Chapter 1

The Engineering Problem-Solving Cycle

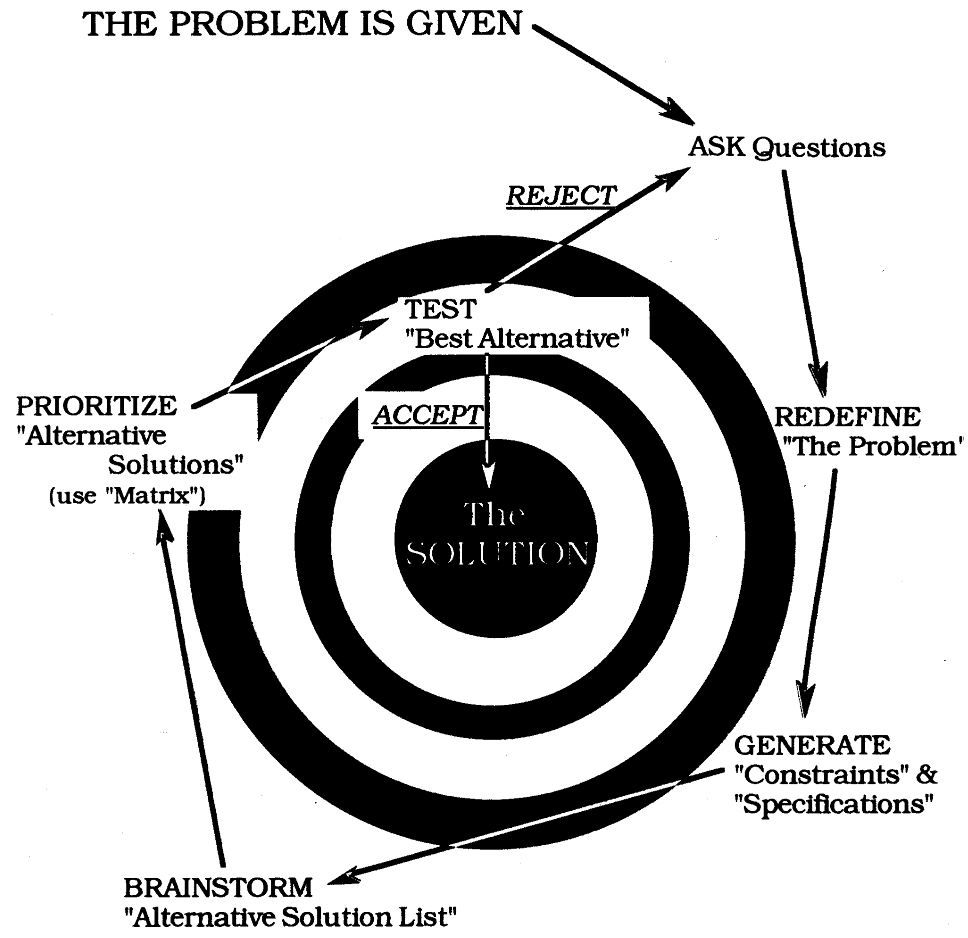


Figure 1. The Problem-Solving Cycle as conceived by Carl Mehrbach, Science Coordinator at Hanover High School, Hanover, New Hampshire.
© 1993 Carl Mehrbach. Used by permission.

Engineering and Problem Solving

Engineers see opportunity where others see problems.
—John Collier, Myron Tribus Professor of Engineering
Thayer School of Engineering

How do you solve a problem?

One way is to think for a minute and then start working with the first idea that comes to mind. If nothing comes to mind, then surely the problem is unsolvable.

If you are working with people who know how to brainstorm, you'll perhaps make a list of ideas, pick the one that appears most feasible, and go to work. But what do you do when your most likely solution pulled from brainstorming seems to lead to a dead end? Do you go back and brainstorm again?

For engineers, the approach to problem solving is more orderly. Engineers—particularly engineers trained at Thayer School—solve problems by proceeding through a problem-solving cycle, step by carefully documented step. If they run into a wall, they don't need to go back to square one. They examine their paper trail and move back only as far as they need, perhaps only a single step. When they have gone the full round of the problem-solving cycle, they look at the original problem and decide whether their solution is specific enough to solve it or whether they need to iterate the cycle.

Each step of the engineer's problem-solving cycle is clear:

- look at the problem carefully
- redefine it to eliminate bias
- identify constraints and set specifications for solutions
- brainstorm alternative solutions
- analyze the alternatives
- select the best potential solution and test it
- look at the original problem statement and decided whether or not you have solved the problem

The problem can involve any kind of decision making, from a social problem such as "Students are taking too long to get into the lunchroom" to a complex one such as developing a device to sort Drosophila fruit flies.

Whatever the problem, the engineering team approaches it with interrogating minds. Team members clarify every word in the original problem statement and, if necessary, redefine the problem to make it more precise. They determine constraints that might apply. From constraints they develop specifications that any proposed solution must meet.

Setting specifications aside for a moment, the team plunges into a session of free-for-all brainstorming. "Anything goes" is the rule. A good engineer knows that even an apparently silly idea is nonetheless a valid contribution to the process, that a totally impractical suggestion may indeed trigger the idea that *does* lead to the best solution.

With specifications and a list of alternative solutions, engineers have a method for analyzing every idea before it is either rejected or selected for further development. This method is the matrix.

The Problem-Solving Matrix

The process of homing in on the best possible solution is framed by a series of problem-solving matrices. The columns of a matrix are headed by the specifications, the rows by the ideas for alternative solutions.

Alternatives can be ranked on a simple scale of good, bad, and neutral (+, -, and 0) or a more sophisticated scale that gives additional weight to the most important specifications. The best solution is the one that garners the most points by satisfying the most specifications. For example, an engineering team working on a town's parking and traffic problems might brainstorm the idea for banning cars from the downtown area. This idea would score well for reliability but not for practicality. The best solution will score well for all specifications.

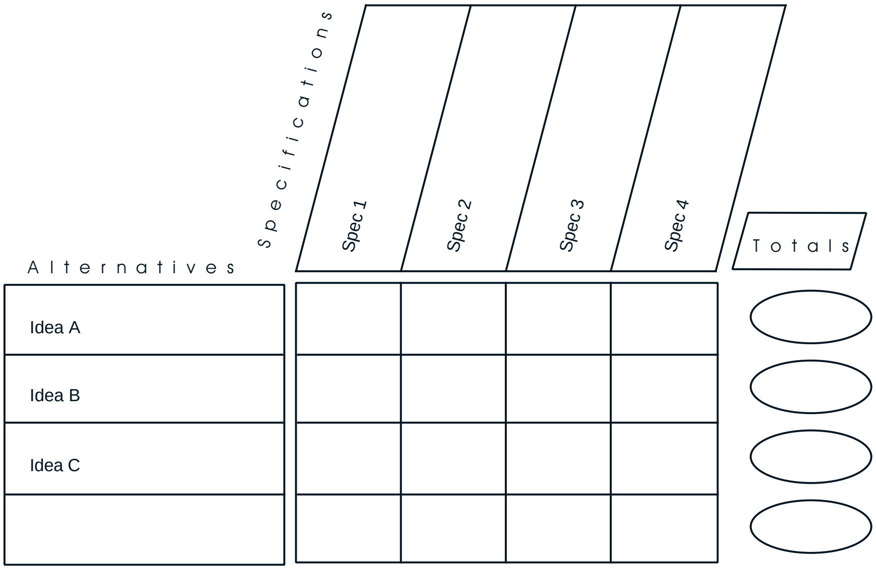


Figure 2. Problem-solving matrix

Iterating the Problem-Solving Cycle

The first round of the problem-solving cycle narrows the focus of the original problem. Then it's time to start another round.

- Redefine the problem to develop a more specific solution.
- Generate tighter specifications.
- Brainstorm more focused alternatives.
- Analyze the alternatives and use the matrix to select the one that best narrows the focus of the problem.
- Reiterate this process until the problem is solved, using a new matrix for each major decision.

For a complex problem, a team may go through the problem-solving cycle a number of times. The first matrix answers the question, "How do we go about…?" The second matrix answers the question, "How will we implement…?" Further matrices answer such questions as "How will we test…?" or "How can we evaluate…?"

As the team iterates the problem-solving cycle, they research and experiment with every aspect of the potential solution. With each cycle, the problem becomes clearer, the contraints more focused, the alternatives closer to solving the original problem.

Iterative problem-solving is "messy." The process involves investigating resources, gathering data, experimentation, and analyzing test results. Any one of these activities may require further investigation, gathering, experimenting, and analysis. With every task carefully documented, at times the paper trail may threaten to spill out of its folder, the project seems out of control. A good team keeps going, knowing that however messy the process, it is also thorough. As shown in the next sections, which follow a team solving an environmental problem, the matrix helps both to narrow the focus and to serve as documentation. The iterations of the cycle assure the team that the best possible solution will be found.

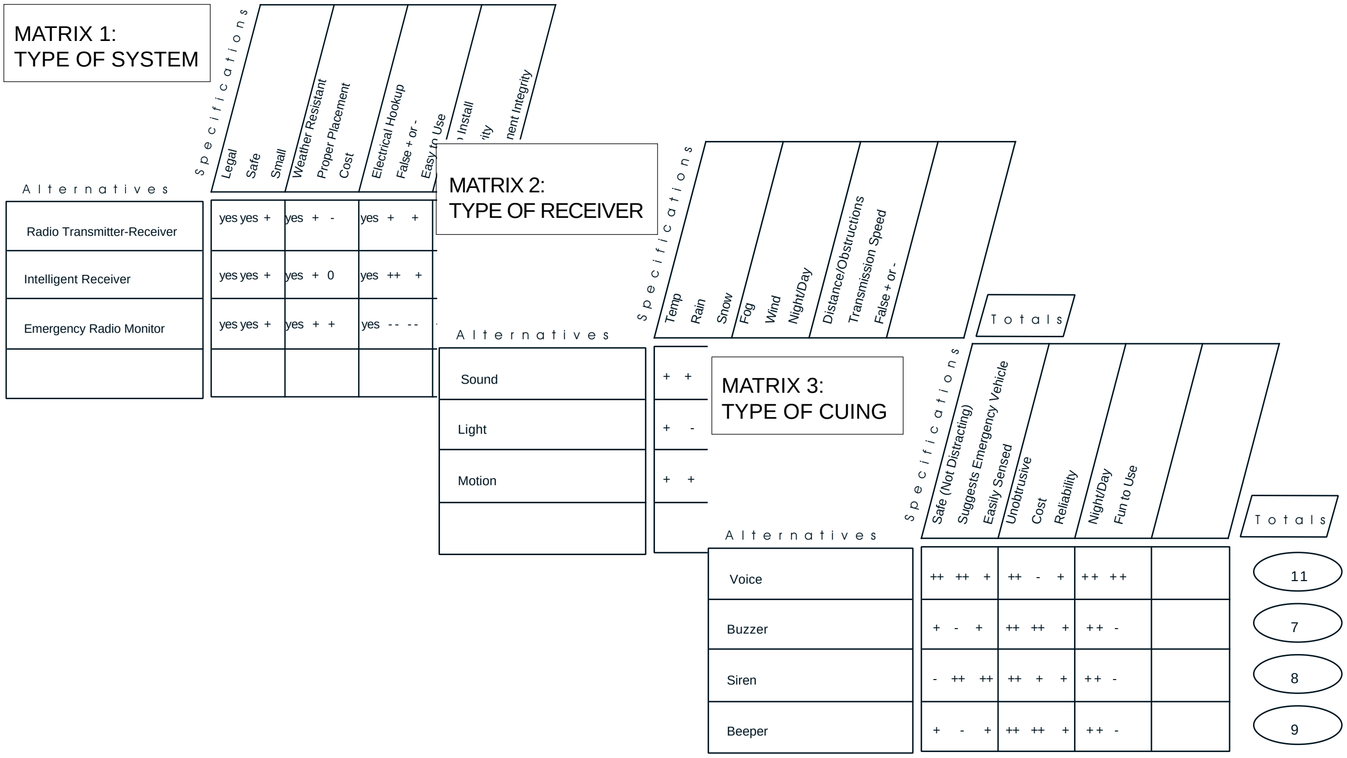


Figure 3. A workshop team's iteration of the problem-solving cycle for an emergency vehicle warning system.

What's the Problem?

The first step in the engineering problem-solving cycle requires a problem statement, one that focuses on a content area of the course or a concern taken from the real world. A problem statement can be

- an open-ended question
- an existing condition in need of change
- a challenge to look ahead for problematic conditions of the future
- a kit of materials provided to design and build something
- a research proposal for a student project

A physics teacher might present students with materials and a narrowly defined problem in aerodynamics, as Jennifer Groppe, of Washington, D.C., did:

> You will be given two sets of identical "parts" with which to make two objects. One object is to be as aerodynamic as possible, one to be as air-resistant as possible.

Another physics teacher might present students with an open-ended proposal that requires the use of electronics:

> Design an electronic device to aid in the prevention of crime.

A third might, as did Tom Woosnam of Hillsborough, California, take a local problem—such as a dangerous road on which students drive every day—and create an RFP from a ficticious funding organization:

> The Triple B Auto Association has published a survey stating that the number of accidents on Route 92 between Half Moon Bay and Crystal Springs Reservoir varies during the different months of the year. CSU Engineering Foundation is interested in developing devices that will prevent the greatest number of accidents.

Each of these problems requires the application of some principles of physics. For a narrowly defined problem, the application is specific. For an open-ended question, the link between textbook physics and the actual problem may seem less clear to students. Such a problem reminds them that the world beyond the classroom is not neatly divided into chapters with questions at the end.

Many teachers begin their problem-solving ventures with a demonstration problem, moving the entire class as a team through one or two rounds of the problem-solving cycle. The problem statement for such problems does not need to be related to the subject matter of the course. The objective is to have the students experience—and discuss as they experience—the steps of the cycle.

In one of the summer workshops for high school teachers, Professor John Collier demonstrated the problem-solving cycle using an energy conservation problem:

> An ecologically concerned client wants to change her home heating system from electricity to gas in order to reduce her high heating costs.

It's a good model problem to work through the problem-solving cycle.

What’s the Real Problem?

Good problem solvers, according to Professor Collier, assume that the initial problem statement reflects both the customer’s bias and a preconceived notion of the desired solution. There is always more to a problem statement than first meets the eye. An engineering team that simply accepts a problem statement may be bewildered by the client’s hostility to a proposed solution. If the team begins by understanding the client’s implied solution, there will be fewer surprises at presentation time.

Here, again, is the problem.

> An ecologically concerned client wants to change her home heating system from electricity to gas in order to reduce her high heating costs.

Look at it closely. There are really two problems.

- The cost of heating her house is too high.
- Heating with electricity is both expensive and ecologically unsound.

The team starts by examining key phrases.

- *ecologically concerned*: How great is her concern? How much is she willing to pay for it?
- *change from electricity to gas*: Is gas always cheaper than electricity? How much does “change” cost?
- *high heating costs*: How do her heating costs compare to comparable homes in the area?

What, then, is the client’s bias?

- Heating with gas is less expensive than heating with electricity—if you don’t count the change-over cost.
- Heating with gas is ecologically sound, because reduced cost equals reduced energy.

What is the client’s implied solution? Clearly she believes that changing from electric to gas heat would both reduce the cost of heat and have least impact on the environment. But is that solution right? That’s the question the consulting team wants to answer using the problem-solving cycle. They redefine the problem:

> What is the most cost-effective change the client can make to reduce her energy costs?

What Are the Constraints?

With a clearer understanding of the problem, the team sets about generating a list of constraints. What conditions must the solution meet in order to satisfy the client? Research is in order. The team needs to know more about the client than that she is concerned about protecting the environment. For a problem taken from outside the classroom, students will do on-site research; for a theoretical problem, they may use role-playing. Lisa Torres, of Lebanon, New Hampshire, has her students conduct a planned interview with herself or another person acting as the client (complete with costumes and mannerisms).

For the home heating problem, Collier asked all the workshop participants to imagine an in-depth interview and a thorough inspection of the client's home. Their imaginary client, they decided, was

> an engineer who lives alone in a mid-Atlantic state in a sprawling brick ranch heated by an electric baseboard system. Her windows are single-pane crank-outs with aluminum frames. She has installed some energy-saving devices, but her costs are still above average for the area.

What then are the constraints?

In the workshop, Collier pointed out that general constraints, such as feasibility, practicality, or reliability, are those that apply to any problem's solution. Specific constaints, such as cost or environmental impact, apply only to the problem at hand. With a good list of constraints, the team can develop the specifications to which each potential solution must conform.

feasible
reliable
economical
aesthetic
legal
moral
safe
environmentally sound
practical
ethical
efficient
timely

From Constraints to Specifications

Engineers never assume that a word is just a word. What does "feasible" mean? What is "practical?" Before a specification is included on the list, it is defined, quantified and justified in order to ensure consensus. Take the specification "economical." The team decides that economical is

- *defined as:* the greatest savings, considering both capital cost and operating costs, when compared with current costs
- *quantified as:* capital cost, operating costs, and savings
- *justified as:* reducing costs as quickly and efficiently as possible

After taking each suggested specification through the define-quantify-justify process, the list of constraints might be refined into sets of specifications, such as:

feasible: technologically feasible, can be accomplished in less than six weeks

safe: safe for user (trained or casual), safe for installer, safe for bystander

economical: capital cost, potential savings, operating cost

environmentally sound: production and use do not harm environment

At this point, some teachers might ask their teams to record the specifications along the top of the problem-solving matrix. Others prefer to have the students brainstorm before making up the matrix, in order to prevent any negative mental criticism that suggests ideas don't fit the specs.

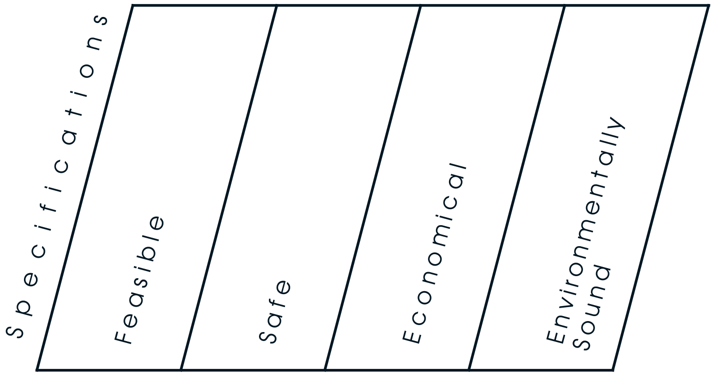


Figure 4. Specifications on the matrix

What Are the Alternatives?

Finding alternative solutions begins with brainstorming. A good brainstorm triggers creative juices. Every suggestion is taken seriously, even ones thrown out for laughs. A recorder makes a list, and every possible alternative goes on it. A long list assures problem solvers that, should a first choice fail, another solution can be worked on.

The high-heating-bill problem generated a lot of ideas.

Install gas heating system.
Add wood stove.
Burn coal.
Bury the house in an earth berm.
Add insulation.
Put a dome over the house.
Fit windows with drapes.
Add shutters to windows.
Install high-efficiency heat pump.
Plant trees to block the wind.
Brick in existing windows.
Install programmable thermostat.

When the brainstorm subsides and giggles taper off, the team is ready to work with the matrix. Some teachers run the matrix analysis with all possibilities, while others ask their students to organize the suggestions into categories, reasoning that a long list on the problem-solving matrix makes the process tedious and unproductive. The disadvantage of the categories is that although a particular idea may be good, it may belong to a category that, as a whole, does not score well.

Organized into categories, the home-heating ideas are placed to the left of the matrix.

Alternatives
Install new heating system
Lower energy losses
Increase efficiency of current system

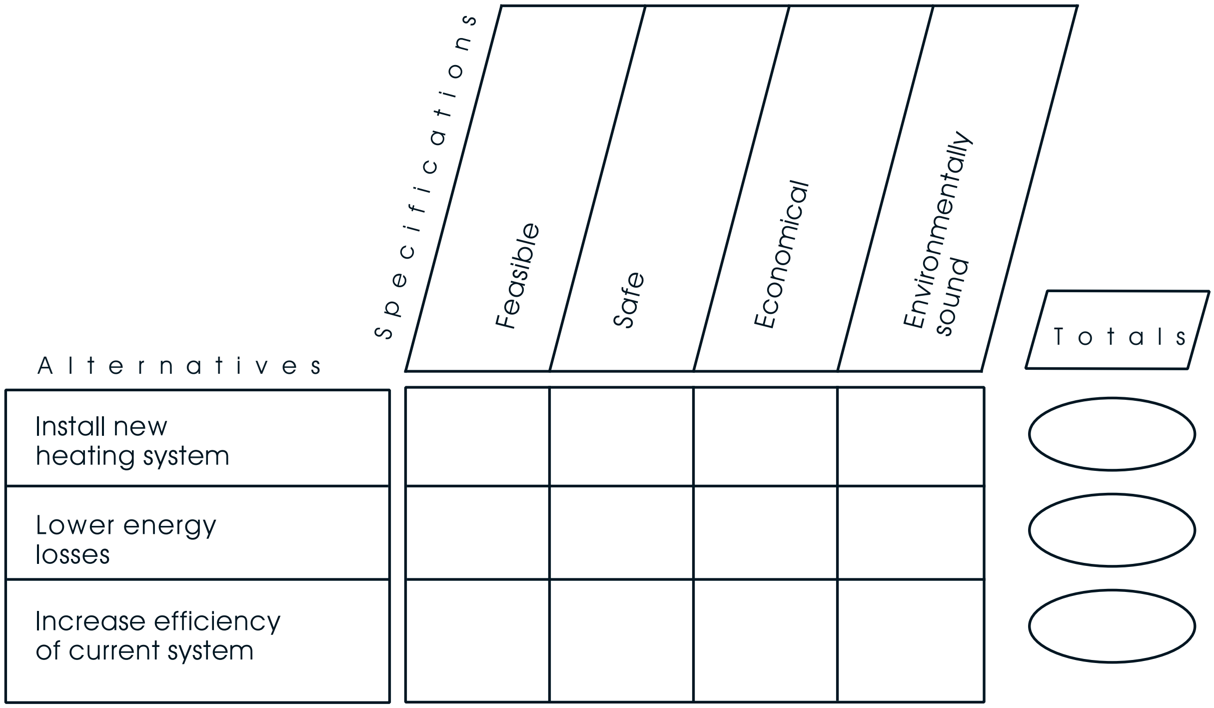
Figure 5. Alternatives on the matrix.

Which Is the Best Idea?

In the analysis, the team weighs the advantages and disadvantages of each alternative. Here the matrix comes to life.

In order to analyze the matrix, problem solvers may need to experiment. They certainly need to get out into the field.

Market research tells them what's available. Technical research tells them what is feasible. In the library, they scan technical references and journals. They use the telephone or the Internet to reach other resources, such as companies and trade associations. They conduct patent searches to learn about new energy-saving devices being developed. By the time they are ready to rank the alternatives, they know a lot about heating systems, energy, and efficiency.



	Specifications				
Alternatives	Feasible	Safe	Economical	Environmentally sound	Totals
Install new heating system					
Lower energy losses					
Increase efficiency of current system					

Figure 6. Setting up the matrix for analysis

Choosing the Best Alternative

The matrix provides a visual means for weighing the alternatives. Each alternative is ranked for each specification, using a scale everyone agrees on. A simple relative scale is "good, bad, neutral." Quantitatively,

+ Better than the other alternatives
– Worse than the other alternatives
0 No appreciable difference

If Ideas A and B are both relatively safe while Idea C is a little risky, then A and B are assigned "0" in the Safe column while Idea C is assigned "–." Another scale might quantify the rankings on this matrix as

+ Having a beneficial impact
– Having a detrimental impact
0 Having a neutral impact

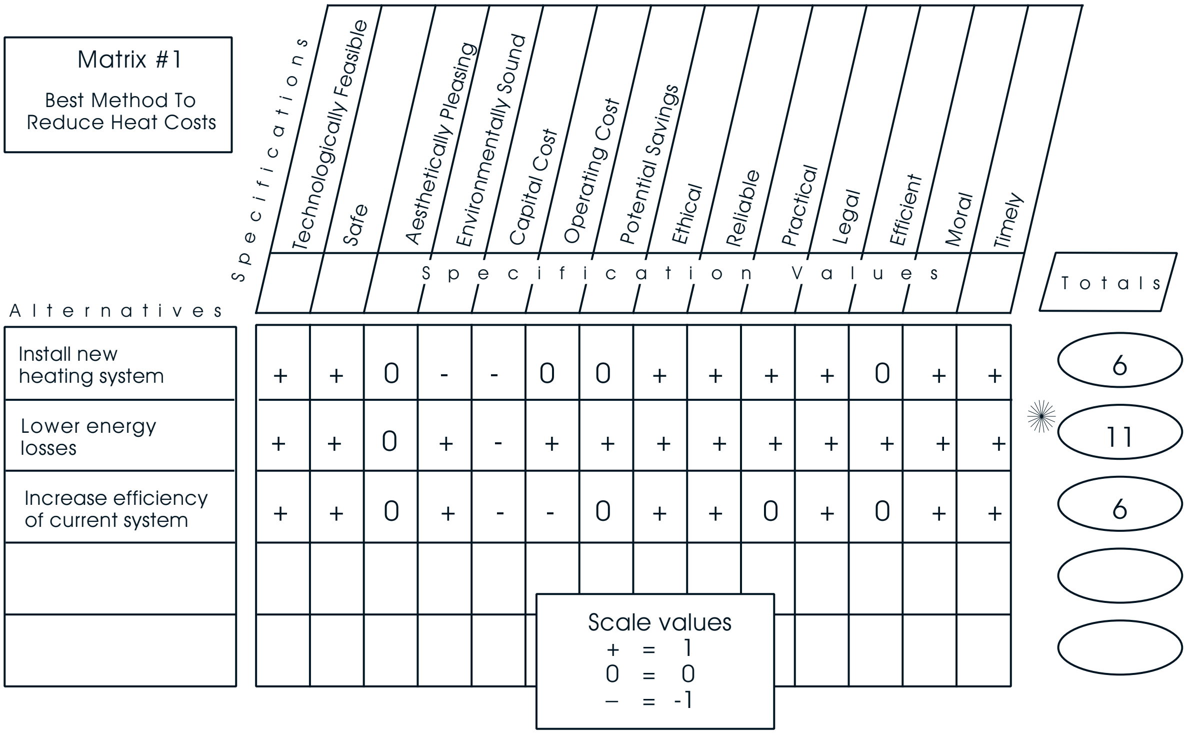
A third kind of scale uses positive numbers ranging from 1 to 3 or the popular 1 to 10. Teachers have reported success with the 1-to-3 scale, especially for interdisciplinary projects with non-science colleagues uncomfortable with negative numbers. Most teachers have found the 1-to-10 scale too broad, leading to careless quantification without real differentiation between, say, a 6 and a 7.

Whatever the scale, the rank for each alternative is totaled by assigning numbers:

+ = 1
0 = 0
– = –1

The best solution is the one with the highest total.

For the client with the high heating costs, the following matrix uses the beneficial-detrimetal-neutral scale, which indicates that the most viable solution is lowering heat losses. It's time to reiterate the problem-solving cycle.



Matrix #1

Best Method To Reduce Heat Costs

Alternatives \ Specifications	Technologically Feasible	Safe	Aesthetically Pleasing	Environmentally Sound	Capital Cost	Operating Cost	Potential Savings	Ethical	Reliable	Practical	Legal	Efficient	Moral	Timely	Totals
Install new heating system	+	+	0	-	-	0	0	+	+	+	+	0	+	+	6
Lower energy losses	+	+	0	+	-	+	+	+	+	+	+	+	+	+	✳ 11
Increase efficiency of current system	+	+	0	+	-	-	0	+	+	0	+	0	+	+	6

Scale values
+ = 1
0 = 0
– = -1

Figure 7. Matrix 1: Best method to reduce heat costs

Another Round, Another Matrix

Now that the team knows the general solution—lower energy loss—they can look for a specific solution. They start by redefining the problem:

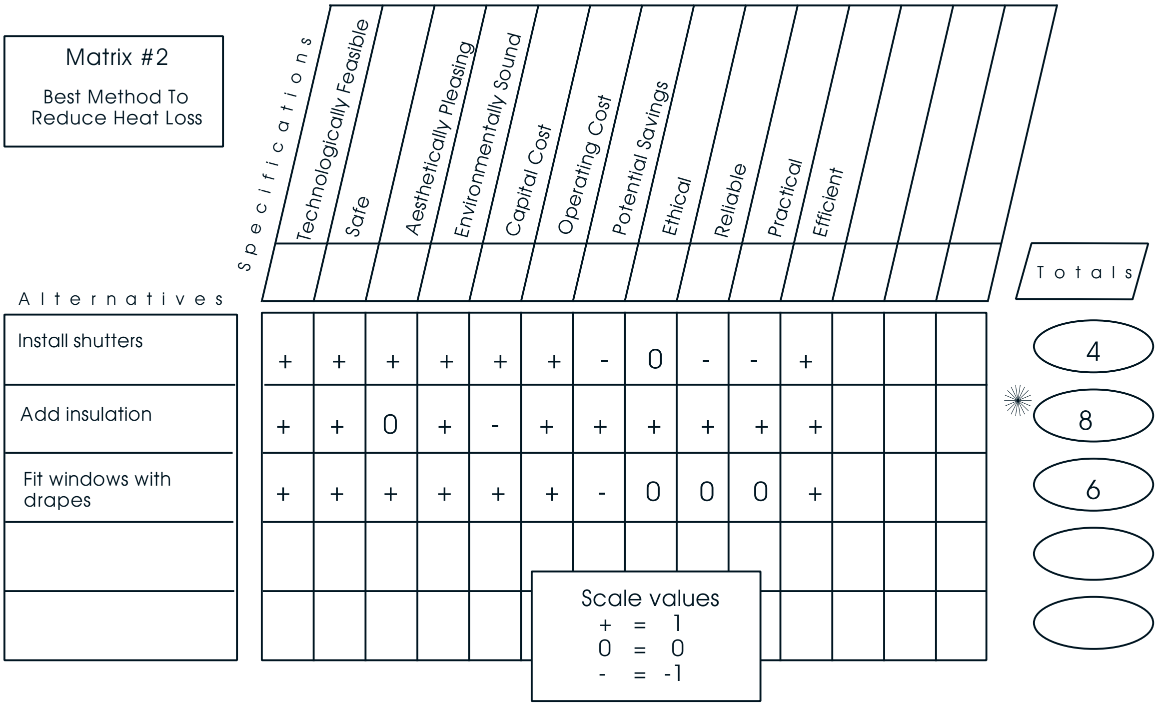
> What is the best way to reduce heat loss?

The specifications are similar to those developed for the first round, because the first matrix analyzed categories, rather than specific ideas. More general specifications—legal, moral, ethical—can be dropped because the top-ranked category rated well in those; or the second matrix can simply repeat the specifications of the first round.

The team extracts from its original brainstorm list the three serious ways to reduce heat loss:

> Add shutters.
> Add insulation.
> Fit windows with new drapes.

Together, the team members form a new matrix and embark on another round of research. They rank each alternative, and begin the cycle again.



Matrix #2

Best Method To Reduce Heat Loss

Alternatives / Specifications	Technologically Feasible	Safe	Aesthetically Pleasing	Environmentally Sound	Capital Cost	Operating Cost	Potential Savings	Ethical	Reliable	Practical	Efficient				Totals
Install shutters	+	+	+	+	+	+	-	0	-	-	+				4
Add insulation	+	+	0	+	-	+	+	+	+	+	+				✳ 8
Fit windows with drapes	+	+	+	+	+	+	-	0	0	0	+				6

Scale values
+ = 1
0 = 0
- = -1

Figure 8. Matrix 2: Best method to reduce heat loss

Round 3, Matrix 3

Selecting the alternative with the highest score from Matrix 2, the team redefines the problem as:

> Where in the home would added insulation be most effective?

For this round, the team redefines earlier specifications more narrowly:

> non-toxic, non-carcinogenic
> having a real impact on heat loss
> having a reasonable installation cost
> not detracting from the home's appearance

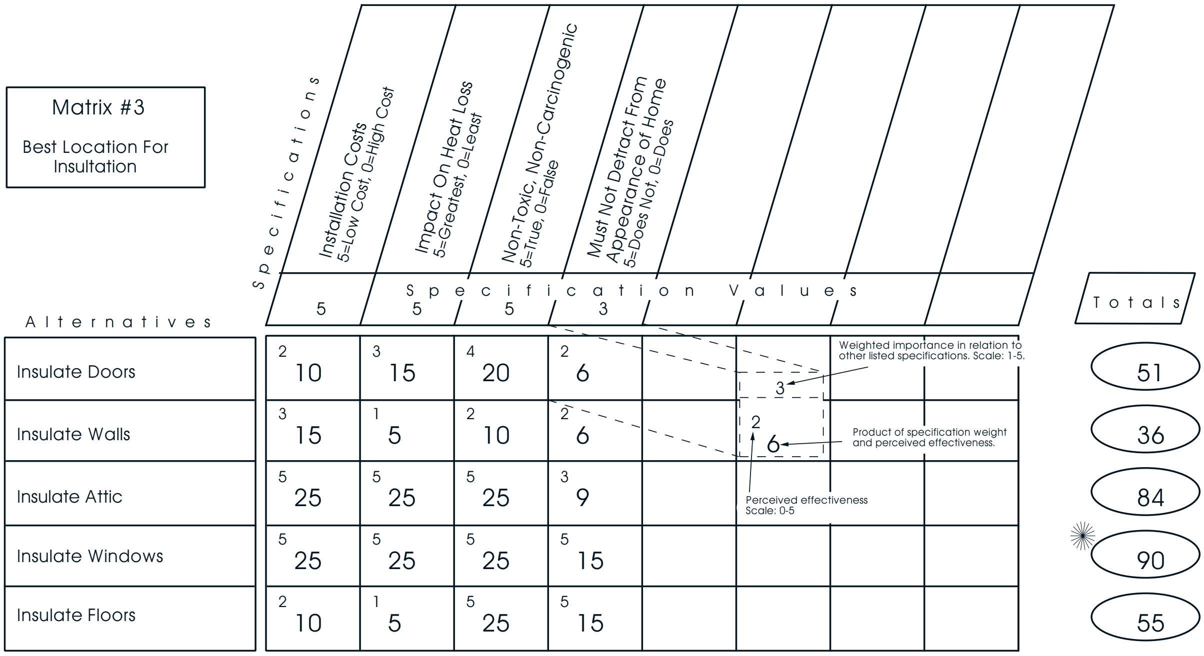
Another round of brainstorming generates potential insulation locations.

- windows
- attic
- floors
- walls
- doors

Another round of research brings in information on insulation ratings, installation costs, and environmental impact.

As the team reiterates the problem-solving cycle, it evolves a more sophisticated ranking scale for the matrix. Team members decide on the relative value of each specification and weights it on a scale of, say, 1-to-5. For example, Matrix 3 weights each of three specifications—"installation costs," "impact on heating loss," and "non-toxic, non-carcinogenic"—as "5," since these three are all very important in solving the problem. The fourth specification, "must not detract from appearance of home," less important to the ecologically concerned client, is weighted at "3."

Under a weighted system, each alternative is given a rating or "perceived effectiveness" value, again perhaps on a 1-to-5 scale. The actual score for any alternative for any specification would be the product of the specification weight and the rating or estimated effectiveness for that alternative. For example, the estimated effectiveness of insulating the doors is 2 (on a 1-to-5 scale). Since "must not detract from appearance" is weighted at 3, the actual score for insulating the doors, insofar as detracting from appearance, is 6.



Alternatives	Installation Costs 5=Low Cost, 0=High Cost	Impact On Heat Loss 5=Greatest, 0=Least	Non-Toxic, Non-Carcinogenic 5=True, 0=False	Must Not Detract From Appearance of Home 5=Does Not, 0=Does					Totals
Specification Values	5	5	5	3					
Insulate Doors	2 10	3 15	4 20	2 6					51
Insulate Walls	3 15	1 5	2 10	2 6					36
Insulate Attic	5 25	5 25	5 25	3 9					84
Insulate Windows	5 25	5 25	5 25	5 15					90
Insulate Floors	2 10	1 5	5 25	5 15					55

Figure 9. Matrix 3: Best location for insulation

Round 4, Matrix 4

With insulation for windows ranking highest on Matrix 3, the problem is redefined as:

What is the best way to insulate windows?

The team can look back at previous matrices to find the appropriate specifications. With an improved understanding of the problem, team members may want to refine the specifications or consider one or two more.

capital cost
non-toxic, non-carcinogenic
longevity (7 to 10 years)
operating cost
potential saving
does not detract from appearance of home

By now, the team members' brainstorming is not only focused, it is also informed by a good deal of research. The list of alternatives is thorough.

plastic film over the windows
shutters on outside of windows
storm windows
fiberglass on outside of windows

Placing alternatives and specifications on another matrix, assigning specification values, determining estimated effectiveness, calculating the rankings—team members are sure of their solution.

The homeowner should retrofit her house with Thermopane windows.

They are prepared to justify the retrofitting even though the capital cost is higher than for the other alternatives.

In their presentation to the client (or to a review board of teachers, administrators, and members of local business and professional communities), the team can back up every decision with solid research. The solution, with the accumulated documentation, is convincing:

Glass is better than gas!

Matrix #4

Alternatives For Insulating Windows

Alternatives	Capital Cost 5=Low Cost, 0=High Cost	Operating Cost 5=Low, 0= High	Potential Savings 5=Low, 0= High	Non-Toxic, Non-Carcinogenic 5=True, 0=False	Must Not Detract From Appearance of Home 5=Does Not, 0=Does	Longevity (7-10 years) 5=High, 0= Low	Participation of Owner 5=No, 0= Yes		Totals
Specification Values	5	5	5	5	3	3	3		
Plastic Film Over Windows	5 25	0 0	1 5	5 25	0 0	0 0	0 0		55
Install Storm Windows	2 10	0 0	4 20	5 25	3 9	5 15	1 3		82
Shutters On Outside of Windows	4 20	0 0	0 0	5 25	4 12	5 15	1 3		75
Fiberglass On Outside of Windows	3 15	0 0	2 10	5 25	0 0	1 3	0 0		53
Install Thermopane Windows	1 5	0 0	5 25	5 25	5 15	5 15	5 15		100

Figure 10. Matrix 4: Best method for insulating windows