DECISION MAKING WITH TRADE OFFS

In both engineering design and management there is a continue succession of decisions. Most of these are informal – you may not even be aware you are making a decision. The decision will be based on what has worked before, or an informal study (in your log book), or simple judgment, or a stochastic process (such as tossing a coin).

There are also formal mathematical decision making tools such as Multistage Decision Making.

Another decision tool is the "Trade Off" study or "Multi-Criteria Decision Analysis" if you want to be posh (or want to look this subject up on the web).

TRADE OFFS

(or "Trades" to our American cousins)

According to the Oxford English Dictionary the everyday meaning of "trade off is:

> *A balance achieved between two desirable but incompatible features; a sacrifice made in one area to obtain benefits in another; a bargain, a compromise.*

Or from Wikipedia:

> *A **trade-off** usually refers to losing one quality or aspect of something in return for gaining another quality or aspect. It implies a decision to be made with full comprehension of both the upside and downside of a particular choice.*

So a trade off study is a way of making decisions when more than one factor is involved. A trade off is part of the process of "optimising" the system in the broad sense. Although more often "optimisation" is a term used in the setting of actual values of the system during the design through modelling.

WHEN ARE THEY USED

Trade offs should be used to make decisions:

on system requirements and objectives in Phase A.

on technical approaches in Phase B (not in Phase A: a common mistake).

You can use trade offs when you are finding a decision difficult and they may also be used within a design team when a decision has become an issue within the design team generally.

However what is of interest here is when it is formally asked for by a customer - This is more common when the customer is involved in the development process. This can be asked for during development as issues arise or even form part of the early design stages contract (in the statement of work) on the developing contractor. In this event the formal stages should be gone through

FOUR TRADE OFF STAGES

1 - Identify all the candidate approaches.
2 - Reject options that cannot meet the requirement.
3 - Compare the remainder against critical parameters.
4 - Score the options and the one that comes out best is selected.

The “trading” which gives the process its name is between the parameters to find the best balance (or compromise) for the system.

Note that the third and fourth steps imply a contest with rules and scoring to decide the winner - and I think that is the best way to look at them.

STEP 1
IDENTIFY ALL THE CANDIDATE APPROACHES.

When doing a formal trade off it is normally expected that an attempt will be made to include all the possible options in at the start. There is a general belief (particularly with customers who have agreed a fixed price for the work) that more options means a better trade off - it is not true of course, but it normally pays to go along with this.

You should always include all the obvious options even if they equally obviously will not work. Step two should sort them out. If you do not do this some moron is bound to query the trade off later!

Many customers like a few "way out" options included - it makes them feel adventurous and radical. However they then like to see them quickly eliminated so as not to cause any further embarrassment. (In many cases I believe the customer likes to have as many options at the start as possible to cover his back. Later on whatever comes up he can say it was considered but rejected).

Message: Trade offs often have much more to do with keeping the customer happy than any real and useful engineering of the product.

STEP 2
INITIAL REJECTION
REJECT OPTIONS THAT CANNOT MEET THE REQUIREMENTS

This may seem obvious but it surprising how often this step is forgotten. A particularly silly omission when examining each option can take a considerable amount of time.

It is particularly important to do this step if you have been enthusiastic about the number of options you are examining.

A rejection can be done anywhere in the analysis - important if working through many parameters on a step by step basis.

Rejection can be due to either:

- A non-compliance with the requirement specification if that can be established.

or

- There is a logical reason why another option will always be superior.

An important point here is to make sure the reasoning is secure. Options should not be eliminated just because preliminary analysis suggest it unlikely to win in the next stages. At this stage you cannot be sure of the eventual outcome (or you have done way too much work).

Eliminating options early makes the trade off simpler as the final detailed comparison is only between realistic options. This makes the trade off easier to understand, have more impact, and generally makes it cheaper to do.

STEP 3
COMPARE THE REMAINDER AGAINST CRITICAL PARAMETERS

The key here is the sensible selection of key important parameters. As with options, the more parameters you use, the more work you make for yourself. NOTE parameters means numbers!

The Parameters should be things that are related to the requirements specification. However since all the options remaining after Step 2 should meet the specification fully, one needs to establish system desirables that are implicit within the specification.

e.g. On a spacecraft or aircraft there is normally a specified mass, but a lighter mass is generally desirable. So mass could be one of the assessment parameters.

A common problem is double counting by using two parameters, which on closer examination are measuring the same basic property.

e.g. For a wing section Drag and Fuel economy

or: using Simplicity, Reliability and Cost (all of which interact).

When a customer disagrees with a trade off he nearly always questions the choice of parameters. It is a good idea to confirm these (in writing) before doing the work to avoid this trap.

FIGURES OF MERIT – A trade off requires numerical parameters and of course not all the things that need to be considered can be easily parameterised. So just as in sports where no fixed winning line is defined like gymnastics or diving we resort to judgement scoring – often called "Figures of Merit"

(Warning – "figure of merit" is a widely used term and can also mean other things)

Figures of merit are little more than dressed up engineering judgement – a point to bear in mind when considering how confident you are about the trade-off's results.

STEP 4
SCORING

The final scoring has three steps:

Raw Scores - The comparison step should have put numerical values on each option's merit in each of the parameters being examined. Sometimes the parameter is directly numerical (e.g. Mass. power usage etc.) if not (e.g. simplicity) then a Figure of Merit score, or the options position in the field is used. At the end of the exercise each option should have some form of numerical score for each of the parameters.

Normalising - In most cases these raw scores will cover different numerical ranges. They therefore need to be normalised so that each has the same range and similar potential spread. Thus the parameters would have equal weighting if added up - but this is not always what is wanted so....

Weighting Parameters - For each of the parameters a weighting factor can be given to ensure those that are considered more important figure more strongly in the final result.

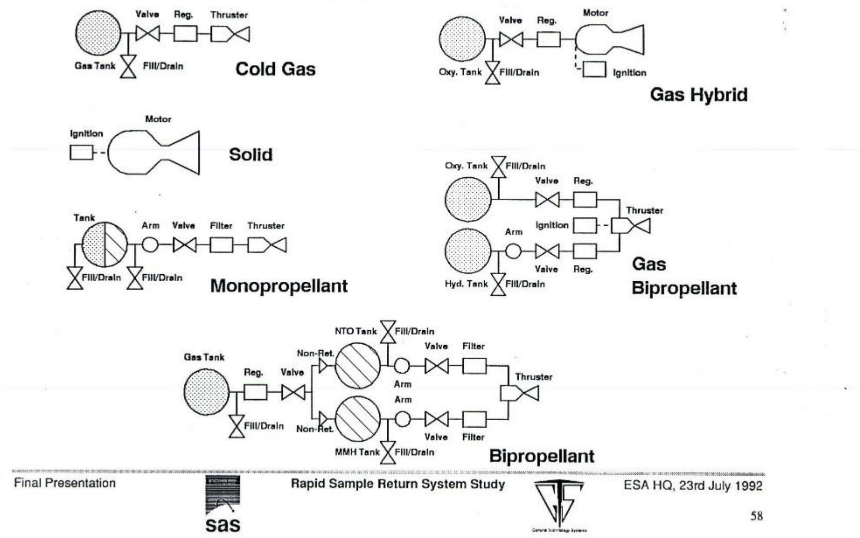
From the final score the winner is selected.

TRADE OFF EXAMPLE

This is a real life example from a small European Space Agency study of a vehicle concept called the "Rapid Sample Return System" (1992). The idea was for a small re-entry capsule to return samples from a manned space station. It would be stored in the habitable part of the station (with the crew) and deployed through the airlock when experimental samples needed to be rapidly returned to Earth.

The trade off is to find the best type of propulsion technology for the deorbit propulsion subsystem.

Step one: 6 candidates were considered. These were a combination of standard propulsion approaches with two unusual options; Gas/Hybrid and Gas Bipropellant. The aim being to cover all the possible options.



Step two: The cold gas system is too heavy and too bulky to be practical therefore that was not considered further

PROPULSION OPTIONS

Option	Specific Impulse N s kg $^{-1}$	Propellant Mass kg	Tank/Case Diameter m	Tank/Case Mass kg	Other Mass kg	Total Mass kg
Cold Gas	500	9 (N2)	0.37	5.4	0.6	15.0
Solids	2600	2	0.15	2.2	0.2	4.4
Monoprop	1700	3.0 (N2H4)	0.23	1.2	0.9	5.1
Biprop	2900	0.8 (MMH) 1.0 (NTO)	0.12 0.12	0.2 0.2	2.3	4.5
Gas Hybrid	2600	0.8 (O2) 1.2 (solid)	0.16 0.12	0.5 1.3	0.6	4.4
Gas H2/O2	4000	0.19 (H2) 1.11 (O2)	0.24 0.18	1.6 0.7	1.4	5.0

Final Presentation sas Rapid Sample Return System Study ESA HQ, 23rd July 1992 59

OPTION	TOTAL MASS (kg)	COMPLEXITY (no of Components)	TECH. RISK (score out of 10)	SAFETY (score out of 10)
Solid	4.4	2	4	6
Monoprop.	5.1	7	5	7
Biprop.	4.5	17	8	9
Gas hybrid	4.4	6	6	2
Gas H_2 /O_2	5.0	11	7	4

Step three: In this case the initial assessment (shown in the table above) provided all the data for the scoring process. The simplicity is rare, most trade offs involve considerable work obtaining and evaluating data.

Step four: The options are scored against the system parameters that are considered important. Those scores are then normalised and the various parameters weighted in accordance with their importance. Note: because of the manned presence safety was a very high concern.

The raw scores for the four selected parameters;

OPTION	TOTAL MASS (kg)	COMPLEX.	TECH. RISK	SAFETY	TOTAL SCORE
Max Score	1.00 / 2.00	1.00 / 1.00	1.00 / 1.00	1.00 / 4.00	8.00
Solid	0.73 / 1.46	0.34 / 0.34	0.40 / 0.40	0.60 / 2.40	4.50
Monoprop.	0.85 / 1.70	0.64 / 0.64	0.50 / 0.50	0.70 / 2.80	5.64
Biprop.	0.75 / 1.50	1.00 / 1.00	0.80 / 0.80	0.90 / 3.60	6.90
Gas hybrid	0.73 / 1.46	0.59 / 0.59	0.60 / 0.60	0.20 / 0.80	3.45
Gas H_2 /O_2	0.83 / 1.66	0.80 / 0.80	0.70 / 0.70	0.40 / 1.60	4.78

Normalised score before weighting / **Final weighted score**

and the weighted scores - Note in this case low scoring is good – in other scoring system a low score could be bad there are no set rules.

The winner is a Gas/Hybrid system – a case where a "wacky" non-conventional option put in for completeness turns out to be the best. But this result was mostly because it scores well in safety that has a massive weighting. And note how much of the trade off is a result of judgements (figure of merit and weightings) rather than measurable parameters.

ANOTHER EXAMPLE – COMMITTEE ON RADIOACTIVE WASTE MANAGEMENT

This was a Government exercise to establish the best approach to the permanent disposal of radioactive waste they established the Committee on Radioactive Waste Management (CoRWM) who did a trade off. They reported in July 2006 (Managing our Radioactive Waste Safely – CoRWM's Recommendation to Government). The process they used is described in the final report (http://www.corwm.org.uk/)

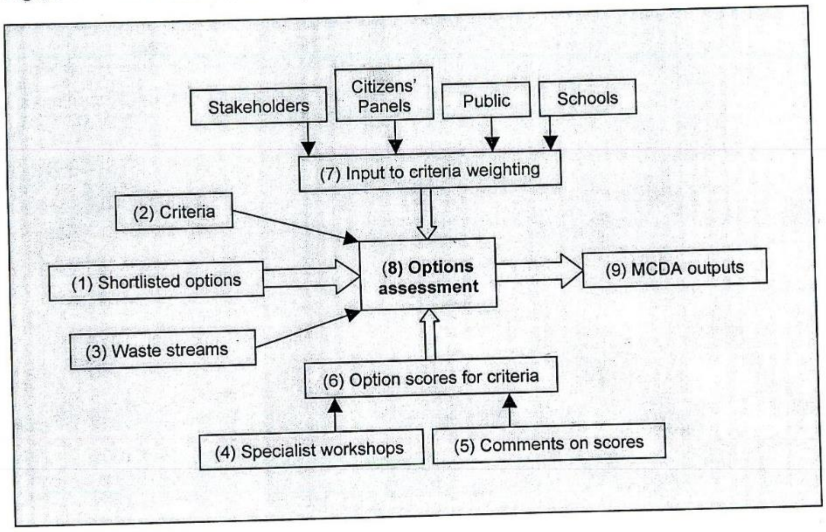
> *CoRWM divided its programme into three phases. The first phase ran until September 2004 and was primarily focussed on information gathering, testing methods, drawing up the long list of potential options for managing radioactive waste and deciding how to undertake a shortlisting process. The second phase from September 2004 until July 2005 included the shortlisting process and deciding how to assess that shortlist. The third and final phase lasted a year from August 2005 until July 2006 and included the assessment of the shortlisted options, the formulation of recommendations, and drafting the report to Government. The various activities that took place within these phases, sometimes spreading across all three*

In other words a trade off. They combine the detailed investigation and the scoring into one phase (I have split it in this lecture) otherwise it is the same process. Note the elimination stage to reduce what is examined in detail (it halved the long list). The list of all option examined (and their fate) was:

1. *interim or indefinite storage on or below the surface*
2. *near surface disposal, a few metres or tens of metres down*
3. *deep disposal, with the surrounding geology providing a further barrier*
4. *phased deep disposal, with storage and monitoring for a period*
5. *direct injection of liquid wastes into rock strata –* ***OUT Phase 2***
6. *disposal at sea –* ***OUT Phase 2***
7. *sub-seabed disposal-* ***OUT Phase 2***
8. *disposal in ice sheets - -* ***OUT Phase 2***
9. *disposal in subduction zones-* ***OUT Phase 2***
10. *disposal in space, into high orbit,* ***- OUT Phase 2***
11. *dilution and dispersal in the environment-* ***OUT Phase 2***
12. *partitioning of wastes and transmutation of radionuclides*
13. *burning of plutonium and uranium in reactors*
14. *incineration to reduce waste volumes*
15. *melting of metals in furnaces to reduce waste volumes.*

CoRWM used Multi-Criteria Decision Analysis to evaluate the shortlist (i.e. a trade off). There diagram outlining the process from the final report is shown below.

Figure 11.1 Overview of the MCDA assessment process



Note they have two separate processes to evaluate and weigt the scores in the different criteria. The criteria (and there weighting) were:

Table 11.2 Relative weights given to headline criteria

Headline Criterion	**Weight (%)**
Public Safety, individual, short term (up to 300 years)	23.3
Security	23.3
Burden on Future Generations	16.0
Flexibility	16.0
Worker Safety	7.7
Environment	7.1
Implementability	4.0
Amenity	1.7
Socio-economic	0.9
Total	**100**

The final conclusion was for a phased Geological deep disposal. Was it the right option? – maybe. But the dismissal of the Space option in Stage 2 was based on very limited and uncertain data and very questionable environmental ethics which greatly influenced this rejection – so maybe not.

The committee budget was very limited (a million or two) and it could not commission research where it found insufficient evidence. This is a reminder that the trade off process can be very expensive when dealing with major decisions. The final option selected by CoRWM has a bill of about £40 Billion so on 5% basis we would need to spend around £2 billion (and spend it properly) in order to get a good enough picture to make the decision.

THE LIMITATIONS OF A TRADE OFF

A trade off formalises engineering judgement it is not a certain route to a undeniably correct decision (there isn't one!).

From the CoRWM final report.
"It is important to recognise that MCDA models are not intended to provide the 'right' answers. They are a tool to aid exploration and not a means to identify a result."

(MCDA = Multi-Criteria Decision Analysis)

and from Wikipedia.
"Since MCDA involves a certain element of subjectiveness, morals and ethics of the researcher implementing MCDA plays a significant part on accuracy and fairness of MCDA's conclusion."

So if they are not conclusive why do them?

1) it introduces some objectivity were it can be introduced another way,

2) it makes clear what is objective and what is subjective,

3) it presents the decision in a formal and readily understandable format.

ALTERNATIVE SCORING - COST

Rather than having several parameters - which tend to be matters of judgement - a better approach is to compare the options against one parameter only - almost universally cost. In practice once a system has reached the performance required by the specification the only real parameter of importance is the cost of meeting that specification.

This normally still means looking at many separate factors but rather than some dimensionless scoring system every issue is turned into a cost preferably a lifecycle cost but sometimes only acquisition cost. For example on a satellite mass can be costed at $7000 per kilogram - the cost of launching it.

In the Rapid Sample Return System propulsion system example – mass is a problem because of the cost to launch it. Complexity and technical risk are both important because they imply more money would be required to develop a system to meet the specification. Even safety could be seen as a measure of the investment needed to reach a given safety level.

One could quibble that since we are now dealing with a single parameter it is no longer a trade off (as there is not another parameter to trade off against) – alternatively since we are still looking and many factors money can be seen as a superior and more objective scoring system. I leave the resolution of this semantic dilemma as an exercise!

Cost trade offs involve a lot more work, but it is the best approach if a genuinely objective result is required.

An example of this in practice was the BAe HOTOL project examining the feasibility of a single stage to orbit launch vehicle. All trade offs were judged on a lifecycle cost basis as a matter of policy which was consistent with the system's objective of a minimum cost launcher.

However use of a cost based trade off does not make the result totally objective. Even if the **cost** is able to be completely obtained from totally objective methods (normally an unlikely eventuality) there is still a question of **value** and that is always a matter of judgement.