ENGINEERING DESIGN: A PRAGMATIC APPROACH

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Preface

This handbook will serve as a concise personal reference tool that can be used to develop an engineering design idea, concept, or project. Using the detailed design process outlined in this handbook, I will be able to more effectively tackle engineering design problems and provide a tool that can be utilized by other engineers to develop their own works of engineering design. I will also provide real-world examples at different stages in my handbook to illustrate where the principles of my handbook can be applied.

Reflecting on my experience in Praxis I, I feel that the ESC101 course provided me with a fundamental understanding of how to construct a design process from a theoretical standpoint. Upon the completion of the Praxis II Showcase, I believe that I developed a more comprehensive understanding of the design process and I am now able to bridge the gap between design theory and application. Praxis II provided me with the opportunity to see the entire design process from the “recognition of an identified need” to “prototyping the final solution”.

This handbook will serve to explain my own personal design process and conclude by demonstrating how my experiences in Praxis I & II have shaped my understanding of engineering design. I hope to finally address the fundamental question “what is engineering design?” upon the completion of this handbook.

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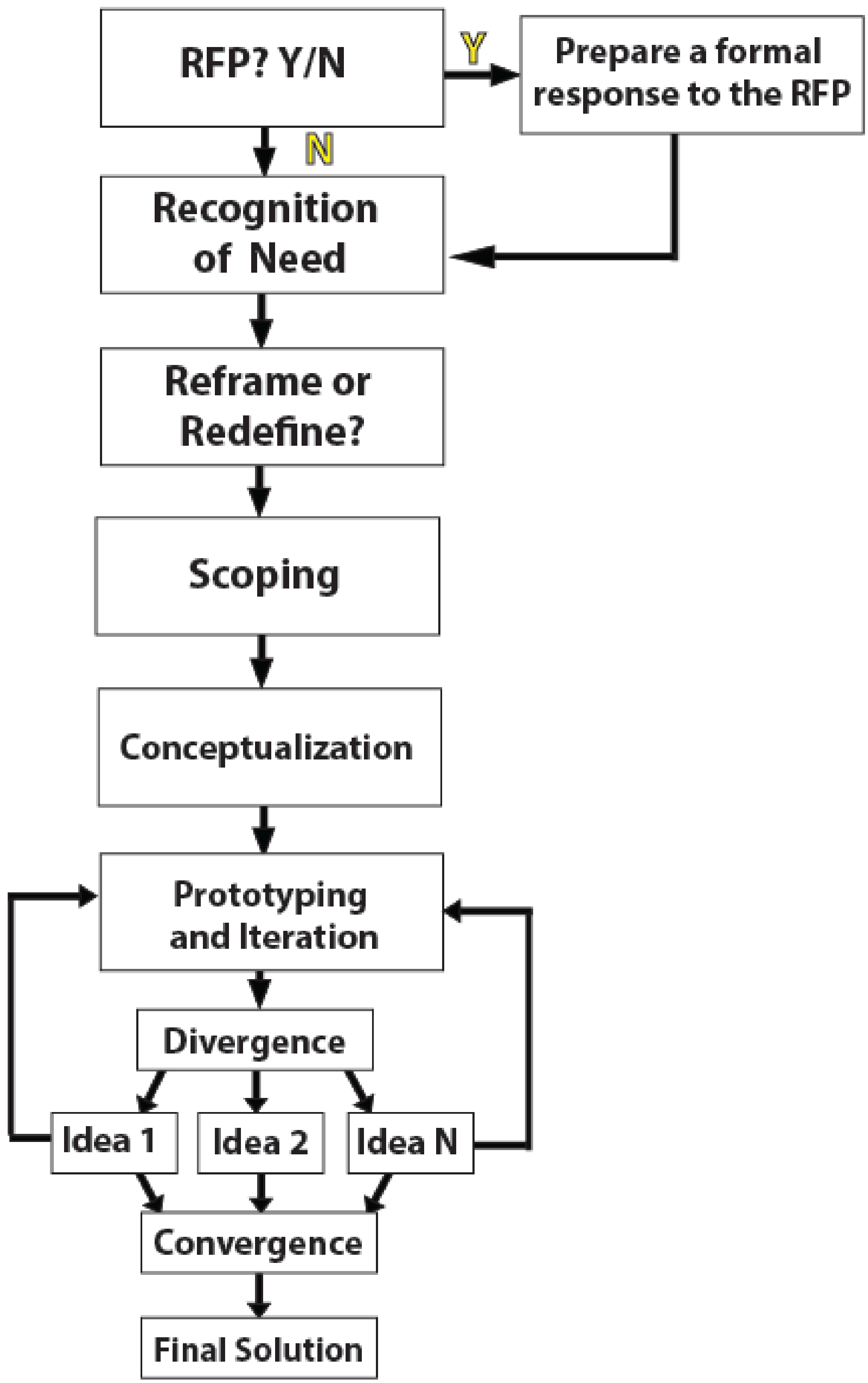
1. Schematic Representation of the Design Process



2. Responding to a Request for Proposal

A request for proposal is a formal document that outlines key aspects of a proposed work of engineering design. Often in industry, multiple engineering firms will bid on a particular engineering project after their potential client has presented them with an RFP. To demonstrate their interest in the project, the engineering firm must respond to the request for proposal with a detailed report that explains how their team is best suited to solve the problem. A detailed RFP will outline budgeting, potential design solutions, the expected duration to complete the project and various other key elements.

Although this type of formal documentation process is not necessary when dealing with smaller scale engineering design projects, I believe that having a firm grasp of how to address an RFP is crucial for any engineer. As such I have outlined the key elements that are usually present in an RFP and how to address each component individually.

A significant amount of work goes into addressing an RFP and as such it is necessary to read and reread the document multiple times. This may seem obvious, however it is necessary that each member of the engineering team become familiar with the RFP and give their opinion on each section. If the team ultimately decides to bid on the RFP, they must be vested in the project and be prepared to put a significant amount of effort into developing a well-structured response to the RFP since there is also the potential to lose the bid if multiple teams are bidding for the same project.

Some of the key aspects of any request for proposal include[1]:

1) Overview of business issue

Includes a description of the problem.

2) Description of products or services

Provides a detailed description of the services that are required to solve the proposed problem.

After reading 1) and 2) the engineering team will have established a general understanding of the problem. Immediately, the team should be able to determine if the project relates to their field of expertise.

[1] Please note that the aforementioned "key aspects" for developing a- request for proposal are not my own and have been adapted from [1].

3) Detailed business requirements

Includes "…support requirements, delivery guidelines, design specifications, [and] quality metrics…" that will be used to assess the quality of the proposed designs [1].

4) Performance metrics

Includes a detailed description of how the client will assess the performance of the engineering team that wins the bid. Therefore, certain expectations are put on the contracted team to meet the business requirements and criteria measured using the performance metrics.

5) Descriptions of Products or Services

Includes a brief but comprehensive description of the services that the engineering team is required to provide.

Any engineering team that hopes to win the bid, must ensure that their design complies with the requirements and metrics in 3) and 4). If the engineering team feels that they can develop a design that meets all or almost all of the requirements it is considered a "high probability bid" and worth pursuing.

6) Approach suggestions

Provides the design team with possible ways of approaching or solving the problem. Often this portion of the RFP is not included to encourage teams to develop varied and unique solutions to the problem.

Section 6) of the RFP effectively provides the team with potential paths for addressing the problem and welcomes potential "reframings" of the problem. This is where the engineering team can demonstrate their creativity and possibly win over the approval of the stakeholder if their reframed solutions meet the requirements outlined in an innovative way.

7) Due date

Specifies the date when the proposal is due.

8) Selection criteria

Describes how the engineering teams will be evaluated and how each component of the RFP will be weighted.

Ensure that your team has addressed the requirements in such a way that coincides with the selection criteria. Pay special attention to fully developing the parts of the RFP that have been given the highest priority first, before addressing secondary requirements that have not been assigned as high a value.

9) Questions

This outlines the means by which the engineering team can contact the client if they have any questions about the proposal.

10) Timeline

Lists the "RFP creation date, the RFP send date, the time period for questions, the due date for the selection period, and the projected award date [1]."

11) How to respond

Often a section will be included at the end of the proposal that describes the process and means for submitting a response.

It is critical that the team respond to the RFP in a sequential way so that it is clear to the client that each component of the RFP has been addressed. Meeting the specifications of the response format should not be overlooked. When multiple teams are bidding on a project, not meeting the format requirements or having a document that is difficult to follow is a poor first impression on the client and may result in their decision to discard the proposal outright.

3. Recognition of Need

Any work of engineering design must aim to address "an identified need. [2]" Identifying this need justifies the necessity for developing a framework to solve the candidate problem. However, it is clear that if no problem is identified there is no need to apply an engineering design process as there is no problem to solve. This may seem trivial, however I believe that this must be made explicitly clear. It is not just the duty of the engineer to identify elegant solutions to problems but also to be able to recognize when a problem does not actually exist. There may be a perception that a problem exists (as perhaps suggested by a request for proposal), however it is the responsibility of the engineer to use their judgement and scientific methods to fully comprehend the context of the candidate "problem" and then apply an engineering design process to solve the problem when required.

3.1. Satisfying the Requirements for an Engineering Problem

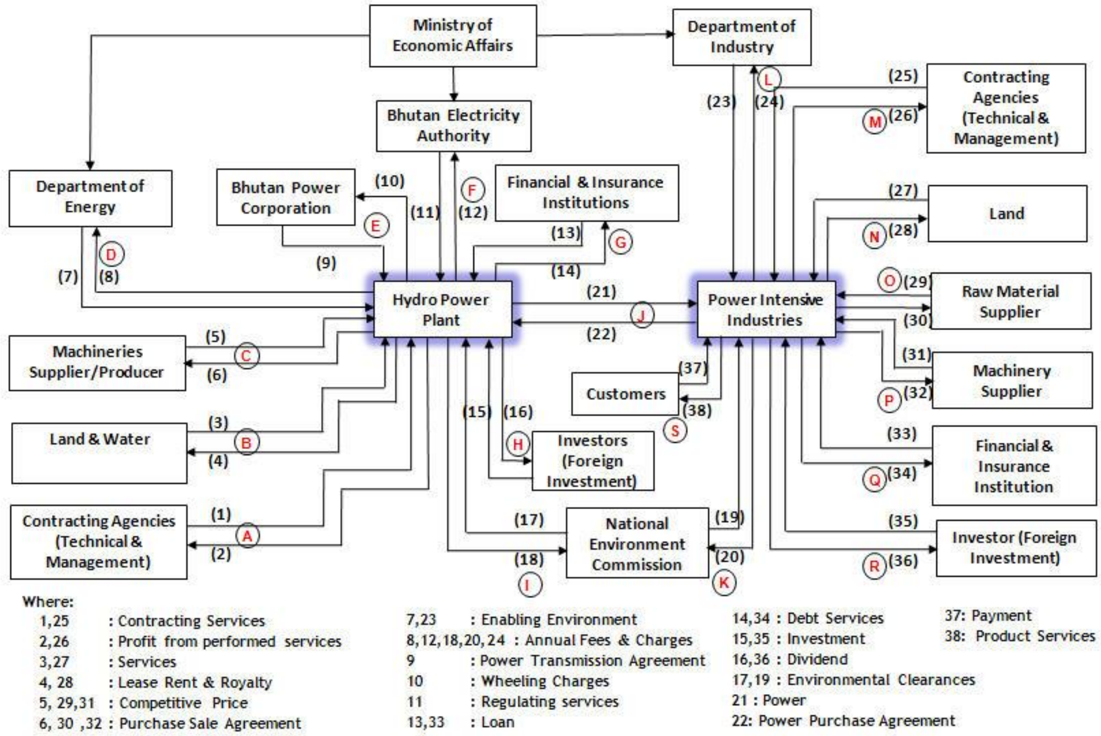
Beitz and Pahl state that an engineering problem must address the following fundamental precepts [3]:

1. Affect almost all areas of human life

Developing a solution to a candidate problem using engineering design principles is a process that requires the integration of individuals with different skill sets and ideas. For instance, consider the effort that goes into building a new hydro plant. There are many stakeholders involved in this type of a project with different opinions and expertise that must be considered. There are civil engineers who are responsible for determining the structural integrity of the design, chemical engineers who will perform environmental checks to ensure that the development of the hydro plant will not have any adverse effects on the environment, residents in the surrounding area where the plant will be built and countless other secondary and tertiary stakeholders. As a project increases in magnitude, the intricacy of addressing different stakeholder concerns and opinions becomes exponentially more difficult.

Consider the following ...

In 2007, the Tala Hydroelectric Dam in the Chukha district of Bhutan was completed. This dramatically increased Bhutan's production of hydroelectricity and resulted in one of the world's least developed countries, to become the fourth-fastest growing economy in the world [4]." However, many environmental concerns have been raised surrounding the project as there is a concern that the country's rich biodiversity will be compromised. Yet, these conflicting viewpoints only scratch the surface in a design project of this magnitude. The following schematic illustrates the stakeholders involved in the construction and operation of the Tala Hydroelectric Dam and the intricacy of the project.



[5]

2. Use the laws and insights of science

Hubka argues that "with the help of existing knowledge of observed physical, chemical and biological phenomena (effects) and the rationalised, and codified experiences (laws) abstracted from those observations [man is] able to realise certain changes [6]." Essentially, Hubka elucidates the scientific method and how it can be used to bring about change. This is the essence of applied science and engineering and has given rise to a variety of engineering disciplines where specific skills are required to solve problems in construction, mechatronics, aeronautics, finance, and a variety of other fields. Science is an integral part of engineering design and is critical if the problem presented is to be categorized as an engineering problem.

3. Requires professional integrity and responsibility

Although this qualifier may not be inherently obvious when analyzing a supposed work of engineering design it is perhaps one of the most important elements of the entire design process. A practiced engineer must continually reflect on their work and the implications of what they are creating. They must ask themselves "Have I demonstrated throughout my design process that my solution is reflective of what the stakeholders want? Have I considered the environmental, social and cultural implications that will follow as a result of my design?" Schaub states that the "…individual engineer is caught between potentially conflicting sets of obligations and responsibilities: (1) to the public, (2) to the client or employer, and (3) to other engineers…" as part of the self-regulatory nature of the engineering profession [7], [8]. The final product which they have created is the culmination of their efforts and communicates most effectively what factors they felt were most important.

4. Reframe or Redefine

Once an engineering problem has been identified, it is necessary to decide how the problem will be framed. Framing aims to identify what aspects of the problem are relevant so that the designer can focus on developing a solution that addresses these areas in particular. If a valid need has been identified but the designer feels that the stakeholder has presented a problem that does not capture the essence of the "true problem," the engineer may choose to reframe.

It is the responsibility of the engineering designer who is working for a client or stakeholder to communicate his or her findings and demonstrate that in fact the problem statement can be articulated in a more defined way.

It is also possible that the designer may discover that the factor that is directly influencing the problem may be different than how the problem is originally framed. This factor is known as the causal or causation factor [9]. When responding to an RFP, this may be where the engineering team addresses the **approach suggestions** and explain their rationale for reframing the problem.

For instance, there may be a need on a commercial airliner to make seats more comfortable. The airliner has commissioned a team of engineers to redesign the chairs on their planes so that their customers will have a more pleasant flight. However, the team of engineers may discover that it is not that the chairs are uncomfortable but in fact that there is not enough leg room on the plane for the passengers. As such the engineer may decide instead to redesign the seating orientation in the fuselage instead of redesigning the chairs specifically.

5. Scoping

Once the problem is clearly defined it is necessary that the designer determine the following:

1. High level objectives
2. Requirements

The scoping stage in the design process involves determining what requirements and high level objectives are central to solving the problem. The stakeholder identifies what the designer must address in his or her solution to the problem. With this information the designer can abstract the higher level objectives which he or she will use to gauge the effectiveness of the design solution. If the design solution meets these high level objectives to a certain degree, it can be said that the solution was successful.

Returning to the example of the commercial airliner, the engineering team must identify what aspects of the problem are relevant. This is determined by comparing the inputs of the different potential stakeholders that influence how the design will take form. For instance, if the stakeholders have outlined a budget of x dollars, this is a pricing constraint that the engineer must not exceed. Similarly, if there is law that that mandates that Boeing 747 fuselages must have seats that are oriented in compliance with a certain standard, the engineer must develop a solution that meets these requirements otherwise the solution will be deemed invalid. As such it is not uncommon to see engineers from multiple disciplines working together on a common project. Each engineer will be able to contribute different types of expertise depending on their area of specialization.

6. Conceptualization

The conceptualization phase is used to develop an array of possible design solutions that address the problem. To achieve this, the designer must iteratively apply divergent and convergent design tools to refine the design. Divergent design tools provide multiple possible solutions to the problem while convergent tools filter out potential solutions that fail certain specified criteria as outlined in the request for proposal. For instance, the proposed solution may fail to meet a constraint outlined by one of the stakeholders and thus is no longer viable. However, the advantage of this iterative process is that it allows the designer to draw upon successful elements of a potential solution even if the design was not entirely successful. This makes the final solution even more effective as it will incorporate different successful aspects of the all of the candidate solutions.

6.1 Divergent and Convergent Design Tools

To categorize divergent and convergent design methods, I have used Shah's *Classification of Idea Generation Methods*

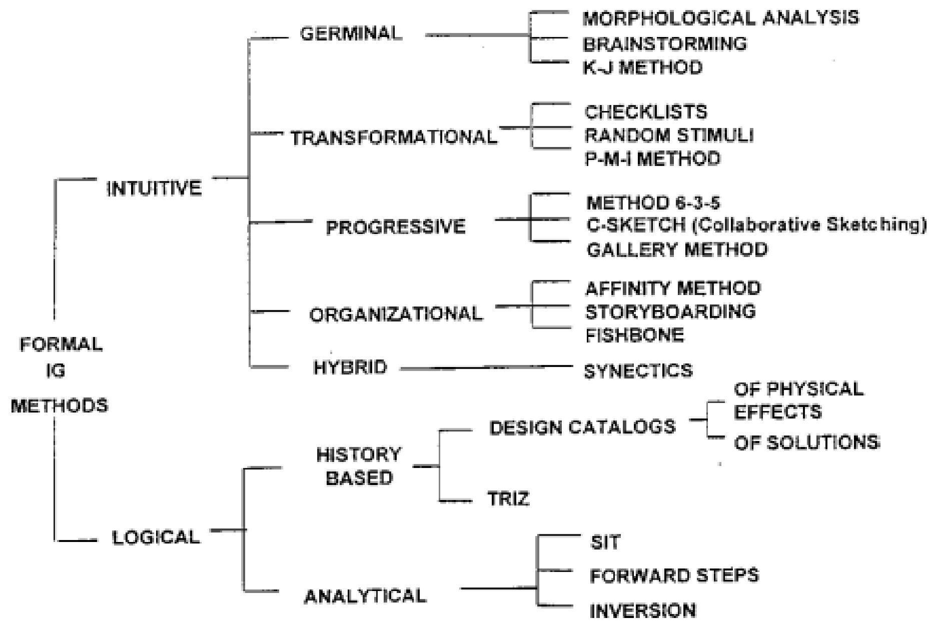


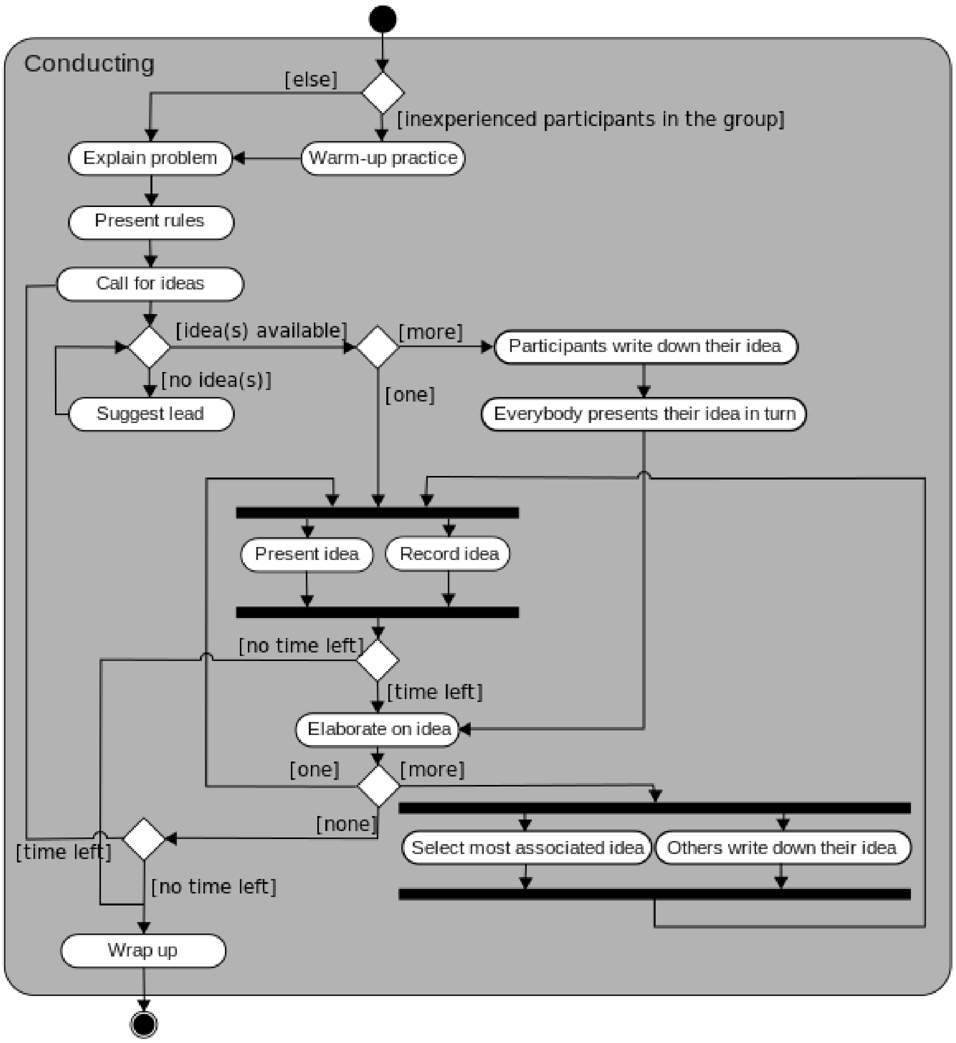
Fig. 1 Classification of idea generation methods

[10]

Intuitive design techniques act to "stimulate the unconscious thought processes of the human mind" while logical idea generation is meant to promote the "systematic decomposition and analysis of the problem. [10]"

Some of the key design methods are explained below:

- **Germinal:** idea generation in the early or developmental stages
    - Morphological Analysis: described as a method for developing a set of all the possible "relationships or 'configurations' contained in a given problem complex. [11]" This type of method is often used when there are many potential stakeholders and conflicting factors. It is both a divergent and convergent method as all involved parties try to develop ideas (divergence) and then the most "associated idea" (see diagram) is selected (convergence).



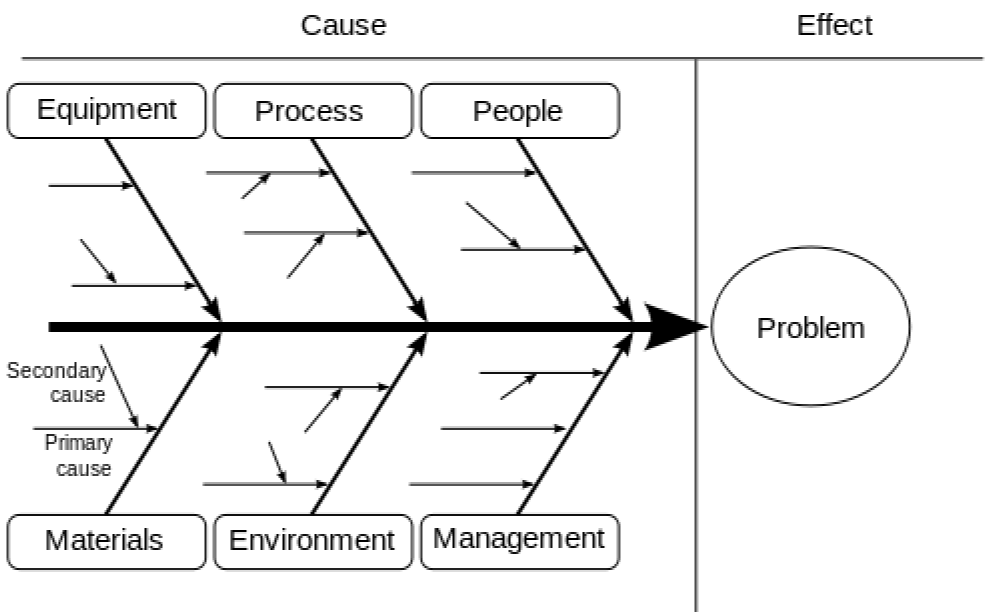
[12]

- Brainstorming: This divergent method is used to generate as many ideas as possible to address a problem. Varied ideas are encouraged.
- K-J Method (similar to the affinity method below): Effective in large groups and commonly used in project management. All of the involved parties brainstorm and try to develop solutions to the presented problem (divergence). The solutions are then sorted into clusters based on their similarity to each other (convergence).

- **Transformational:** steers ideas in a new direction
  - Random Stimuli: using random heuristics, images, and concepts, the goal of this idea generation method is to initiate unique associations between the problem and seemingly unrelated media. This aims to create ideas that originally would have been unlikely as the types of associations made are spontaneous and do not follow a “logical” or systematic thought process (divergence).

- PMI Method: Used to synthesize ideas after having generated them (i.e. during the germinal stage). Ideas that are well-received are given a "**p**lus," a "**m**inus" if the idea is not used and an "**i**nteresting" if the idea is plausible but perhaps not enough idea generation has been accomplished to make the idea easy to integrate into the current working solution at this stage in the design process. This is considered a convergent method as it narrows the solution space.

- **Progressive:** meant to produce multiple ideas in a short period of time
  - Method "6-3-5": This is a team idea generation method in which **6** members write down **3** ideas each for a set time limit of **5** minutes (the quantities are variable but the concept remains the same). This method is meant to generate as many ideas as possible in a short period of time (divergence).
  - C Sketch (Collaborative sketching): This team collaboration process requires each designer to draw a sketch of their proposed solution for a predetermined amount of time. Once the time has elapsed the sketch is passed to the next designer. At this point, the timer is restarted and the designer must "add on" to the original sketch. This process continues until all of the members of the group receive their original sketch. The final products are then presented and each group member explains what they contributed to the design and their own personal comments regarding how they felt that the design progressed (divergence).
  - Gallery Method (see the C Sketch)
- **Organizational:** breaking down ideas into their components
  - Affinity Method (see the K-J method)
  - Ishakawa (fishbone) diagrams: An organizational method used to identify the potential factors in the design. Often fishbone diagrams will be employed before any preliminary design begins so as to keep future designs focused on the core elements. This is considered both a divergent and convergent method as it encourages the development of multiple solutions (divergence) however it focuses the possible solutions around central themes (convergence).



[13]

Example of a fishbone diagram.

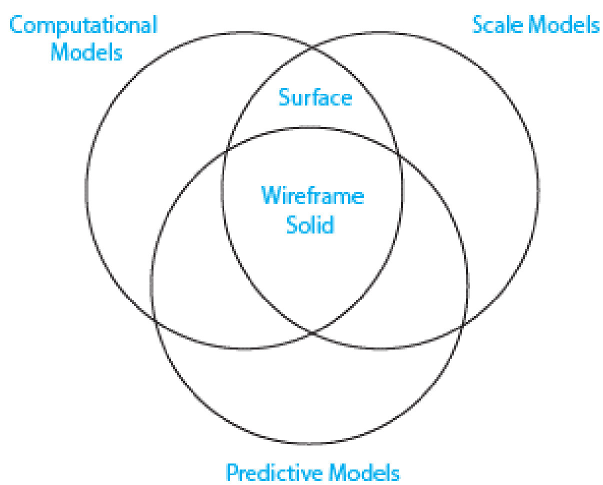
- **Hybrid:** combining multiple idea generation methods
  - Synetics: refers to the combination of any of the aforementioned or following methods (divergent, convergent, or both).
- **History based:** "involve[s] the use of past solutions that have been catalogued or archived in some form of database [10]"
  - TRIZ: a "problem-solving analysis and forecasting tool derived from the study patterns of invention in the global patent literature [14]." The underlying design theory behind TRIZ is that typically inventive solutions to problems will involve the need to mediate between contradictory factors. This process challenges designers to minimize the negative effects of trade-offs while coming as close to the idealized solution as possible by developing a matrix that considers all the contradictory factors. These candidate solutions are then compared against existing ideas that are part of the TRIZ patent database.
- **Analytical**
  - SIT (Systematic Inventive Thinking): is a modification of the TRIZ method whose fundamental precept is the closed world assumption [15]." This type of methodology suggests that designers must restrain themselves to use only the information and resources that are provided in the context of the outlined problem and not to draw upon

extraneous ideas or resources. This may seem counterintuitive as idea generation is normally thought of as a free-flowing process where innovation is welcomed, however this type of idea generation instead challenges the designer to work within the confines of the context of the problem and pay closer attention to the information presented. This method hopes to promote the development of new connections between resources that may not have been made otherwise.

7. Prototyping and Iteration

When prototyping, the goal of the designer is to communicate one or more aspects of the final solution to a certain degree of detail. If the aspect (or aspects) of the prototype can be made more akin to how the final solution is expected to function it is said that this prototype is of a "high-fidelity." The goal of the designer is to develop as many "high-fidelity" prototypes as possible to refine the final design solution. It is likely that through this prototyping process that certain functional requirements of the final design solution will change. Often functional prototyping reveals that a specific design aspect may have seemed feasible from a theoretical standpoint but is in fact difficult to implement or does not achieve the desired effect. As such the designer may have to reapply the divergent and convergent tools outlined in **4.1** and **4.2** to find a way to fix these newly-discovered design flaws.

To actually develop the prototype there are a variety of different methods that can help to demonstrate different high-fidelity aspects of the design. Some of these prototyping methods[2] include:



[2] Dominick, Peter G. *Tools and Tactics of Design*. (John Wiley & Sons, Inc., 2001)

Descriptive Models provide the engineer with a better means of depicting "ideas, products, and processes in a way that is recognizable [16]." This group of potential prototyping options aims to "show what a design would look like if it were created [16]." Descriptive models are especially important for communicating with stakeholders that do not have a scientific or engineering background. Often providing a means of visualizing the problem may be the only way to communicate a specific aspect of the design to the stakeholder.

Predictive modelling provides an insight into how "design ideas, products and processes will perform. [16]." This type of prototyping is often mathematical and theoretical. It uses scientific principles to develop a justification for the physical design of the product; i.e. the dimensions of a beam in a bridge due to predicted loading and shear conditions that the beam may be subjected to. Referencing Professor Collins iconic mantra; "you must know the answer to find the answer." It is important to have the scientific tools and knowledge to determine the answer before being able to develop a solution.

Wireframe models provide the "input geometry for simple analysis such as kinematic analysis and finite element analysis" and **solid models** are "mathematically accurate descriptions that can be assigned different proportions and properties [16]." These types of models can be viewed as a cross between a descriptive and a predictive model. They provide a low to medium fidelity visual prototype of the final solution and a high-fidelity prototype for the physical characteristics of the model; i.e. determining the boundary conditions in a bridge design. **Surface models** allow you to "visualize [the] design by allowing you to add things like color and shading. [16]" These types of models are more geared toward developing a high fidelity model of the visual characteristics of the final solution.

The actual prototyping refinement comes into play by applying the divergent and convergent methods described in **7)** and the analysis methods that will be described in section **9).** As the design becomes more well-defined the prototype will come closer to the final solution described in **10).**

8. Quantitative and Qualitative Analysis Methods

The following analysis methods described below are meant to be used in conjunction with the descriptive and predictive models described in section **8)**. The following are different methods that can be used to assess the success of a design:

- **Pugh Chart**: A quantitative method that is used to compare and contrast different potential candidate designs relative to a reference design. Each design will be assessed based on a list of criteria; i.e safety, maintainability, cost, etc. If the design in question fares better than the reference design it receives a +1 score. If the candidate design does not score well against the reference design it is given a -1. The values are then summed algebraically. The design that has the highest algebraic sum at the end of the comparison process is determined to be the "ideal solution."

	Prevent Contamination: Concepts					
Selection Criteria	**Release Cleansing Agent**	**Butterfly Valve**	**Solenoid Valve (Reference)**	**Mechanical Plug**	**Servo Valve**	**Guillotine Valve**
Seal Quality	-	0		+	0	-
Seal Ease	-	0		-	0	+
Complexity	+	+		+	-	+
Cost	+	+		+	0	+
Durability	+	0		+	0	-
Availability	-	+		+	0	-
Integration ease with piping	-	0		-	0	-
Integration ease with sensing unit	-	-		-	0	-
Consumable parts	-	0		0	0	+
Ease of reset	0	-		-	0	-
Speed of actuation	0	0		-	-	+
Sum + 's	3	3		5	0	5
Sum 0's	2	6		1	9	0
Sum -'s	6	2		5	2	6
Net Score	-3	1		0	-2	-1
Rank	6	1	T2	T2	5	4
Continue?	NO	YES	Maybe?	NO	NO	NO

The example diagram above compares the contamination prevention of different candidate designs. [17]

- Pairwise Comparison Matrix

  A pairwise comparison matrix is similar to a Pugh Chart, however the different criteria that the designs are being scored on are given a specific weight. This means that if a certain design succeeds in a section that is considered to be "more important" to the design problem, it has the potential to outscore other designs that may succeed in more categories that are not as highly weighted. (Figure to the right: [18])

$$V_i = \sum_j w_j x_{ij}$$

where

V_i is the overall value of alternative i;
w_j is the weight assigned to criterion j to reflect its importance relative to the other criteria;
x_{ij} is the score of alternative i on criterion j.

Table III — A pair-wise comparison matrix					
Level (1)	A (2)	B (3)	C (4)	D (5)	Relative weight (6)
A	1	3	1	9	0.410
B	1/3	1	1/3	4	0.148
C	1	3	1	8	0.398
D	1/9	1/4	1/8	1	0.044
CR value =					0.006

Note that each criteria is given a ranking relative to the other criteria. For example criterion D is ranked to be weighted 1/9th the importance of criterion A [19].

It is important to note, that while these qualitative and quantitative analysis methods may help to provide insight into a design decision, they are not meant to dictate the entire design process but instead supplement the rationalization process of the engineer. These methods will be used in conjunction with the models described in **8)** that provide a scientific justification for choosing a certain design.

9. The Final Solution

Once the designer has exhausted all means of iteration and analysis and is satisfied with his or her solution the design can be presented to the stakeholder in a formal response to the RFP. Although no design is ever truly "perfect" and can always be refined, the final solution usually comes as the result of a culmination of factors that include deadlines, exhaustion of resources, and financial considerations.

The final solution is the culmination of the engineering team's efforts and should meet all the requirements and specifications.

10. My Definition of Engineering Design

"Change that is the product of combining theoretical and practical scientific methods with a creative sensibility and a moral conscience."

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