While the ideas presented here represent my interpretation of best practice in professional engineering, they have universal relevance to solutions for complex problems.

The purpose of the paper is to describe the basis of engineering methodology and to suggest that those who need to solve complex problems should consider adopting it.
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Introduction

I use the word engineer as a verb with the meaning 'to solve complex problems skilfully'.

A complex problem:
- is normally non-determinate, i.e. there is no single solution that will fit the requirements precisely.
- is solved by an approach that is dominantly top-down, i.e. by starting with a solution (or solutions) and checking whether or not they satisfy the requirements.
- tends to involve uncertainty and risk.

Problem Solving

Top-down or bottom-up?

In Logic for Problem Solving, Robert Kowalski makes the following statement:
‘... the distinction between top-down and bottom-up reasoning is one of the major themes of this book. It is the distinction between analysis (top-down) and synthesis (bottom-up), between teleology (top-down) and determinism (bottom-up). Moreover, the use of top-down inference reconciles the classical, logical view of reasoning as it ought to be performed with the psychological view of reasoning as it is performed by humans in practice.’ [Kowalski’s emphasis]

From this we can infer that two fundamental strategies in problem solving are:
- The top-down strategy (trial and error): start with a solution and assess whether or not it is indeed a solution.
- The bottom-up strategy: use rules to reach a solution.

In real problem solving, a combination of these strategies may be used. Boxes 1 and 2 give examples.

BOX 1  U2 travelling to a concert

‘U2’ has a concert that starts in 17 minutes and all members of the band must cross a bridge to get to the venue. All four men begin on the wrong side of the bridge. It is night and there is one torch. A maximum of two people can cross at one time. Any party which crosses, either 1 or 2 people, must have the torch with them. The torch must be walked back and forth, it cannot be thrown. Each band member walks at a different speed. A pair must walk together at the rate of the slower man’s pace.

Bono: 1 minute to cross; Edge: 2 minutes to cross; Adam: 5 minutes to cross; Larry: 10 minutes to cross. In what order should they cross?

Top down strategy This problem can be solved by trial and error, by trying out all the possible combinations. It does not take long to work out the time for all combination of crossings and find that.

If Bono and Edge cross first, Bono returns, Adam and Larry cross together, Edge returns and Bono and Edge again return together, it would take 17 minutes.

Bottom up strategy If the principle that ‘Larry and Adam must cross together and neither must come back’ is established (bottom-up rule), then the problem can be solved quite quickly using this rule.

[Photo: CC BY 2.5 (http://creativecommons.org/licenses/by/2.5)], via Wikimedia Commons
The nature of determinate and non-determinate problems

When solving a determinate problem, i.e. a problem for which there is a solution that meets the requirements precisely, i.e. one can establish a truth. The band crossing the bridge puzzle – Box 1 – is determinate. It is possible to verify that the band can cross the bridge in 17 minutes.

For non-determinate problems there is no single correct solution. The choice of solution is based on judgement. The objective should be to seek to identify reliable outcomes, i.e. outcomes for which the uncertainty about the decisions will be at the lowest level that is practical in the context.

The supercharger problem outlined in Box 2 (where the objective is to get the best performance possible from an aero engine) is non-determinate. In such cases the basic strategy can only be top-down. However Box 2 shows how use of information that predicts behaviour, a bottom-up approach, can provide important insights that lead to better outcomes. Without Stanley Hooker’s use of applied physics, the Rolls Royce engineers might never have come up with the intercooler idea.

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**Box 2 Stanley Hooker and supercharging of the Rolls-Royce Merlin engine**

In 1938 Rolls-Royce hired an applied mathematician for the first time – Stanley Hooker. He started by investigating the design of carburettors for aero engines and found that the R-R engineers did not have a good understanding of the physics of supercharging. The basic principle in supercharging is that if the air in the combustion chamber is compressed, more fuel can be burned and hence the power of the engine can increase. (Note that in supercharging, the pump to compress the air is driven from the engine whereas a ‘turbocharger’ for compressing the air is powered from a turbine driven by the exhaust gas.)

The ‘charge’ is the mass of the mixture of air and fuel that enters the cylinder at the end of the suction stroke. The charge rate is the mass per minute being supplied to the engine. The charge rate is a measure of the power that the engine can generate. So the main objective in the design of the carburettor was to get the charge rate as high as possible.

On the basis of some quite simple physics and some measurements on the Merlin aero engine, Hooker developed the expression shown below for $W_c$ the charge rate.

This relationship shows that, as was obvious, increasing the charge pressure increased the charge rate but it also shows that if the charge temperature increases the charge rate will decrease. When a gas is compressed, the temperature increases so there would be two features working against each other. Hooker and his team asked the question ‘How can we increase the pressure and lower the temperature?’ They came up with the solution of having two stages of compression with intermediate cooling, i.e. the process is: compress, cool, compress, inject. Doing this made a very significant improvement in the maximum power of the engine. The addition of an intercooler is now a standard technique in supercharging/turbocharging.

\[
W_c = 0.422 \frac{N}{T_c} \left( P_c - \frac{P_e}{6} \right)
\]

1. Hooker S Not much of an Engineer, Airlife1984

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**TEMPERATURE OF THE CHARGE**

**SPEED OF THE ENGINE**

**AMBIENT AIR PRESSURE**

**PRESSURE OF THE CHARGE**

**CHARGE RATE**
What I now describe is my understanding of best practice for the design process in professional engineering. It is a widely used decision-making process as illustrated in Box 4 (page 7) and Box 5 (page 8).

Figure 1 is a diagram of the design process. When people seek to define this process the words and the diagrams they use varies, but there is always a core of ideas similar to those in Figure 1.

The basic activities are: Inception, Conception, Production, Review and Revise.

**Inception**
Two basic actions for this stage are:

1. An intensive search for Information about the context is carried out. Reports about similar projects are retrieved. Investigations may be commissioned (e.g. site investigation). Codes of practice are identified. All issues that need to be considered are identified.

2. A Requirements Specification is established based on the identified issues. This incorporates the client brief (if there is one). Addressing all relevant issues in the Requirements Specification is a major goal towards achieving reliable outcomes and to keeping down the cost of the project. If appropriate, items are added to the Requirements as the process develops. Design decisions are regularly checked against the Requirements.

**Conception**
Options, i.e. different partial solutions/designs that may satisfy the requirements specification, are identified. How far a solution is developed for each option depends on the degree of reliability needed and on cost. The more information about the options the greater the success of the assessment.

The options are assessed against the requirements. A range of techniques for doing this may be used. A decision about the general form of the solution is made. It is important that at the end of this stage, the overall feasibility of the solution is established.

**Production**
Full details of the solution are established so that it can be implemented.

**Review and Revise**
While inception/conception/production represents the general order of the stages in the process, there should be continuous review and revise activities that lead to forward and backward loops in the process.

**FIGURE 1** The design process
**Solving non-determinate problems**

**Strategies**

Strategies for solving non-determinate problems include:

1. **The intuitive leap** The problem solver devises or hears of a solution and goes for it without any attempt to identify unintended consequences or consider risk issues – Box 3.

2. **Copy** Find a solution that someone has found for the same problem and copy it. That can save a lot of trouble and expense but one needs to be sure that (a) the contexts are the same and (b) that the solution worked adequately in the original case. It is never a risk-free strategy.

3. **Use of the design process informally** The basic activities of the process are used tacitly as illustrated in Boxes 4 and 5 (page 8).

4. **Use an engineered design process** The process is used formally as illustrated in Box 5 (page 8). The requirements are written down. Many options may be considered. Special techniques may be used for deciding on the option to be adopted as the solution.

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**BOX 3 The intuitive investor**

An investor had funds available and wanted to invest them to make a good return. He got a phone call to suggest how he can make 20% p.a. All he needed to do is to transfer money to another account and the gains will come rolling in. He leapt for it and...

The investor’s intuition told him that this was the opportunity that he was looking for. He did no risk assessment. That seems to be a silly way to invest but making decisions on the basis of intuition appears to be the norm² and it appears that in some circumstances intuitive decision making can work well³. Experts can use intuition based on experience. However making intuitive leaps in situations of complex uncertainty is a very high-risk strategy even for experts.

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References:


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**BOX 4 Choosing a meal at a restaurant**

It is likely that when you order from a menu at a restaurant you will be in a non-determinate situation, i.e. there will be more than one set of choices that will satisfy your requirements. It is likely that you will use the steps in the design process.

At the inception stage start by reading the menu (gather information) and think about your preferences such as dietary needs and cost (specify requirements).

At the conception stage set up a list of options from the menu that would suit your preferences. Narrow the choice down to maybe a couple of options. Then make a decision.

At the production stage give the waiter your order.
Monitoring of performance, finding faults

Having used a reliable process to come to a decision, one hopes that no faults will emerge post-implementation. But ‘reliable’ does not mean that risk has been eliminated; that tends not to be possible. One should always monitor performance to identify faults and correct them – Box 6. If one identifies a fault or if someone else points it out, the reliable response is to recognise it and make corrections – Box 7.

BOX 6 Safety in air travel

The mechanical reliability of modern aircraft is very high. Airline pilots are unlikely to experience an engine failure in their careers. This has resulted from very careful monitoring of performance resulting in modifications and maintenance regimes that bring down the risk.

It is very common to avoid admitting to errors – Box 8. The engineered approach uses the opposite strategy: faults are sought out and fixed. Where practical, a prototype is built and subjected to stringent tests leading to modifications. After the product has been released, the search for faults continues.
**BOX 7 High integrity, The Citicorp Center Tower**

The Citicorp Tower is a 58-storey building in New York. After it had been built the designer, William LeMessurier found that he had made a fundamental error in the calculations and that the building did not meet the safety criteria for wind loading. He could have let it go and hoped that there would be no failures but he decided to alert his clients to the problem and modifications were made to the structure to make it safe. Did this ruin LeMessurier’s business? Not at all. He was hailed for his ethical behaviour and his professional standing was enhanced rather than diminished.


**BOX 8 Wilful Blindness, Alice Stewart and foetal x-rays**

In her book *Wilful Blindness*, Margaret Heffernan lists many examples of how people and organisations seek to avoid addressing the consequences of errors. Despite overwhelming evidence of serious faults, it is common to resist calls for action to correct them.

For example she describes how, in the 1950s, Alice Stewart, a physician, sought to identify the reason for the unexpectedly high proportion of leukaemia in 2 to 4 year old children.

She found a very strong correlation between such incidence of the disease and of X-ray investigations of a foetus. Further analysis confirmed that if a mother had an x-ray during pregnancy there was a 40% increase in the chance that the baby would develop leukaemia.

Once this had been established, the obvious action would be to ban the use of foetal X-rays. But it took the medical profession worldwide 25 years to put this into effect.

Heffernan attributes this delay to the fact that Stewart’s finding challenged a fundamental principle in radiation treatment: that there exists a threshold dose of radiation below which no ill effects will occur in humans. The statistics showed that despite being well below the accepted threshold level, the dose being used for foetal X-rays was not safe. The medical profession found it very difficult to face up to this.

The problem of antenatal screening was solved in the 1970s using ultrasound by a collaboration between an electrical engineer, Tom Brown and Ian Donald, a professor of gynaecology at the University of Glasgow.

Ethos

How you think is as important as what you know in solving complex problems. ‘How you think’ can be expressed in a number of ways:

- Ethos – the guiding principles and attitudes that are associated with a person, a group of people or a particular type of activity\(^6\).
- Attitude – a way of thinking or feeling that commonly reflects the social culture of one’s upbringing.
- Mindset – similar to attitude.
- Habits of mind\(^7\) – particular ways of thinking.

How you think is a crucial issue but just thinking is not enough. A guiding principle implies not just thinking but action. I use ‘ethos’ since it best implies the necessary combination of thought, behaviour and action.

Guiding principles that support engineered solutions include:

1. There is a relentless drive to achieve reliable outcomes. This means that the risks will be reduced to as low a level as is practical in the context. All activities that can help to achieve this are considered and used where appropriate.

2. A reflective ethos is adopted. Healthy scepticism about all inputs to, and outputs from, the processes and about the processes themselves is adopted.

3. A detailed plan is used.

4. When faults/errors are identified they are admitted and corrected.

5. Constant consideration is given to improving processes and products.

6. If predictive models are available and appropriate, they are used. If data can be made available it is analysed.

7. An ethical approach is adopted. Professional integrity is a key issue.

8. The effectiveness of communication and collaboration among all the parties involved is kept under review.

9. Action is taken to ensure that everybody involved in the project has the necessary competence. Expert advice is sought when appropriate.

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7. Lucas B, Hanson J and Claxton G _Thinking like an engineer, Implications for the education system_ Royal Academy of Engineering, May 2014
A reflective ethos

Key reflective actions include:
- Constantly asking questions such as “Is that correct?”; “Is there supporting evidence for that?”; “Can I do a check calculation?” – Box 9; “Are all relevant issues being addressed?”
- Seeking reliable answers to the questions.
- Taking appropriate action in relation to the answers.

When errors are identified ‘own up and move on’. Alice Stewart (Box 8, page 9) posed the question about deaths due to leukaemia and found the answer. But the medical profession delayed taking appropriate action. Not facing facts can be a very high risk strategy. If you are avoiding action in the face of incontrovertible facts, you are not engineering a solution.

BOX 9 The Sleipner Oil Platform Collapse

In 1991 a large concrete oil recovery platform was close to completion in a Norwegian fjord. A loud bang was heard and the floating structure began to sink. The bed of that fjord now has a very large piece of concrete on it. The reason for the collapse was that the designers used a complex model to predict the stresses and assumed that it would give accurate results.

They did not ask the reflective question “Is it possible to do a check calculation on the maximum shear stresses in the tricell wall?”. The answer, if they had posed the question, would have been “Yes” It is possible to do what is called a ‘back of an envelope’ check calculation (right) that would have shown that the results from the complex model were out on the unsafe side by a factor of 3! Taking action on such a finding could have saved an estimated $700m in direct and consequential losses.

Validation and verification questions

When developing a process or a product it is essential to keep asking validation questions such as: “Is the process capable of meeting the requirements?” “Will the product be fit for purpose?”

It is also essential to keep asking verification questions such as “Has the process been correctly implemented?” “Is the product to specification?”

Continuous improvement, Innovation

William Deming (1900-1993) was an American engineer/statistician whose ideas about how manufacturing processes should be managed have become very popular worldwide. One of his main principles is that if one wishes to improve production, rather than setting production targets, the focus should be on improvement of the process. Everybody involved in the enterprise should adopt such a focus – not just the managers.

A reflective ethos prompts questions such as “How can we improve this process” “How can we improve this product?” which lead to innovation.

Holistic thinking

Reflective thinking leads to holistic thinking, i.e. seeking to ensure that all relevant issues are adequately addressed, e.g. business issues such as costing and financial risk, and long term issues.
**A learning ethos**

Enterprises that seek to achieve engineered solutions need to adopt a pervasive learning culture that includes:

- Learning to extend what you know in terms of factual, conceptual, procedural knowledge, etc.
- Learning to develop skill, i.e. to improve ability to do things
- Learning to develop good ways of thinking, i.e. to identify and use guiding principles that will support the objectives of the enterprise and of society

- Constantly seeking to learn in ways that will improve personal performance and the performance of colleagues.

Carol Dweck\(^8\) emphasises the importance of having a ‘growth’ mindset where one constantly seeks to improve one’s ability. She wrote: ‘Create an organisation that prizes the development of ability – and watch the leaders emerge’.


**Taking an ethical stance**

The engineering of solutions to complex problems must be underpinned by a high level of professional integrity. The Royal Academy of Engineering/Engineering Council’s Statement of Ethical Principles list four fundamental issues:

- **Accuracy and rigour** – People have a duty to ensure that they acquire and use wisely and faithfully the knowledge that is relevant to the skills needed in their work.
- **Honesty and fairness** – People should adopt the highest standards of professional conduct, openness, fairness and honesty – see Box 6 (page 8) and Box 10.
- **Respect for life, law and the public good** – People should give due weight to all relevant law, facts and published guidance, and the wider public interest.
- **Responsible leadership: listening and informing** – People should aspire to high standards of leadership. They should seek to serve wider society and to be sensitive to public concerns.

The adherence to an ethical code should be pervasive in every enterprise.

**BOX 10  The Collapse of the Tay Rail Bridge**

In 1879 the Tay Rail Bridge collapsed with the loss of over 60 lives. The likely trigger event was the failure of a tie assembly that was not fit for purpose. The bridge designer admitted that, when designing the tie, he was trying to keep the cost down. In seeking to thus please his client, he compromised the safety of the users of the bridge. This situation may be described as a consultant’s dilemma – what action should be taken when the client’s wishes are in conflict with the needs of others?

This is a very common situation often resolved more in favour of the client. The Tay Bridge failure is an extreme example of unsatisfactory resolution of the dilemma. Where public good is an important issue, consultants need to explain the true nature of contexts and be prepared to resign a commission if the client will not agree to the public good requirements. Not easy to do.

Ethical dilemmas also involve employees who identify faults but are unwilling to report them to avoid being labelled as a whistle blower and risk losing their jobs.

When a project is engineered, such dilemmas are avoided. All involved, including the client, contribute to the safety culture – see page 13.
Use problem solving strategies

Control risk

Formal approaches to risk assessment and control
A common use of the word ‘risk’ is that it is the combination of the likelihood of occurrence and the consequences of a negative event. Therefore the basis of a risk assessment is that:

- The negative events/hazards are identified
- Their likelihood of occurrence and consequences are evaluated
- Action is taken to ensure that risks are kept to an acceptable level.

The Health and Safety Executive use the ALARP (As Low As Reasonably Practicable) Principle in risk assessment. This is stated as:

- Risks above a certain level are intolerable
- Risks below a certain level are negligible
- Between the two levels, risks are tolerable providing that it can be demonstrated that the cost of reducing the risk further would be disproportionate to any improvement achieved.

Strategies used to reduce risk

- Take action so as to prevent or lower the likelihood of occurrence of negative events
- Arrange that the consequences of negative events, should they occur, will be reduced.

Quantify risk
It is good practice that, if sufficient data is available or can be made available, risks should be quantified in relation to their probability of occurrence. An acceptance criterion for this probability is then defined taking account of the potential consequences of the event. For example in the control of an electricity system it is possible to assess the risk that demand will not be met and to set a probability criterion that limits such an occurrence.

An important question is: ‘How much resource should be allocated to risk assessment?’ The answer depends on the degree to which the context is safety critical, i.e. whether the consequences of negative events may be death or injury to people, or excessive economic, physical or environmental damage.

Adopt a safety culture
Adoption of a safety culture (Box 11) is now pervasive on construction sites and is particularly evident if you visit a nuclear power station where safety is the key issue. An important feature of a safety culture is that management is required to consider suggestions from any employee about improving safety. Those who point out faults may be rewarded for their contribution. An organisation in which ‘whistle-blowers’ are vilified is not properly addressing risk control.

BOX 11 The 2012 London Olympic Park

In the early stages of the construction of the 2012 London Olympic Park the incidence of accidents was deemed to be unsatisfactory – see diagram. A safety culture was adopted where all involved were required to think about safety, to act safely and to make suggestions about how safety might be improved. As a result there was a dramatic drop in the frequency of accidents. No construction related deaths were recorded on the site.
**Use standards. Be wary of innovation**

A main strategy for risk control in engineering is to use codes of practice that are based on the experience of practitioners. If the provisions of an accepted code are satisfied, then the risk of failure should be relatively low. This is an important strategy especially when it is not possible to fully predict behaviour and empirical rules need to be used.

Creativity may be defined as the formulation of original ideas whereas innovation is the transformation of such ideas into working outcomes. When innovating, the level of risk tends increase significantly and therefore the processes used to develop an innovative idea are of special importance.

While innovation can be an essential ingredient of successful outcomes, there is a tension between innovating and following standard practice. It is bad practice to innovate in order to achieve a result that is no better than using conventional methods because it is very bad practice to take unnecessary risks.

**Seek reliable advice**

When in-house expertise on a particular topic is not available, one may have to seek external advice. This will increase the cost of the project but one has to weigh that against the risk of making errors.

Ignoring expert advice is a high-risk action. On the other hand, experts can make errors and therefore it is wise to approach all advice with healthy scepticism and to consider getting second opinions – see Box 12. It is important to ensure that advice comes from sources that are impartial.

---

**BOX 12 Class 3 Checking for long span bridges**

UK bridges that have spans of over 50 metres require a ‘Class 3 check’. This requires that a consultant designs the bridge seeking to ensure that all the statutory safety criteria are satisfied. Information is then passed on to a second consultant who repeats the safety checks without reference to the original calculations. Differences between the check and the original work then need to be resolved. The need for such a check does not imply lack of competence on the part of the original designer. It recognises that even with rigorous quality management procedures, an independent check is worthwhile in safety critical contexts.
It takes time and money to define and work with a detailed project plan. Not having a proper plan is likely to be expensive. Figure 2 is an indicative plot of cost of a project against cost of planning it.

The cost of planning a project includes carrying out risk assessments, predicting outcomes, working with a detailed plans, ensuring that staff are competent, etc.

If the level of resource for planning the project is too low, i.e. in Sector A, the risk of unsatisfactory outcomes is high, the costs are likely to escalate, expensive reworking may be required, numerous errors may arise and the project may fail completely. In Sector C, a project can be over-engineered; the levels of staffing for management can be too high, decision-making processes take too long, the costs can rise.

The target is to be in Sector B; to optimise the amount of resource allocated to planning. This should be a project goal.

A typical process for planning a project is:
- Break down the project into units of work in the form of sub-projects, tasks, subtasks.
- Estimate the time it will take to complete each unit of work.
- Define the precedence of the tasks, i.e. decide which tasks can be carried out in parallel and which need to be handled consecutively.
- Identify any lead times needed for starting the tasks – e.g. where there is a need to wait for information to be delivered.
- Identify critical tasks, i.e. those which if not done on time will cause delay in the overall completion.
- Draw up a chart which shows when each task should start and finish. Leave some slack in the system to allow for unforeseen circumstances.
- Record progress and update the task times as the work proceeds.

It is good practice to address the most difficult tasks at the earliest practical stage since they may control the success of the project.
A major principle for engineered solutions is that: if something can be quantified, it should be. Another way of expressing this is to say that, wherever appropriate, the power of mathematics and science should be used.

**Predictive models**

One of the great intellectual achievements of the human mind is to use mathematics and science to predict the behaviour of things leading to, for example:

- improvement in the safety of structures such as bridges (Box 12, page 14)
- improvement in the design of machinery (Box 2, page 5)
- ability to design electrical circuits including microchips
- being able to estimate costs more accurately

In the past the main problem with complex predictive models was doing the calculations. The situation now has completely changed because computers do that. Now the problems are focused on deciding whether or not a model is fit for purpose and whether it has been correctly implemented rather than on checking that the arithmetic is correct.

**Data gathering, performance monitoring**

W Deming stated that ‘Without data you are just another person with an opinion.’ A fundamental principle in engineered activities is that, where practical, data should be gathered and used to seek to avoid making errors, to identify faults and to improve products and processes.

**Statistics**

Complex problems normally involve uncertainty. Statistical theory can be viewed as a means of quantifying uncertainty. If data is available, use of statistical analysis should be considered. For example public health (Box 13) and medical studies (Box 8, page 9) rely heavily on statistics.

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**BOX 13 Public Health: John Snow, the Broad Street pump**

In 1854 a serious outbreak of cholera occurred in London. A physician, John Snow, plotted – see diagram – the incidence of deaths due to the diseases that showed a strong correlation between incidences of the disease and the position of a pump in Broad Street, London. This led to a conclusion that the source of the disease was in the water that people were drinking. This was the dawn of public health measures that have made major contributions to health.

![Incidence of deaths due to cholera](By John Snow [Public domain], via Wikimedia Commons)
Communication, collaboration, leadership

Since complex problem solving is normally carried out in teams, often interdisciplinary teams, it seems unnecessary to state that good communication, collaboration and leadership are essential ingredients of engineered solutions. Issues that need to be addressed include:

- Appropriate treatment of other people needs to be adopted.
- Ability to work with people from other disciplines needs to be developed.
- All involved need to understand the principles of good leadership.
- In engineered contexts, a clear and concise style of writing should be adopted. The efficacy of developing such a style does not seem to be widely appreciated.
- Where graphics are needed, competent use of sketching, drawing, working with 3D graphics, working with images, etc. is needed.

Learning to engineer

Having to address problems that do not have clear solutions and involve uncertainty and risk is part of the human condition. The social and environmental problems that we face are all in this category. Conventional education seeks to impart an understanding of these problems but tends not to provide practice in addressing them in an engineered mode.

There would be significant benefits to society if:

- All learners were introduced to the principles of engineered problem solving.
- Education initiated a lifelong development of ability to solve complex problems.

The core strategy for achieving this aim is to have a suitable proportion of project work in the curriculum at schools, at colleges and at universities. In project work, students, normally working in groups, should be required to respond to a brief that relates to a real-world problem, not necessarily in an engineering context. They should learn to adopt the principles discussed in this paper.

Barriers to doing this include:

1. Programmes that focus on problem solving are often deemed to have failed because learners are judged to perform less well in tests for knowledge.

2. It is not easy to decide what should be removed from a curriculum so that engineered project work can be included.

3. Some learners are very uncomfortable in an open-ended problem-solving environment. They can find it a negative experience.

4. Teachers tend not to be experienced in the use of engineered solution strategies.

On the other hand:

5. It is unrealistic to suggest that knowledge acquisition should be the sole objective of education and that skill in complex problem solving and other educational objectives should be left till later in life. Curricula that balance the competing needs of education need to be devised.

6. While there are complex issues in the underlying theories for say quantification, learning about the principles of engineered solutions is not complex. It is not difficult for teachers to help learners to adopt an ethos for solving complex problems.

7. While less able students may struggle to be effective in working with engineered solutions, that must not prevent the more able students from developing skills that are nationally and internationally important.
Conclusion

It seems to me that there has been a revolution in global thinking. In stark contrast to what happened in the past, at the time of writing (2017), while there are some civil wars, there are no wars between nation states. Countries are now more focused on solving global environmental and social problems concerned with food, water, energy, climate. This is a very promising trend but a second revolution in thinking is needed to address such problems. Reliance on intuition to solve complex problems should be replaced by the engineered approach outlined in this paper. Doing this will not guarantee that all complex problems will be solved, but it will guarantee that the risk of making bad decisions will be significantly reduced.