numerically by determining their inter-rater reliability coefficient. The inter-rater reliability coefficient is a metric of the agreement between responses from independent, qualitative, analysts for a given data set. A high inter-rater agreement implies high objectivity in the rating.

In this paper, Pearson's reliability rating is used [34]. The Pearson's coefficient is a measure of the fitness of a data set to one-to-one mapping between two variables (the Pearson's correlation for the function y=x would be 1, and for y=-x would be 0). Modifications are made to the Pearson's, Equation 3, method for rigor.

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i - \bar{X}}{s_X}\right)\left(\frac{Y_i - \bar{Y}}{s_Y}\right) \quad (3)$$

where r, is the inter-rater agreement, $\frac{X_i - \bar{X}}{s_X}$ *is the standard score and* s_X *is the sample standard deviation, X and Y correspond to each rater (variable set) and n is the number of rated elements (points- i.e. each subdimension)*

Firstly, a 'weighting by reliability', Equation 4, function is used on the quality, novelty, and feasibility values to reduce noise in the measurement. It has been previously shown that there is noise in such qualitative responses [34].

$$Q = \frac{\sum_{j=1}^{n} q_j \times r_j}{Q_{max}} \quad (4)$$

where q_j *is the quality score for quality subdimension j,* r_j *is the reliability of the coding*[8] *for that subdimension, and* Q_{max} *is the maximum possible overall quality score, which would be given by setting* q_j *to 4 for each subdimension. The contributions of subdimension scores to the overall quality score were weighted by reliability to minimize the influence of measurement error. Since the overall quality score was a proportion of the maximum possible quality score, the score ranged from 0 to 1 [34]. For feasibility and novelty, respectively replace quality with these in the above equation.*

The second modification was to include a third rater: two of the raters are PhD. candidates and one is an M.S.M.E. student in the mechanical engineering department. One of the raters is the primary author, the other two are design theory researchers who are independent from this project. Three inter-raters were used to increase accuracy of the analysis.

The Pearson's method was modified for three raters. The reliability between each combination of raters[9] was computed for each subdimension. Among all of these values (15 metrics, per each of 7 teams, per phase), the maximum inter-rater agreement (between any of the three combinations of raters) for

[8] The reliability coding is the inter-rater reliability rating for that subdimension (calculations for this are the same as in section 5.10). The coefficient was the agreement for that specific subdimension i.e. if the inter-rater agreement for a value was low, that aspect of the quality is proportionally suppressed to enhance accuracy [34]

[9] For raters 'A', 'B', 'C'- inter-rater coefficients A-B, A-C, B-C are each calculated.

any subdimension was .94 and the minimum was .47. The over-all between coders was strong (r = .83). Beyond this, the average standard deviation between the three sets of coders was also evaluated – a sort of meta-inter-rater coefficient. The standard deviation over-all was .1 on a scale of 0 to 1. This complex review of the ratings indicates that the QNF results in section 6 are highly accurate.

6 RESULTS

This section provides a summary of the various aggregated results from this series of experiments.

6.1 CORRELATIONS TO QNF

Throughout the experimental phases the same problem set has been solved by three teams (seven teams per year, three years). Each set of teams was exposed to a different level of the method: ideation with standard methods (control); ideation with exposure to indicators but not computed indication; ideation with exposure to both the indicators and the computed indication. The QNF values associated with the final design concepts from these three groups are presented in Figure 8. The y-axis value of each category: quality, novelty, or feasibility represents the average score from all teams in the associated experimental group (as indicated in the legend).

6.2 PERCEPTUAL IMPACT TO DESIGNERS

Eighty percent of teams which reported a positive reaction (on the survey described in 4.3) to the Indicators method, greater than 3[10], reported significant changes in design requirements throughout the three primary phases of the project. These teams reported an average influence value of 4.2- strong agreement that the method was influential. Teams that reported a negative reaction to the method, less than 3, did not report design requirement changes[11]. This correlation directly implies that the Indicators method encourages ongoing contextual re-evaluation of the design process. Additionally, as 80% of teams reported positive reaction and high method-influence, it can be inferred that this method is well accepted, and significantly influential to the design process. QNF analysis also supports that this psychological acceptance is important to design value. Teams who reported positive feedback developed concepts with an average .2 $QNF_{average}$ score increase over the average $QNF_{average}$ score of negatively responding teams.

6.2.1 INFORMAL OBSERVATIONS

The undergraduate researchers reported several interesting results from their intra-contextual qualitative analysis.

The Indicators Cards and the associated process received both positive (majority) and negative reviews. The indicators were accurate in predicting the design outcomes for each of these team's projects.

Students quoted this method as "supporting outside of the box thinking", "providing 'real world' examples", and permitting applied synthesis of concept ideation methods and design context. Additionally, the method encourages the designer to contemplate the requirements in other reference frames, "Illuminating the possibility for concepts that may have been looked over." The indicators provided specific guidelines that "accelerated the brainstorming process" and provided a broader range of solutions that were directly applicable to the problem at hand.

Suggestions for improvement often included possibilities to "integrate the method recurrently throughout the design process.

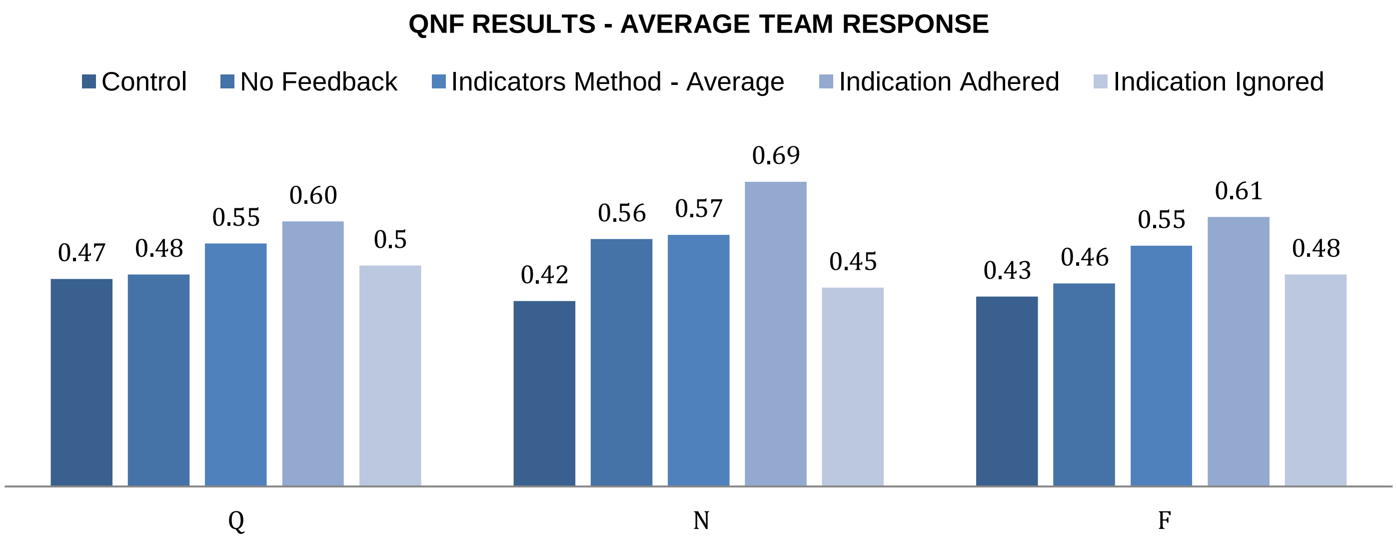


Figure 8: Quality, novelty and feasibility ratings on a normalized scale for the method and control groups. From left to right the groups are: control, indicators introduced without feedback, average for complete Indicators method, teams that adhered to indication and teams that ignored indication

[10] Notably, in each case of positive reaction the team adhered to the Indicators method suggested archetype.

[11] Correspondingly, each of these teams ignored the archetype indication.

6.3 ACCURACY

In the second phase experiment, described in Section 4.1, teams were not provided with the indication archetype. The archetype prediction was accurate for 86% of teams and for 84% of individuals. That is, the majority of designers inevitably pursue the contextually indicated archetype.

6.4 PRECISION

When individuals assess indication values for a common problem, responses are very similar. For 85% of teams, the standard deviation of Likert response value between team members is only .08 (average for the method). The sensitivity of the indicators method is .1 and each team in this majority group had indication differentials greater than .2. The method has resulted in precise indications for the design team case studies. As sections 6.3.1 and 6.3.2 detail, the method is accurate and repeatable (objective).

The 15% minority of teams, i.e. those with high variance, were all teams for which the indication differential was less than .1 (that is it the Indicators method provided an ambivalent guidance). The protocol for such circumstances is to iteratively apply the method to subproblems. Unfortunately there was not time to apply this protocol given the limitations of a one-year design process and the academic commitments of the designers. However, this iterative method was effective in two micro-experiments outside of this study.

Another measure of precision was the common-design-problem (zero-gravity writing utensil) experiment, described in 4.2. This study produced similar results. Statistical analysis of group responses results from the common-design-problem experiment can be found in Table 4.

Table 4: Variance for common design problem – TI and MI are calculated from equations 1 and 2

METRIC	VALUE
Mean (expected) indication	TI - .25, MI - .6 TI-MI = .35 Monomorph indicated
Mean standard deviation	.07
Maximum standard deviation	.09
Minimum standard deviation	.05

6.5 GLOBAL ARCHETYPE QNF

Given the large database of transformable and monomorphic devices for which QNF values were determined-it was possible to determine and compare the average values for each. In Figure 9, it can be seen that the $QNF_{global\_average}$ for transformable designs is somewhat higher than that for monomorphic designs (especially quality and novelty). The two archetypes score nearly equally for feasibility. The source of this difference remains an open question; although, intuition suggests it may be the inherent multifunctionality of transformable solutions.

On average, transformable designs had a relatively high QNF value. However, adherence to the Indicators method was correlated to an even greater relative QNF increase. As a consequence, it is advisable to explore transformable solutions if there is a very close indication for both archetypes, or if for some reason the Indicators method cannot be applied; and to explore the archetype indicated by the method in clear cases.

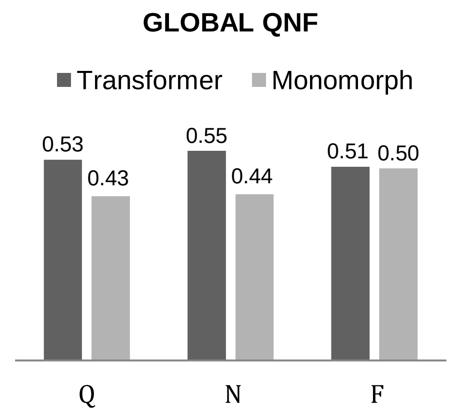


Figure 9: $QNF_{global\_average}$ for all Transformers (dark gray), and all Monomorphs (light gray)

7 CONCLUSIONS/CONTRIBUTIONS

Transformers ideation methods have a quantitatively established positive effect on creative ideation [1-3, 5-7, 9]. This paper presents the culmination of a several-year long study to develop and evaluate a set of highly accurate context indicators that will guide the use of transformation ideation methods and greatly enhance design solution QNF. These indicators are used to characterize the archetype of a design problem. The experiments under-gone in this study have explored the influence of employing this Indication method on the design process.

Utilization of the Indicators method is correlated to solutions with higher quality, novelty and feasibility than solutions developed for the same problems when the designer did not use the Indicators method, especially when the archetype indication is adhered to. Evaluation shows that the results are repeatable accurate and precise. The Indicators assessment can provide the designer with a new kind of information during early design phases. Additionally, adherence to the method is correlated with dynamic awareness of design requirement changes. Responses indicate that the method provides a strong, encouraging influence to designers. Some of these key results are summarized in Table 5.

Although the data set, detailed in section 4, is significant to provide a firm implication of results, further study could be employed to eliminate noise and other confounding factors

The most recent iteration of the context indicators on graphic cards has been presented for distribution to the academic community (APPENDIX). This ensures that this publication is a complete reference guide for designers to deploy the Indicators method

Table 5: Summary of results/correlations (average values)

The Indicators method provides useful information from context analysis during early design phases.
Introduction to the context indicators without instruction results in a $QNF_{average}$ increase of 14% from control
Employment of the Indication method results in a $QNF_{average}$ increase of 26% from control
Adherence to method results in a $QNF_{average}$ increase of 44% from control, and 80% of such teams track design requirement changes
Employment of the method while ignoring the indication results in a $QNF_{average}$ increase of 8% from control, and only 10% of such teams track design requirement changes
All teams which adhered to the indication reported a positive view of the method – 4.2 average on the 5 point Likert scale

8 FUTURE WORK

Ultimately this project will stand to benefit from examining other implementations of the context indicators. More integrated methods for deploying the Indicators method throughout the design process are in need. It has been shown that the indicators relate to 'real-world' design scenarios in a repeatable way. This relationship may be leveraged to create additional (other than 'selective') design methodologies. Ongoing preliminary research is exploring use of the indicators for concept generation enhancement.

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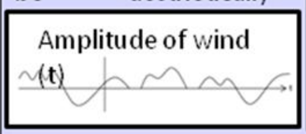
APPENDIX A

CONTEXT INDICATION CARDS

A-PERIODIC USE

When the frequency of demand for a products function is a-periodic, the device must be monomorphic so that it is ready to perform at any given time.

i.e. a windmill must retain its primary form because wind patterns are a-periodic, even though transformation would be aesthetically



Monomorph Indicator

INDICATOR CARDS

The indicator cards provide descriptions of general scenarios. The scenarios describe either:

Contexts ideal for designing monomorphs

Contexts ideal for designing transformers

If more transformation indicators match your problem, design a transformer and vice versa.

PARALLEL MULTIFUNCTION

When multiple functions are performed in parallel, consider a monomorphic design for high performance.

i.e. the dashboard of a vehicle is monomorphic and multifunctional

Monomorph Indicator

EASE OF USE

When the user has a limited opportunity to learn how to use the device, consider a monomorphic device for safety or convenience.

i.e. a defibrillator must be monomorphic so that its function is obvious

Monomorph Indicator

VITAL FUNCTION

When consideration of a single function dominates all others, tend towards a monomorphic design.

i.e. memory storage systems have tended towards a monomorphic architecture

Monomorph Indicator

LOW COST

When cost savings is a primary driver, consider a monomorphic design; reducing the number of manufacturing features will lower cost.

i.e. disposable cups must be low cost

Monomorph:
Few features
and low cost

Transformer:
Many features
and high cost

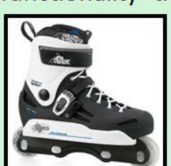
Monomorph Indicator

SHARED FUNCTION

Transformation Indicator

When two devices in a usage area share similar function, combine them into a single transformable device.

i.e. shoes and rollerblades are stored co-locally and share similar functionality- thus they can be merged.

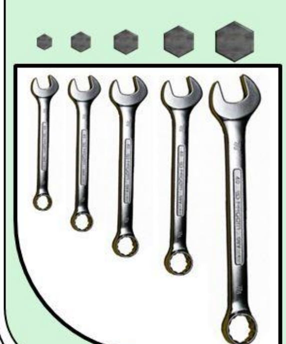


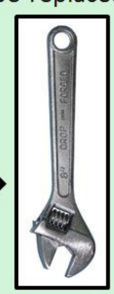
ADHERE to VARIABLE

Transformation Indicator

When the there is a change or variance of input/output to a device, consider using a transformation to adhere to the variable.

i.e. a set of wrenches can be replaced by an adjustable wrench.





STORAGE

Transformation Indicator

When a device can be stored while not in use, and space is at a premium, consider designing in a collapsed state.

i.e. space is at a premium when camping and a chair is not always needed

ADHERE to SEQUENCE

Transformation Indicator

When a device addresses one step in a process, utilize transformation to address other steps in the process with the same device.

i.e. compare the use of monomorphic or transformable devices for leaf removal