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Establishing Criteria and Evaluating Alternatives

Defining criteria and evaluating alternatives are aspects of design that students have had little experience with. The purpose of this document is to help students understand the process of defining a problem (creating and defining criteria) and evaluating solutions based on the criteria.

1.0 Understand the Problem or Need

It is essential to understand the problem before developing solutions! This seems obvious, but it is often neglected. The following may define the problem or need:

- “customers”
- management
- personal observation or experience
- marketing

1.1 Ask questions

- What really is the problem? Why is this a problem?
- What do you really need? Why do you need it?

1.2 Write a need-statement or problem-statement

Do not solve the problem before defining it!!! A narrowly stated problem may limit alternative solutions; a vague statement does not provide sufficient guidance. So put thought into the statement.

Examples:

No - I need a new car (*limiting definition*).

Yes - I need a reliable, safe, and comfortable way to get to work.

No – Develop a new airplane (*vague*).

Yes – Develop a commercial airplane to transport 250-310 people 3500 miles.

Hard work is valued in our society. We are brought up with the idea that we can accomplish great things by working hard. But hard work is not sufficient! Not only must you work hard, you must work on the right problem. There is a saying in business: “work smarter, not harder.” The following examples illustrate the critical importance of having an appropriate and clearly defined problem statement.

There is a story regarding the design of a solar panel dampening system for the Mariner VI space probe (Ullman, *The Mechanical Design Process*, McGraw-Hill). Engineers were concerned that the panels would be damaged when they were opened in space.

The problem statement that was pursued may have read something like: “*Design a dampener to slow the motion of the solar panels as they reach their fully opened position.*” Obviously, it was the engineer’s responsibility to develop a dampener that could operate in the vacuum of space, slow the panels down during deployment and not otherwise hinder the

performance of the vehicle. Literally, after spending millions of dollars and thousands of hours, a design to meet the demanding requirements was still illusive. Engineers decided to analyze the worst-case scenario: total failure of the dampening system. Amazingly, the analysis showed that the panels would open without being damaged! The design effort was abandoned and the vehicle performed perfectly without damping.

A more appropriate problem statement might have been: “*Prevent the solar panels from being damaged during their deployment.*” This would allow for various alternatives to be considered (strengthening the panels, etc.). It would also suggest analyzing the current (no damper) design to determine what could cause damage.

Mariner VI was a success with no panel dampening system. This is clear case of solving the wrong problem. Another aerospace example of solving the wrong problem occurred on early manned missions. The United States pursued the following problem statement: “*we need a pen that can be used to write in the weightlessness of space.*” American engineers spent thousands of hours to solve this problem. The Soviet Union pursued a slightly different problem statement: “*we need a device that can be used to write in the weightlessness of space.*” They used a pencil. For this problem, the Soviets did not work as hard as the Americans, but they worked smarter!

2.0 Define the Criteria

The purpose of defining criteria is to provide guidelines for the design. They are like a football end-zone, without them you have no idea what direction you should go. Students are very familiar with solving problems with very clearly defined criteria, but have little experience developing the criteria. Without well-defined criteria the design work will founder. A single problem statement, as discussed above, is a good first step but is insufficient to guide the engineer in developing a solution.

Completed criteria (some times referred to as *design specifications*) must clearly define the performance of the completed project. They should be sufficiently stated such that they could be given to an engineer unfamiliar with the project and that engineer could develop a successful design. The following are *design considerations* that should serve as a *starting point for defining criteria* on any project (these are **NOT** criteria):

Performance – How is the design to function? What need is it filling? What does it have to do? Is it reliable?

Serviceability – Is maintenance or repair a concern? If so, can it be easily performed?

Economic – Is the production and/or use costs considered?

Environmental – Does this have positive or negative impact to the environment? Are there any environmental effects due to the production, use or end-of-use of the design? Are appropriate materials selected?

Environmental Sustainability – (*Sustainability refers to the practice of having minimal impact on the environment. Completely sustainable practices do not deplete or degrade the environment.*) Does the design consider recycling, and using sustainable materials and manufacturing methods? Are renewable energy sources used (such as solar)? Does the product promote sustainable practices?

- Manufacturability – Can the design be economically produced? Is the design “manufacturable”? Can critical elements be inspected?
- Ethical – Has the student followed the code of ethics established by professional organizations such as ASME? Does the design benefit humanity? Have appropriate standards been applied? Are the design documents accurate with claims not overstated?
- Health and safety – Have appropriate codes and standards been applied to prevent harm? Does the design mitigate harmful effects of failure to prevent injury? Does the design directly improve the health and safety of users?
- Social – Does it benefit society? Are there societal implications of the product?
- Political – Are there political implications of the project? What materials or parts would need to be imported? Would this device be exported or imported?

Establishing design criteria is often an iterative process. It can be approached by starting with “high level” descriptions (somewhat ambiguous) and then be refined to clarify purpose. Start by listing all criteria that may influence the design and define its success. For example the criteria for a “lawn mower” may include:

- Safe to operate
- Be portable
- Be able to cut the grass to various lengths
- Easy to start and operate
- Economical
- Easily serviced
- Esthetically pleasing

2.1 Clarify the criteria

The above criteria are rather vague. What does “safe to operate” or “portable” mean? If you cannot define “portable” how will you know if a given design meets that criterion? “Portable” could mean lightweight, easy to lift, easy to push around, or something else. The criteria need to be more clearly described. To continue with the above example:

- Safe to operate: meeting all governing regulations and standards including:
Requirements for Walk-Behind Power Lawn Mowers, 16 C.F.R. Part 1205
- Portable: weigh less than 40 pounds and be easily lifted.
- Cut the grass to lengths: between 1.5 and 4.0 inches, with ½ inch adjustments
- Easy to start: It should require no more than 20 pounds force to start (if using a manual starter system)
- Easy to operate: should require no more than 10 pounds to push on flat level ground covered with 4 inch tall grass.
- Economical: Maximum production cost of \$100, maximum development cost \$90K.
- Easily serviced: routine service should possible with standard tools (screwdrivers and hammers) and should be able to be performed by untrained users in 15 minutes.
- Esthetically pleasing: as determined by Marketing Department

Continue to refine the description of each criterion until it provides a measurable value (quantitative) or at least a clear unambiguous statement (as much as possible). There are three basic ways to describe criteria: quantitative, qualitative, and subjective. Quantitative means measurable (example: weigh less than 100 pounds). Qualitative means clearly defined but not measured in quantity (example: easily serviced using standard tools). Subjective is a matter of opinion (example: must be esthetically pleasing).

2.2 Prioritize the criteria

Not all criteria are equally important. Classify each of the criterion as *Essential* (design is useless if it does not fully meet the criterion), *High* (very important to meet this criterion, but not an absolute must), and *Medium* and *Low* (*nice, but not very important.*) Offer a brief description to elaborate on the meaning of the criterion.

2.3 Communicate/Formalize the criteria

Creating a table to summarize the criteria may be of benefit. The criteria should be numbered so they can be referred to specifically in the text. They should be listed in order of priority with the most critical criteria at the top. The completed and formalized criteria may appear as shown in Table 1.

3.0 Evaluate Alternatives and Down-Select

Brainstorm ideas to generate viable concepts. Evaluate each concept in terms of how well it meets the criteria. Testing, analysis, and collecting more information may be required in order to accomplish this accurately.

Many sources and methods exist to help generate ideas. Patent and literature search, existing products, talking with coworkers and friends are all sources for help. Various methods of brainstorming to create ideas have been developed. *Synetics* is a method that requires brainstormers to look at the problem from four perspectives [1]: by *analogy* (what is similar in nature or industry), by *fantasy* (imagine the impossible), by *empathy* (imagine being the product – how would you function), and by *inversion* (look at the problem back words, inside out, etc.).

3.1 Tabularize

Make a table to summarize the evaluation process. The table should state whether all of the essential criteria have been met for each specific design and then list the advantages and disadvantages. The advantages and disadvantages must be based on the criteria, but may include other comments. Table 2 is for the lawn mower problem. Three various design concepts were evaluated. It may be necessary to gather information before filling in the table (such as conduct testing, perform calculations, etc.).

Table 1 – lawn mower design criteria.

#	Criteria	Priority	Description
1	Safe to operate	Essential	Satisfy: <i>Requirements for Walk-Behind Power Lawn Mowers, 16 C.F.R. Part 1205</i>
2	Economical	High	Maximum unit production cost of \$100, maximum development cost \$100K
3	Portable	High	Weigh less than 40 pounds and be easily lifted
4	Easy to start and operate	High	Require no more than 20 pounds force to start (if using a manual starter system), should require no more than 10 pounds to push on flat level ground covered with 4 inch tall grass
5	Easily serviced	Medium	Routine service should possible with standard tools (screwdrivers, wrenches and hammers) and should be able to be performed by untrained users in 15 minutes
6	Cut the grass to lengths between 1.5 and 4.0 inches	Medium	With ½ inch adjustments
7	Esthetically pleasing	Medium	Determined by Marketing Department

Table 2 – Evaluation of various designs

#	Criteria	Gas powered, manual start	Electric powered	Gas powered, electric starter
1	Safe	1	1	1
2	Economical	\$100	\$80	\$170
3	Portable	2 (40lb.)	1 (25lb.)	3 (50lb.)
4	Easy to start and operate	3	2*	2
5	Easily serviced	2	1	3
6	Grass to lengths	1	1	1
7	Esthetics	2	1	3
	Comments		*Must be recharged	
	Selected	No	Yes	no

1 = Meets or exceeds criterion, 2 = meets criterion less well, 3 = does not meet criterion

Note that **all** of the advantages and disadvantages must be related to the criteria. However, in this example, a criterion not previously considered came to light during the evaluation process. The electric powered design requires recharging. This is not relevant to the

original criteria, and if it is now believed to be important **the criteria tables need to be revised** before submitting in a report! This is an iterative process.

3.2 Down-select

The table will assist in making an appropriate decision regarding the best design, but it does not provide a definitive answer. Each of the designs has advantages and disadvantages. The purpose of the table is to help summarize the information. All appropriate “stakeholders” (people affected by the project such as the engineering team, management, marketing, etc.) should be involved with fully evaluating all viable alternatives and selecting the best option.

3.3 Detailed design

The above process should not only be applied to the overall design concept but to more detailed design work as well. For the lawn mower example, this same process could then be applied to evaluate alternatives regarding motor design, blade design, wheel design, etc.

4.0 Material Selection

A similar process can be applied in selecting the materials to be used in the design. However, criteria are often imposed on the material in addition to in-use performance requirements. Manufacturing and environmental aspects are often critically important. The engineer must select the appropriate material based not only on performance but also on how the part can be produced, and to minimize negative environmental and regulatory effects (due to extraction of raw material, processing, and disposal).

Material selection will have a profound impact on both the cost and performance of the design. Individual engineers rarely have sufficient knowledge to select the best material on their own. Manufacturing personnel, materials engineers, and past designs all can assist the engineer in selecting appropriate materials. Four steps should be employed in selecting the materials.

- 1) List all requirements placed on the material (i.e. determine the criteria)
- 2) Prioritize criteria
- 3) Identify candidate materials
- 4) Start with general categories of materials and iterate to down-select to the best specific material

M. F. Ashby has developed extensive two parameter charts to assist engineers with material selection. These charts can help engineers identify general classes of materials to meet specific needs, such as materials having high strength to weight ratios. Students are encouraged to take advantage of Ashby’s book as well as a number of other texts available in the University’s library.

4.1 List requirements

Typical performance requirements placed on materials include:

- Loading (magnitude of force, static or cyclic loads, impact loads, wear, etc.)
- Weight and specific properties (such as strength per weight)

- Environmental exposure (thermal, corrosion/chemical, optical, nuclear, etc.)
- Environmental concerns (safety, recycling, sustainability, etc.)
- Raw material cost and availability
- Production and fabrication (welding, casting, forming, machining, etc.)
- Typical manufacturing requirements:
 - Economically produced by existing methods (casting, forming, machining, etc.)
 - Consistently achieve sufficient part quality
- Typical environmental requirements:
 - Require no special handling, storage, or disposal methods
 - Produce no harmful products during processing
 - Can be recycled when useful life has ended

4.2 Prioritize criteria

Using a process similar to that described in Sections 1 to 3 above, determine the priority of each criterion.

4.3 Identify candidate materials

Using handbooks, company publications, previous design experience on similar parts and other available resources (such as experts in manufacturing or materials), compile a list of viable materials. Make a table similar to Table 1 if it will help summarize your findings (see Table 3 for an example).

4.4 Down-select

After considering how well each material meets the requirements, a decision as to which material would work the best must be made. Due to numerous criteria placed on the material, it is likely that the decision will be a compromise. For example, performance may be slightly reduced in order to be able to fabricate the part economically or the part may weigh more than desired in order for it to perform properly. Table 3 shows that steel and titanium alloys are viable materials for this example, but aluminum alloys and ceramics do not meet all essential criteria. Steel costs less but weighs more than titanium. In order to select between these two materials, the engineer must determine how much saving weight is worth. Of course, the next step would be to define which specific alloy is the best. Design is an iterative process.

Table 3 – Initial material selection evaluation table.

Criteria	Priority	Description	Material Evaluation			
			Al	Steel	Ti	Ceramic
750°F exposure capability	Essential		N	Y	Y	Y-
Hold 2000 lb static loads at 800°F	Essential		N	Y	Y	N
Weldable	Essential		Y	Y+	Y	N
Low weight	High	200 lb max, lower is better	Y+	N	Y	Y+
Low cost of part	High	\$500 max, lower is better	Y+	Y+	N	Y+
Be recyclable	High		Y	Y	Y	N

“N” does not meet criterion, “Y-” marginally meets criterion, “Y” meets criterion, “Y+” exceeds criterion.

After selecting the appropriate general material type, the next step is to refine the selection. Assume we have decided to use steel, the next question is what type of steel. Table 4 shows an evaluation of several steels.

This table helps the designer focus in on specific materials. Additional tables should be developed to refine the selection to a single specific material. Assuming high alloy has been selected what type of high alloy steel would work best? Of course, each of these tables could evaluate numerous materials, not just three or four at a time.

Table 4 – Evaluation of steels.

Criteria	Priority	Description	Steel	
			Plain Carbon	High alloy
750°F exposure capability	Essential		Y	Y
Hold 2000 lb static loads at 800°F	Essential		Y	Y
Weldable	Essential		Y+	Y-
Low weight	High	200 lb max, lower is better	Y	Y
Low cost of part	High	\$500 max, lower is better	Y+	Y
Be recyclable	High		Y	Y-

Etc., etc., etc.

REFERENCES:

1. R. J. Eggert, Engineering Design, Prentice Hall, 2005.