IES
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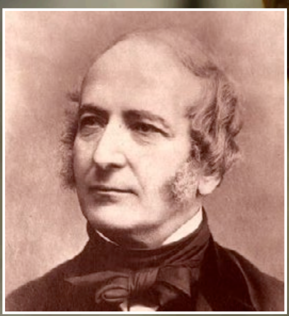
Manufacturing Matters



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The editorial team for this edition was: Iain MacLeod, Laura Clow, Dick Philbrick and Andy Pearson.

Science in engineering
Engineering beyond science

In his paper *Why society needs engineers*, Peter Noble states that: "In the history of humankind, engineering and technology most often precede science." Prior to the 19^{th} century, engineers used technologies involving mathematics, measurement, data, etc. but there were few theories that could predict physical behaviour. I refer to such technology as *engineering mechanics*. While Isaac Newton introduced the mechanics of force in the 17^{th} century, it was not until the 19^{th} century that engineering mechanics started to 'take off'. It is remarkable that, in the second decade of that century, foundations were laid for three of the most important branches of engineering mechanics: in 1824, Sadi Carnot introduced the concept of a thermodynamic cycle; in 1826, Louis Navier published his *Leçons* that represented the introduction of the use of mechanics in the design of structures; in 1827 Georg Ohm published a paper on the mathematics of an electric circuit.

Use of engineering mechanics developed rapidly in the 19^{th} century and was given a major boost in mid 20^{th} century by the use of digital computers that have allowed engineers to do calculations of a size and complexity that were previously unattainable. This is well illustrated in Erkan Oterkus' paper on the *Science of Cracks: Fracture mechanics*. This branch of mechanics also was also introduced in the early part of the 19^{th} century. The development of the use of mechanics by engineers and scientists has been of inestimable value to society and represents one of the great achievements of the human intellect. However, of course, science does not answer all questions: it is just one of the technologies used by engineers.

Peter Noble emphasises the importance of professional engineers in society – and his case for the importance of maritime engineering is well made. In my paper on *System planning for government and education,* I suggest that the fundamental objective in engineering is the 'methodical achievement of outcomes in situations of complex uncertainty' and that (a) the need for such an approach is widespread in society, (b) such achievement is not confined to engineering but that (c) the processes used in system planning need to be better understood across the spectrum of human endeavour – particularly by our political leaders.

Dick Philbrick's paper on *Manufacturing Matters* clearly demonstrates his passion for a better understanding of the importance of UK manufacturing. His descriptions of the difficulties involved in developing equipment for foundries well illustrate the problems involved in managing uncertainty and coping with what 'you do not know'.

The Scottish expression 'lad o' pairts' relates to a talented person with wide-ranging interests – possibly touched by genius. Such people are important in the development of any discipline. It is clear from John Mellis' paper on *Great ships, solitary waves and solitons* that John Scott Russell was such a person: engineer, naval architect, businessman, scientist (at the age of 24 he rejected an invitation to apply for appointment to the Chair of Natural Philosophy at Edinburgh University). Is having such a range of abilities a rare occurrence or could it be that there are many polymaths whose worth is not recognised? Education should encourage the development of such competence.

Use of data is another important techology in engineering. In his paper on *Energy benchmarking*, Andy Pearson uses a Specific Energy Consumption metric for cold stores based on the energy rate per unit of cooled volume. It seems to me that this metric could be useful for assessing energy use in the heating of buildings.

Iain MacLeod

IES Journal of Engineering, Vol 161, 2022, Paper 1706
The Institution of Engineers in Scotland

Presidential Address Manufacturing Matters

Dick Philbrick

Dick Philbrick is a former managing director and co-founder of Clansman Dynamics. He was installed as the 86th IES President in September 2022

Abstract

I was distracted from a career as an engineer, but not as a manufacturer. I could not help but compare how farmers and their farm workers, in the Suffolk village where I was born, collaborated in hard work with the poor management, lousy productivity and working relations of the shipyard where I trained. There were numerous strikes, sabotage and demarcation disputes between unions, but excellent craft skills in the shipyard. I sought answers to the demise of UK manufacturing in other industries and countries.
In this article I:

1. describe the avoidable collapse of UK manufacturing.
2. trace, from personal experience, the silent death of Europe's then largest mobile crane maker.
3. describe commercial lessons learned in starting an engineering company.
4. explain how many of the technical mistakes we made in the start-up might have been avoided.
5. argue the case for how we can achieve collaborative working.

Dick Philbrick

20th Century Collapse in UK Manufacturing And Its Consequences

Peter Drucker, the management guru, argued that British manufacturing could have remained great after WW2. He believed the UK had a strong position in anti-biotics, jet engines, body scanners, even computers were a British invention, and we still had our traditional industries like shipbuilding and vehicle manufacture. This optimism was undone by 'short termism', industrial disputes, a wildly fluctuating currency; all a dreadful climate for serious manufacturing.

The 1970's was an unhappy period throughout British industry as the post WW2 consensus broke down and the easy flow of orders ceased. UK shipyards were overwhelmed with orders after 1945, building half the world's merchant ships, and simply continued with 'craft based' methods while other countries invested[1] in new methods that produced a 40% productivity advantage by the 1970's. Of 246 all-welded ships built in the world, above a certain size, between 1946-49, only 7 were made in the UK. Japan had overtaken the UK in shipbuilding by 1956. A UK industrial crisis was brewing.

399,000 of the 523,000 cars made in the UK in 1950 were sold abroad which amounted to half of all cars exported worldwide. Competition was limited then. The car industry became blighted with unattractive and unreliable designs and then struggled with poor industrial relations with many working days lost.

Younger readers may find the level of industrial strife of the 1970's hard to envisage. Derek Robinson, known to the press as Red Robbo, was union convenor at the Oxford Cowley car plant that was then BL (British Leyland, now

1 Weldon D (2022) *200 Years of Muddling Through: The surprising story of Britain's economy from boom to bust and back again*, Abacus

BMW producing the Mini). His despairing sentence in one interview, "*But that is what we had to make*," (referring to the unsuccessful Morris Marina, Allegro etc) neatly encapsulates so much that was wrong with the management of British industry. Robinson claimed, "*workers, were progressively demoralised by knowing that the cars that they were producing were mostly wrong for the market and often sub-standard. Worse, we also knew that in the opinion of management, our views would be worthless and never be listened to*."

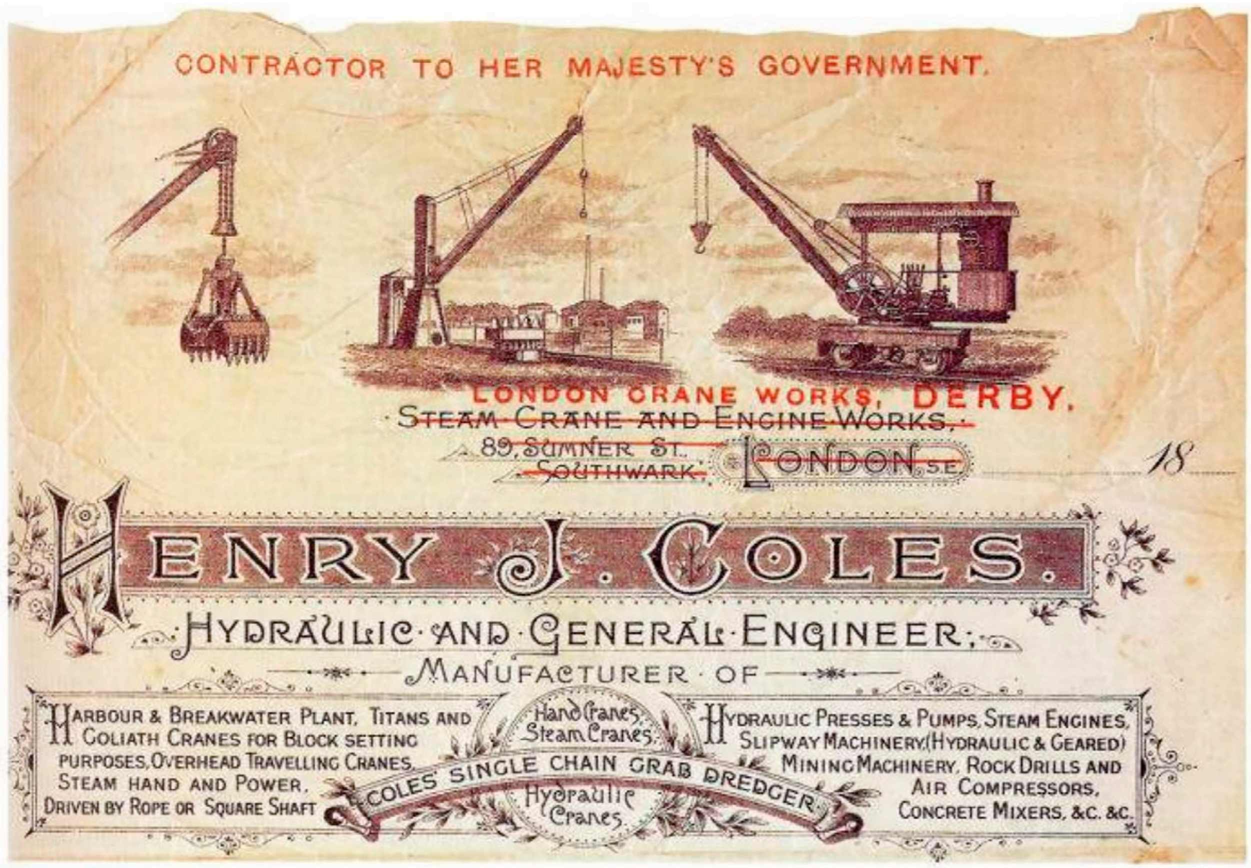
The placing of an MI5 mole in the BL factory's Trade Union committee, illustrates the serious concern of some in government.

We have to make stuff and we have to export it, if we are to achieve a balance of trade. In the 1970's we faced the strongest international competition since the start of the industrial revolution and had lost our captive markets in the colonies. It was thought by some politicians that we could live off our service sector, while employment in manufacturing declined, as it had in agriculture (now 1% of employment). There is another consequence of this decline, which is only now being fully understood. Manufacturing provides a band of skilled and well-paid jobs, that cannot so easily exist in the service sector. Germany has three times the numbers employed in manufacturing as the UK. The result is a less stable economy and greater inequality in UK society. We have many on low and high incomes compared to other developed countries, but many fewer with middle incomes, as manufacturing has shrunk.

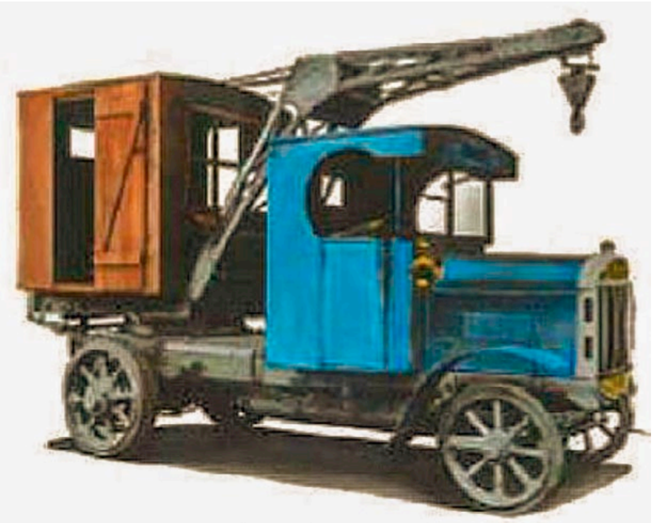
German industry, with its miraculous recovery after WW2, was often cited as a great example that we could learn from. I went to Germany with the pretentious aims, for a 23 year old, to learn the language and experience how they managed their companies, while taking any low-grade job I could get. Germany has a system of 'Mitbestimmung' ('Codetermination') in their larger companies, whereby trade unions sit on company Boards and are directly exposed to issues affecting the business. I met nobody in Germany in 1974 who was aware of the system and with the impetuousness of youth, concluded that imposing changes in U.K. like 'Mitbestimmung' would not foster the collaboration we desperately need. I still believe we need something more radical.

Rapid Decline and Fall of Europe's Largest Crane Maker

I am not an academic and this liberates me to describe some of the lessons learned from my brutal experience at Coles Cranes (maker of mobile cranes) in a more anecdotal, but hopefully still useful way. It is not just shipbuilding, motor bikes and power generation manufacture that declined.



The story of Coles Cranes shows a company that grew from solid engineering foundations in 1878 to become, post WW2, the largest European mobile crane maker,



employing 3,500 at its peak. Henry Coles was a significant contributor to the proceedings of what are now IMechE and ICE.

A large order from the Air Ministry triggered rapid growth in 1937 which continued till 1945. Coles Cranes cemented its reputation with a range of reliable diesel-electric powered cranes, rejoicing under names like Adonis, Aeneas… (The names from Greco-Roman mythology perhaps indicate something of the classical education of later generations of directors of the family owned company!)

Coles Aeneas crane in a shipyard

Coles exported widely but not to a number of key markets like USA and Japan. Today's leading mobile crane maker, Liebherr, established sales in Virginia, USA in 1970 and in Yokohama, Japan in 1983 – Coles achieved neither. A capital equipment manufacturer needs to export widely to gain production volumes and more consistent sales. Liebherr remains family owned, with a vast product range, in Germany, having overtaken Coles by 1980 from its 1949 start.

Coles bought a number of related companies until financial troubles loomed in 1972 when it was hurriedly sold to Acrow, maker of the simple Acrow prop – owned by wealthy, Swiss born, Bill de Vijier, in order to escape the clutches of asset stripper Slater Walker; only to be sold later to American competitor Grove Cranes whose owner, Walter Kidde Inc. asset stripped and closed Coles in 1997.

Liebherr's great leap in the crane market came in the early 1980's when Russia tendered for 270 cranes for a new Siberian pipeline. Cranes would have to operate at -50˚C, be made of special steels, have all wheel drive. It became a duel between Coles and Liebherr with negotiations lasting months and switching from Moscow to the Russian Consulate in Cologne and back, till Coles was abruptly excluded. Coles' prospects were snuffed out as if a candle, as Chancellor Helmut Schmidt agreed to buy Russian gas if the Russians bought German cranes and excavators. Mrs Thatcher did not play that game. Liebherr's specially developed 8 wheel drive crane is still in production. Coles never recovered their lead. I learned that politics could severely impact business.

America appears to make that connection between politics and business rather more pragmatically than Britain. We rigidly followed the monetarist wisdom of the Hayek and Friedman/Chicago School that the market would somehow always determine the best course. We were blind to the fact that in the USA, i-pads, pods and phones, touch screens, hard drives, voice recognition, etc had their roots in risky, federally funded projects[2]. Our governments and civil servants are frightened by risk and look for short term returns. Too often projects are abandoned after a short term reappraisal of cost; like the 1 mile of channel tunnel bored into the Kent chalk in 1974, like the TSR-2 fighter aircraft.

Salesmanship is a rather less accepted skill in Britain than in the USA. There is a disdain in society for salesmanship captured in the snobbish lines of a John Betjeman poem:

I am a young executive. No cuffs than mine are cleaner;
I have a Slimline brief-case and I use the firm's Cortina

2 Mazzucato M (2013) *The Entrepreneurial State: Debunking Public v. Private Sector Myths*, Anthem Press

Technical stuff must be sold by technical people. Engineers have a squeamishness about accepting a sales role. Brilliant design and manufacture still needs selling. Certainly it is useful to wine and dine customers, like the Coles salesman here with Haile Selassie's tiger cub, but

Coles salesman with one of Emperor Haile Selassie's tiger cubs

I have observed the most effective 'order-getters' for product selling have combined their integrity with a deep engineering expertise. Without the latter they have simply failed, no matter how good their schmoozing skills. Engineers complain when accountants run their companies. Sales experience, meeting a customer directly, understanding their needs, puts engineers in a much stronger position to lead a company or manage their team.

Coles Cranes understood the need for linguists. Language skills in the UK are notoriously poor in relation to all other European countries. Only a quarter of the world has any knowledge of English and as Nelson Mandela famously said, *"If you talk to a man in a language he understands, that goes to his head. If you talk to him in his language, that goes to his heart."* In reality language skills will allow the salesman to engage with a wider range of customers' personnel, like our German and Italian competitors. We believe Clansman would not have survived beyond a very difficult start-up, without our ability to communicate in French, German and Italian. Senior university personnel claim their engineering students have the opportunity to learn a language – where are those engineering students? Calling foreign languages a soft skill detracts from their importance. Business needs to press for language skills. Unless universities demand them, schools will not teach them. It is a simple chain with missing links. The diagram at the bottom of the page shows the 90% decline in German and 75% in French at Scottish secondary schools from 2002-19.

Coles celebrated 100 years of crane making in 1978. The chairman, Bill de Vijier's, introduction to the Centenary Year Book summarised what I believe manufacturers need to understand and practice:

> Inventiveness, quality, training, exporting—these were the fundamentals on which Henry Coles built. In looking to Coles' second century, I would personally emphasise the necessity of good human relations, the recognition of the essential human dignity of the individual. Today we are in the forefront of technology in our field of operations, investing and marketing aggressively, exporting and enjoying satisfactory labour relations. These are the vital factors on which past successes have been based and on which our future depends.
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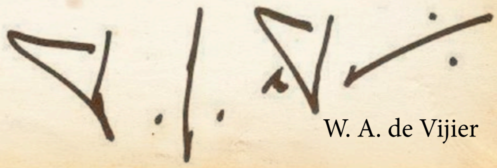
> 
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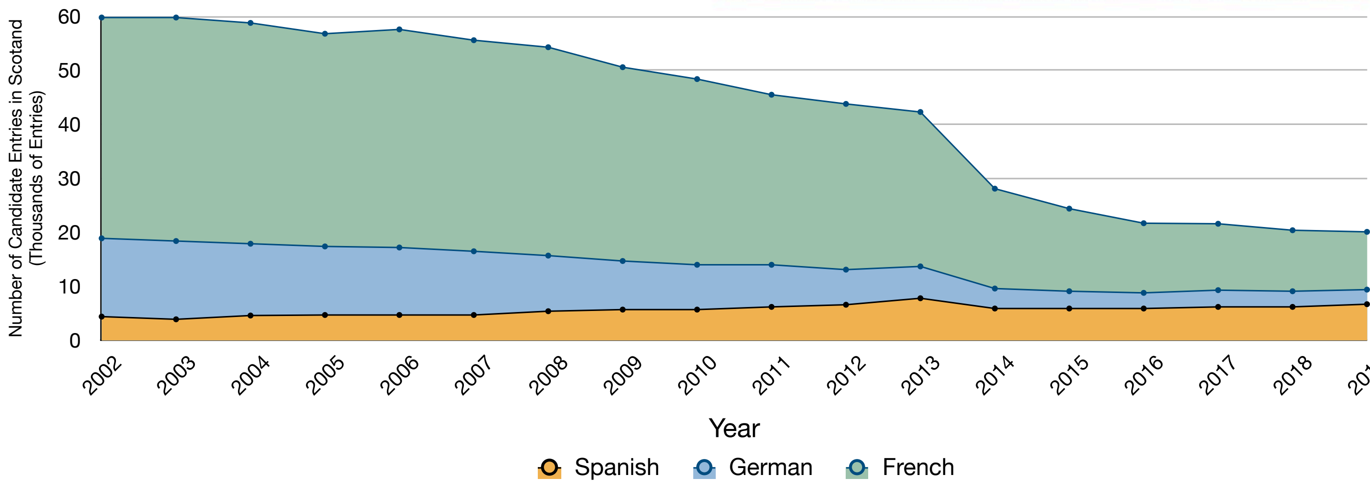
> W. A. de Vijier



School pupil numbers in Scotland learning (SQF3-5) foreign languages

Ref https://dera.ioe.ac.uk/34552/1/Recent_trends_in_modern_foreign_language_exam_entries_in_anglophone_countries_-_FINAL65573.pdf

Coles 80/88T truck crane

Coles Husky 45/50 rough terrain crane

Coles Centurion

'*Enjoying satisfactory labour relations*' was marketing-wash for truly awful. Remember this was 1970's Britain. De Vijier, unlike his directors, had the foreigners' classless ability to mingle, cigar chomping, amongst Coles' then 2,600 Sunderland employees, who might have been preparing for yet another mass meeting. They accepted him, even if by 1982 numbers had been reduced to 1,000, building the same volume of cranes. The Coles story follows a similar pattern to the decline of UK shipbuilding. I had, for example, no formal training of any kind with them!

de Vijier's emphasis on the '*necessity of good human relations*' is telling. Relations were appalling and no matter how good the innovation, engineering, investment and salesmanship, poor relations will lead to poor productivity and financial results and probably poor quality. It did. In 1979, 28 nightshift painters were sacked for sleeping on comfortably arranged mattresses in the attic above the paint shop; a 10 day strike and factory occupation ensued.

In contrast Coles engineering was strong and innovative. Excellent cranes, like the Coles 80/88T, were boldly developed at 4 UK sites, but without a control of design for production. Part numbers mushroomed incontinently to 80,000. Rough terrain cranes had a good reputation and Coles made the world's largest mobile crane in 1962 (Coles Centurion).

Coles did many things right. They had excellent design skills, continuous innovation, an energetic sales force, well developed marketing. External factors such as rampant UK inflation up to 25% in the 1970's and wild exchange rate variations made exporting difficult (for example the £1 exchange rate varied from $1.50 to $2.50 following the 1973 oil crisis), but poor industrial relations was its undoing. There was no Geddes report[3] for the UK's crane industry which died silently. There are now no mobile crane makers in Britain.

Awareness of Serious Industrial Relations Problems in IESIS Articles

It is instructive to look back at IES (then IESIS – The Institution of Engineers and Shipbuilders in Scotland) journals of the 1960's and 70's. There is a focus on issues to do with people management, mostly in relation to the shipyards. Even Sean Connery was attracted to the problem and directed a film 'the Bowler and the Bunnet' about the Fairfields experiment – an attempt to create collaboration between managers, trade unions and shareholders.

3 HMSO (1996) *The Geddes Report on the Shipbuilding Industry*

The chairman of Fairfields, Sir Iain Stewart in a 1961 paper to IESIS[4], wrote about how the 1930's had been an era of '*unbounded poverty and untrammelled wealth…fears of unemployment… such memories lurk in the minds of union leaders and members*.' Stewart recognised the divide that existed and understood that the nub of the problem was an absence of communication between the 2 sides. He held a series of meetings with all employees in the Govan Lyceum, where they tried to explain why managers and managed must collaborate. His 6th point was:

> *"…in large measure we should gradually get rid of the idea that there are two sides in industry and direct both forces towards the common objective of increased profits. Such unanimity of outlook would not only help to lubricate the machinery for settling grievances and for arbitration, but would curtail the basic ingredients of conflict."*

Noble words but without useful impact as Prof. Alexander in IESIS Journal of 1964 wrote three years later:

> *"There is a disturbing absence of any sense of industrial purpose among the shipyard workforce".*

TL Johnson[5], wrote about 'Industrial Democracy' which had been discussed during the heady post WW2 period. He recognised the importance of workers participation in management. The Donovan Commission in 1968 thought this could be achieved through collective bargaining which was supported by the TUC – something we have heard much less about in recent times because of the decline in the power of unions. In reality some token Joint Consultative Committees were set up in larger companies, but many were restricted to topics of Health, Safety and Welfare. That does little for a workforces' understanding of the pressures on their business. The TUC very reasonably argued that meaningful negotiations could only happen if unions were in possession of the commercial facts.

Pat Lowry, (British Leyland Motor Cars – Industrial Relations Director) who was invited to share motor industry experience in the IESIS Marlowe lecture of 1974[6], observed that parents spend much time bringing up their children to behave responsibly, to persevere and to look ahead to the future and then, as teenagers in industry, they are treated like children, with decisions made for them. If people are treated as though they are responsible then they will behave responsibly. He was cautious about the fashionable ideas at the time of unions having a seat in the Boardroom, explaining that it is very hard for a union representative to sell anything which is negative for a single member. He seemed to despair at the impact of the burgeoning Welfare State providing improved benefits '*which allowed the employee to obstruct (*i.e. with less loss of income*)*.' The Redundancy Payments Act did not come in till 1964 for example – before that life was significantly tougher for a redundant employee.

The problem of a lack of collaboration in our industries was recognised but not solved. I have long favoured more radical measures as I will explain below.

Clansman Dynamics – Lessons from a Scottish Start-up

Clansman was established in 1994 by two Scottish engineers, a German and myself, all then working for either Scottish or German specialist material handling manufacturers. Surely if we made a range of products that avoided all the faults of competitors' machines, we could conquer the niche market in foundries and forges worldwide? Surely with the lessons we had each learned in almost 20 years of manufacturing with different companies we were equipped to start our own company?

We submitted our plan many times to providers of finance without success. They doubted a little company, making relatively large and expensive machines, could survive the inevitable lumpy cash flow, or could establish export arrangements worldwide.

In reality there was so much we didn't know that we didn't know. We learned many lessons the hard way, as I shall describe.

Almost 30 years after the start-up we now understand much better the words of Mausuru Ibuka, a former chairman of Sony:

> *'If the weight of invention or discovery for a product is 1, then the weight to bring it to actual development is 10, and the weight to produce and market it is 100. And you must adapt that product as the market changes.'*

4 Stewart I M (1961) *In search of economic stability and security,* IESIS Transactions, 10-50, https://library.engineers.scot/files/original/0208d61be7ced9a6936059133585bf6e.pdf

5 Johnston T L (1968) *Industrial Democracy Revisited*, IESIS Transactions, Vol 112, 1-38, https://library.engineers.scot/files/original/c0a8c829e43f3048c08ab4d7af537dcb.pdf

6 Lowry P (1974) *Willingly to work*, IESIS Transactions, Vol 118, 3-23, https://library.engineers.scot/files/original/eee1b9817e70998603a9d84e188d071b.pdf

Wise words. Every aspect, both internal and external, of a manufacturing company's business has to be in order or it will eventually fail. The demise of Coles Cranes had shown how innovative design, energetic selling and good craft skills were insufficient for long term success.

Knowing What You Don't Know

It's an unhelpful statement in that you will never know what you didn't know until it's maybe too late, but there is a way to minimise disasters that arise when solving indeterminate problems. A classic example of what results when your brilliant team does not embrace a sufficiently wide range of skills and disciplines was failure to spot the 9/11 terrorist actions – there was no Muslim voice among the narrow, but brilliant, hard working CIA team of white Anglo-Saxon, male, Protestant, Ivy League university types[7]. They should have had the widest possible range of knowledge and experience around their meeting table. It is the same for engineering.

Selling Reliability… and dirty tricks

Clansman's goal was to produce the most reliable and comfortable manipulator. Reliability and greater operator comfort is a dull message to convey for a salesman. It might have been easier to sell our machines if they had been faster or had more axes of movement, but that was not what the market needed. We had not anticipated any difficulty in convincing customers, that our very different engineering would undoubtedly produce a more reliable performance. To the sceptical foundryman our machines looked the same as competitors. For them a bearing was a bearing, regardless of whether it had balls, needles, rollers or nothing between its rotating surfaces. We needed references to prove our claims.

We were blind to 'dirty tricks' that might be played by competitors. It never crossed our engineering-focussed minds. Competitors obtained a photo of myself (supposedly the managing director), armed with a large sledge hammer struggling to drive in a reluctant shaft. We had increased our warranty from 12 to 30 months on 3 shifts. In retaliation the competitors' salesmen tabled that photo (obtained by 2 supposed lovers in a parked car) and a copy of our balance sheet from Companies House with a helpful hint, that we might not be there to honour the warranty.

A German foundry, with 6 of our competitors' machines, indicated they would buy a machine at a very reduced price if a 1 week's trial was successful. We fell for that too. The operator's manual and parts list, which they insisted be supplied with the manipulator, 'mysteriously' disappeared after our installation engineer had left. The machine was sent back. Did a German competitor pay for them to do the trial?!

We were insufficiently savvy; too obsessed technically with the problems of achieving the best design to think sideways.

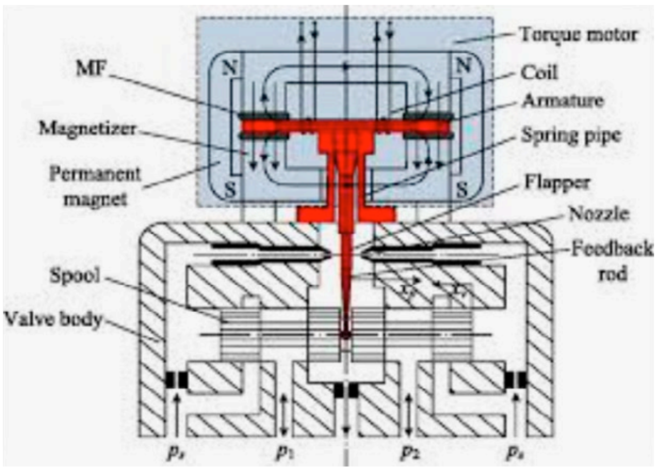
Patenting

Our investors pressed for us to obtain patents. There is a certain kudos in patenting. We established 2 patents, but when in year 3 we could not afford to continue with the patenting fees, the patents lapsed and our competitors knew what to copy. Patenting for niche products, which by definition will be sold in low volumes, seemed foolish.

Servo valve response

Clansman makes manipulators, robots and a number of related tools. We wisely decided to glue 50 strain gauges to the structure of the first machine, to check design calculations and computer models.

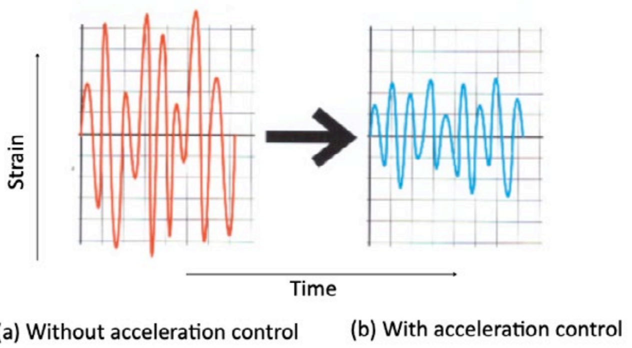
The chief designer, who had never worked with servo valves before, blanched when, even with no payload, he saw the first 'spikey' plots of strain on the chart plotter. We had a range of engineering disciplines around our meeting table, but nobody had experience in all of them; the mechanical and control engineers were in their separate silos! The designer had made a brilliant fatigue analysis but had not grasped the 'instantaneous' response of servo valves.



Section of a servo valve

7 Syed M (2020) *Rebel ideas*, John Murray

The tiny electric motor that moves the spool within the servo valve has negligible inertia and can change direction instantly, whereas the moving structure of the machine has high inertia and the hydraulic cylinders apply the same forces whether loaded or unloaded; only the rate of acceleration changes. A revised fatigue analysis revealed that the structures could not cope with those stress spikes on every cycle. Luckily there was an easy and practical solution.

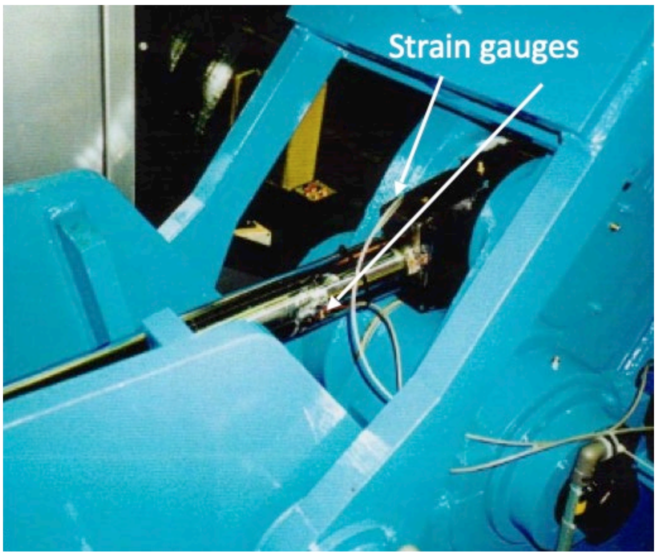


Acceleration control to 'smooth' stress and oil pressure spikes

The analogue control card was modified to smooth the rate of change of acceleration and we escaped the problem. We resolved to strain gauge test all new structures.

Hydraulic versus electric drive for robots

Our next problem was more difficult. Our niche in the market is to produce high capacity, long reach machines. Hydraulic actuators can apply more torque and are cheaper and lighter than electric ones. The operator of a 6 axis, manually operated telechiric-manipulator determines the position of the grippers as the Slave Arm (the working arm)



Strain gauging of hydraulic cylinder cushion performance

mimics the movements of the operator's Master Control Arm in the cabin; in other words whatever movement is made by the operator's hand (Master Arm) is copied by the manipulator (the Slave arm). The operator learns to compensate and anticipate for any overshoot or drift. If it is a robot there is no operator to judge this compensation. Early robots were all hydraulic, which is now the extreme exception. There is good reason for the switch from servo hydraulic to servo electric drives as we discovered.

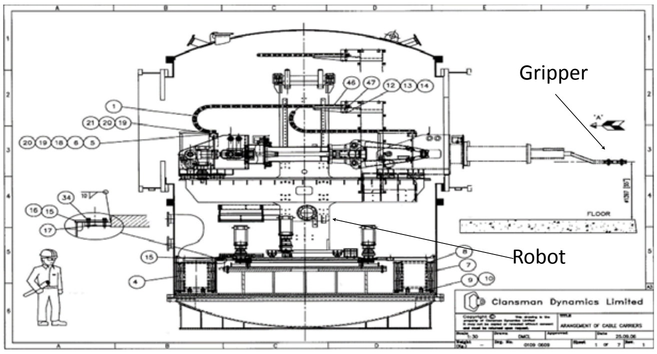
For best repeatability and minimal 'settling times' (i.e time required to achieve a specified range around a commanded position) a stiff, high natural frequency structure is required **and** electric drives.

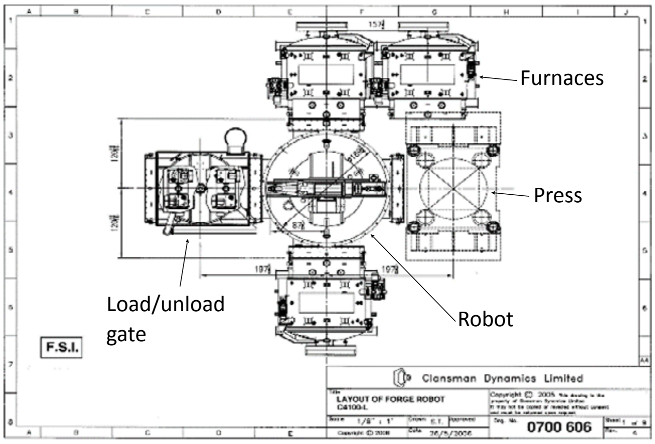
We had successfully made forging robots with 2 tonnes capacity @ 6 metres reach and repeatability of +/– 2mm. This repeatability could be achieved with hydraulic cylinders for linear axes and twin hydraulic motor, anti-backlash drives (copied from rotating radio telescopes where twin motors are controlled to oppose each other, to remove pinion/gear backlash issues) for rotating axes. Conditions in a forge are rather different from a manufacturer's factory. Furnace doors open emitting heat; spring follows winter; temperatures change. Hydraulic oil changes in viscosity with temperature. Servo valves despite 3 microns filtration can become slowly contaminated and 'drift.' Seals in hydraulic actuators generate static friction known as 'stiction', which will vary with temperature and wear. We resolved to investigate electric drives for more precise handling.

Electric drives in a vacuum

We made the leap to servo electric drives with brushless motors. Performance results were spectacularly good. The robots were massive, heavy, stiff and very accurate. An American forge supplier had a contract from an aerospace forge for a hydraulic robot to handle 1 tonne @ 8 metres radius, +/– 1mm repeatability and, after starting design work, had determined that this was unlikely to be achieved. We were emboldened after reading the literature and our successes with twin motor, anti-backlash drives to accept their order to produce an electric robot for the task. If successful it would provide a high status reference in the USA forging industry, which was a strategic target market.

Isothermal forging (where die and forging are at similar temperatures to minimise thermal shock as the forging hits the die) in a vacuum offers certain metallurgical advantages. The surface of the billet will not oxidise when it is transferred at, maybe, 1350°C, from furnace to hydraulic press, which reduces the risks of inclusions (i.e when an oxidised surface is forged into the billet, resulting

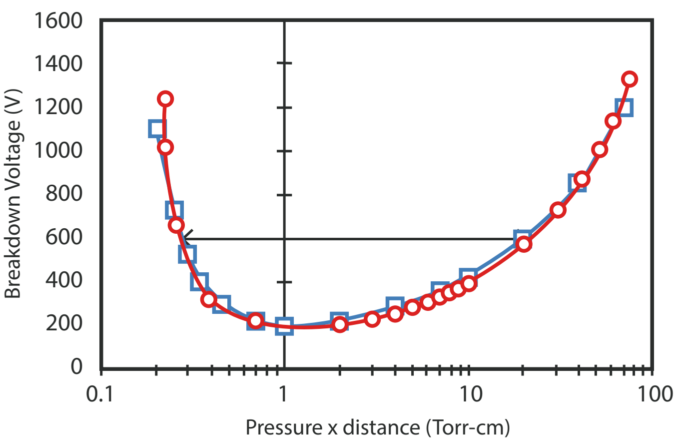




Drawings of cell with robot in a vacuum chamber.

in a crack). The volume of vacuum that would need to be pulled and maintained could be reduced significantly if the forging press did not require side rams to centralise the billet in the die, because the repeatability of +/– 1mm would render them unnecessary. The drawing shows the approximate layout of the cell with a 6 metres diameter and height vacuum chamber, and a Scotsman for scale.

We had no experience of working with machines in a vacuum. The corona effect presents the engineer with a difficult problem. Air is an excellent insulator – an industrial level of vacuum pressure is not. *Corona Discharge (also known as the Corona Effect) is an electrical discharge*

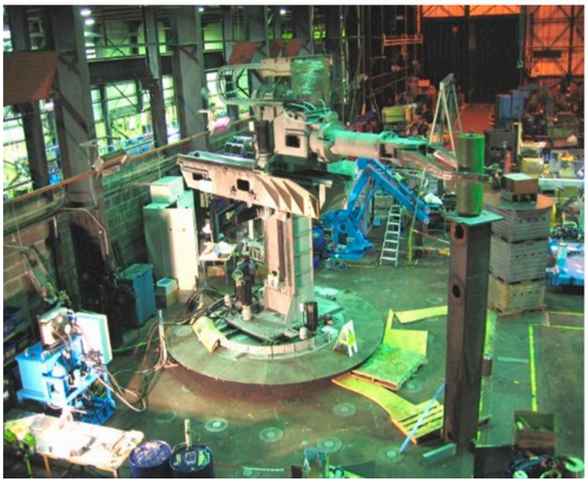


Paschen's Curve

caused by the ionization of a fluid, such as air, surrounding a conductor that is electrically charged… Corona discharge can cause an audible hissing or cracking noise as it ionizes the air around the conductors. Friedrich Paschen discovered empirically in 1889 that arcing between electrodes was related to pressure, voltage and distance between electrodes and produced a curve:

We required electric servo motors and our usual twin anti-backlash drives to achieve accuracy. For the avoidance of outgassing and the Corona discharge problems (think of strip lights which use the Corona Effect) we required to be 'comfortably below the curve'. Our motors require up to 600 volts for the servo drives. If the vacuum level could be guaranteed to remain below 0.2 Torr-cm then they could be used. However even if this level could be guaranteed there would always be the risk of leaks and incorrect operation of the robot or the chamber; standard motors meant operating at max. 100 volts to survive at all pressure levels. This would cripple the performance of the motors. The solution proposed by German and

CLANSMAN DYNAMICS



1000 kgs Vacuum Robot on Test

Italian motor manufacturers was to pot the windings of the motors in resin, to prevent arcing. The Italians promised 8 weeks delivery and the Germans 14. Both were supremely confident of their solutions. We went with the Italians and they delivered 16 weeks later!

The water-cooled motors worked well in factory tests and the customer appeared for a factory acceptance.

The robot was minutely inspected. Dimensions verified. Water cooling and hydraulics for the gripper were checked through each joint of the robot. We had to move the billet 20 times between 2 platforms, simulating pick up from the furnace and placing in the press within the required time cycle, positioning the billet against a clock gauge. A repeatability of +/– 0.1mm was achieved. There were sighs of relief, followed by an excellent celebratory meal in a Glasgow restaurant. How could there be a problem after such an impressive demonstration? Again there was a nasty surprise that could have been anticipated with better consultation.

One by one the motors caught fire when operating in the customers vacuum chamber as they arced internally.

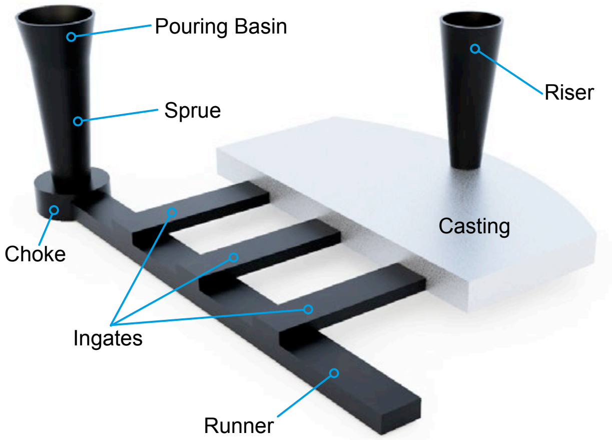
The $30m isothermal forging project ground to a halt and our tenacious commissioning engineer was severely delayed at site in USA. It was the end of July before we established, with help from Turin University, that the motors should have been **potted in a vacuum while being vibrated** so that all air bubbles, in the resin on the windings, were removed. Imagine the 3-way conversation between USA, Italy and Scotland on a tense Sunday morning call:

> *"We need the motors modified quickly," from the American VP.*
> *"It's not possible to do anything till September," from the Italian motor maker.*
> *"Why not?"*
> *"Italy is closed. We are on the beach in August for 4 weeks." There was a very long silence before the American VP exploded.*

We thought we had done our homework specifying motors for operation in the worst vacuum conditions, but had not visited potential suppliers to check their experience with large motors in an *industrial level vacuum*. Our consultant's knowledge was limited. We had not understood what 'potting' involved and the Italians had talked a good game. We should have tested the motors under load in a vacuum – the very conditions they were specially made to survive in! We didn't find someone who had used an electric servo motor in a low grade industry level vacuum. We didn't know what we didn't know. The next, very successful project had motors from Germany that were tested under load in a vacuum!

Why not design electric, manually controlled manipulators?

Once again our enthusiasm to innovate had got the better of us. If electric drives were easier to maintain, more reliable, better for servo mismatch, more precise, cleaner… etc., then surely we should convert our range of hydraulic manipulators to electric drives and stake a large lead against our competitors. By chance these thoughts coincided with the opportunity to design a special robot (not manipulator)

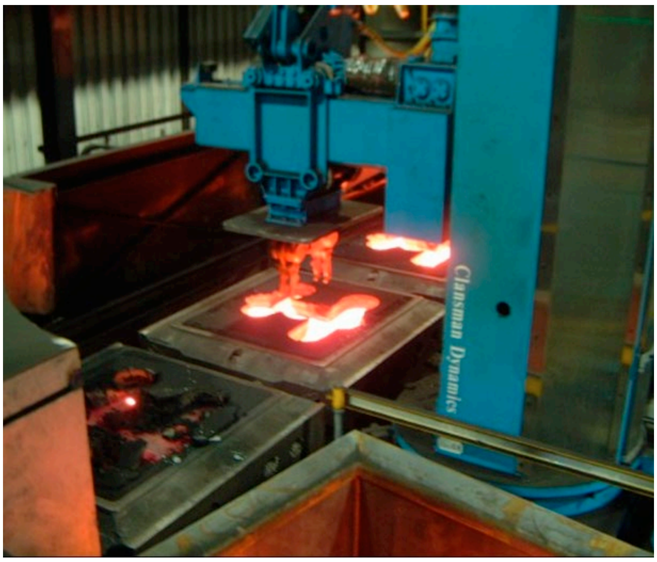


Casting (white) with gating and riser (black).

for an important German foundry. Once again the factory tests were successful.

The robot's job was to remove the gating system, (see drawing above), which can amount to almost 20% of the cast weight from the casting while it was in a semi-molten state.

The gating, still at c. 700°C would be fed back to the furnace for remelting, saving energy. We had a world beating prototype – surely? We estimated and then tested the force with which the gripper of the robot should be plunged into the sand in the moulding box, and then verified this by getting the foundry to supply us with moulding boxes filled with hard foundry sand; we had sand all over the factory floor as we tested keenly, chastened by our experience with the vacuum robot. So far so good. The robot was designed to apply this force. We considered too the forces that would be required on a Monday morning, when the mould, gating and casting would be cold, to break off the gating.



Robot in ambush above mould box

The robot received a signal for grip position from the moulding line that told it what casting was in each mould box. The installation over a New Year holiday went well. How could there be a problem?

We overlooked the many times higher inertia of the electric drives. A hydraulic motor especially when it is a direct drive (with no gearbox) has low inertia compared to an electric motor with required gearbox. If the casting/gating or the mould box itself is out of position then the gripper may hit iron instead of sand and be brought to a sudden stop as it plunges into the mould. The suddenly stopped electric motor/gearbox combination puts the motor shaft/gearbox/rack and pinion under severe load. It was a severe duty; most robots would never face what in effect was a fairly regular 'crash cycle.' The problem was solved with mechanical design and software changes and the black cloud had a silver lining.

We understood that a manually controlled (with no controller restrictions on what the operator could do with his machine) electric manipulator was impractical; a dream of stealing a lead on the competition bit the dust and we had learned another important lesson.

Maximum motivation of employees

Britain seems to need the most fundamental, desperate and unifying purpose to manufacture as productively as the best countries. The last time our factories truly hummed was in the period 1939-50; war (between 1939-45 Britain produced 125,000 aircraft) and its heady aftermath produced these conditions for a period.

Our engineer in USA could have said after 2 months with the vacuum robot, '*I've had enough, I need to come home*.' But he stuck it out. I come back to the words of Bill de Vijier and the lessons from Coles Cranes; the importance of good industrial relations. It is one thing for a tiny start-up, with a team of 8, to work with an endless passion to solve a problem; but how to maintain that spirit, shown by our engineer in the USA, when we are now over 60 employees? I could have closed my eyes to that problem, sold the company to the highest bidder and moved on. Against much concerned advice we chose a different route.

CLANSMAN DYNAMICS

JOHN STUART MILL .....1848 IN POLITICAL ECONOMY

'The form of association, however, which if mankind continue to improve, must be expected in the end to predominate, is not that which can exist between a capitalist as chief, and workpeople without a voice in the management, but the association of the labourers themselves on terms of equality, collectively owning the capital with which they carry on their operations, and working under managers elected and removable by themselves.'

I wanted to avoid a gentle tinkering and make a substantive change to the ownership of Clansman such that the goals of all employees were more closely aligned with those of the company, by changing the ownership structure. J S Mill, who wrote the words below, is hardly a Marxist radical; but his prediction was entirely wrong.

The tinkerings with legislation since the 1960's have not produced transformational change. There are certainly fewer 'ugly industrial relations events,' but surely that is largely due to the disappearance of the most troubled industries, e.g. mining and shipbuilding. Trade union power has also declined.

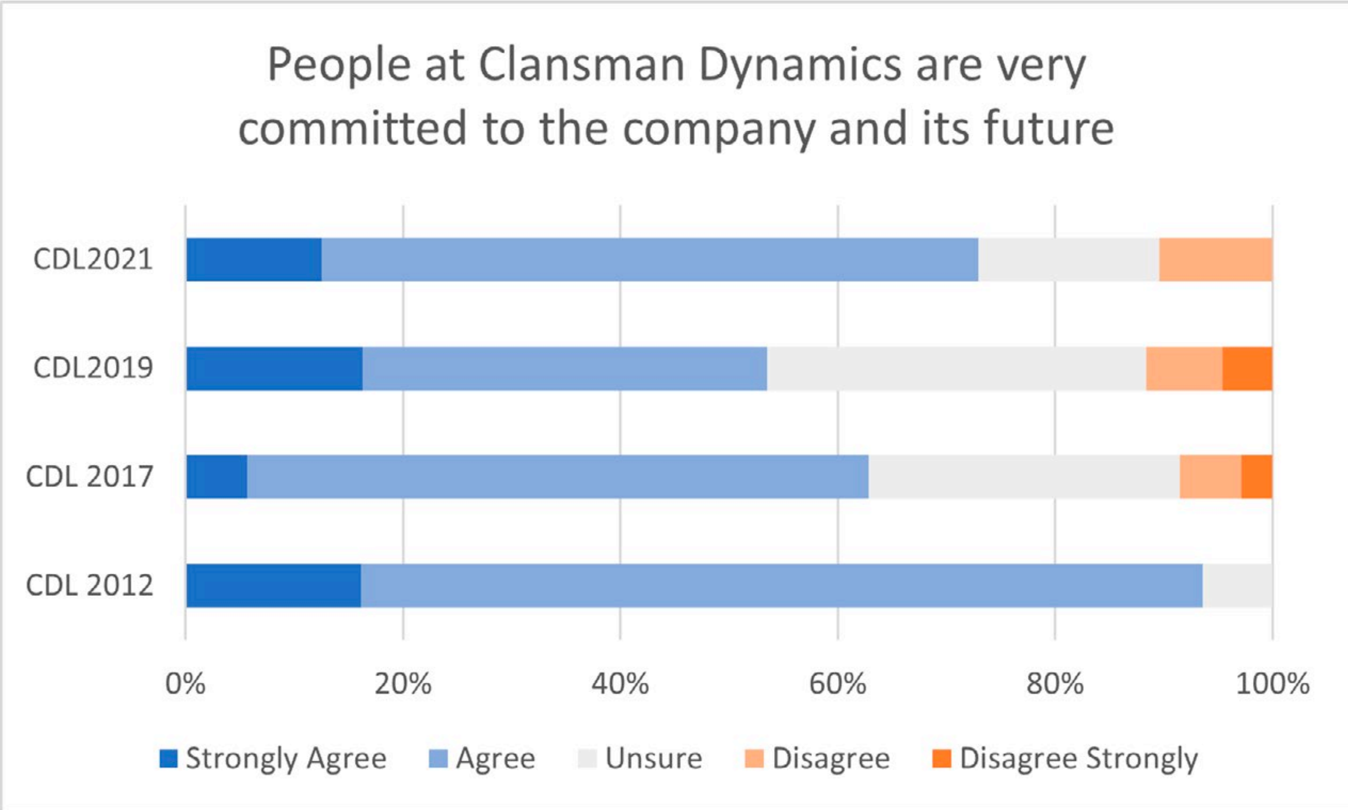
Entrepreneurs who start their own companies are supposed to provide an example of being driven to work hard. I wanted to create a workforce with an entrepreneurial outlook. The employees would need to become owners in some form to achieve this.

Clansman is now owned by the 60 employees. They invest in new technology and they share in any surplus profit. No element of that profit goes to an external shareholder. Lawyers and accountants want to become partners – why not engineers, fitters and electricians too? I was sceptical when we were advised that even in the 'badlands' of Lanarkshire heavy engineering, with its history of mistrust of management and habits of 'hire and fire,' that employees would buy shares in Clansman. Our advisors were right; 80% of the employees bought shares and this was enough to make Employee Ownership possible.

The most extraordinary transformation was in the liveliness of our company meetings. Pizzas and fizzy drinks are provided and the whole company meets in the lunch hour. We had had these meetings for 15 years but had to prod and poke to produce questions, which I thought was due to a certain Scottish reticence; wrong again. After the change to employee ownership in 2009 those meetings involving the same people, same factory and products were hard to bring to an end. Only the ownership had changed.

Even when conventional measures such as turnover and profitability are considered, the change to employee ownership has been successful: both doubled in the first 5 years after the change. Even the best efforts of Brexit and the Covid pandemic have caused just one small loss in the last 8 years.

Things seemed almost too rosy so we commissioned a survey of our employees. Engineers may dismiss such things as 'imprecise social 'science' games', but at the least, if similar questions are consistently asked, trends can be spotted. The results in 2012 were indeed positive as the



responses to 2 typical questions show above. But there is a worrying trend which we believe is directly related to leadership problems.

Again we didn't know what we didn't know. We had imagined the problem would be achieving the change in ownership and not in managing a change in leadership. Apart from enormous difficulties with our bank, the change in ownership was easy. We have elected directors and trustees and their contributions have been absolutely valuable, and in turn they have learned about issues from which they would normally be excluded. Managing a team of owners who have been encouraged to participate and question – there are no secrets apart from individual salaries and that may change – seems to be difficult. Managing directors recruited externally have had no experience of the ownership model. Clansman's culture is apparently peculiar. Maybe the characteristics of a typical managing director do not normally include a subdued ego!?

Short Termism

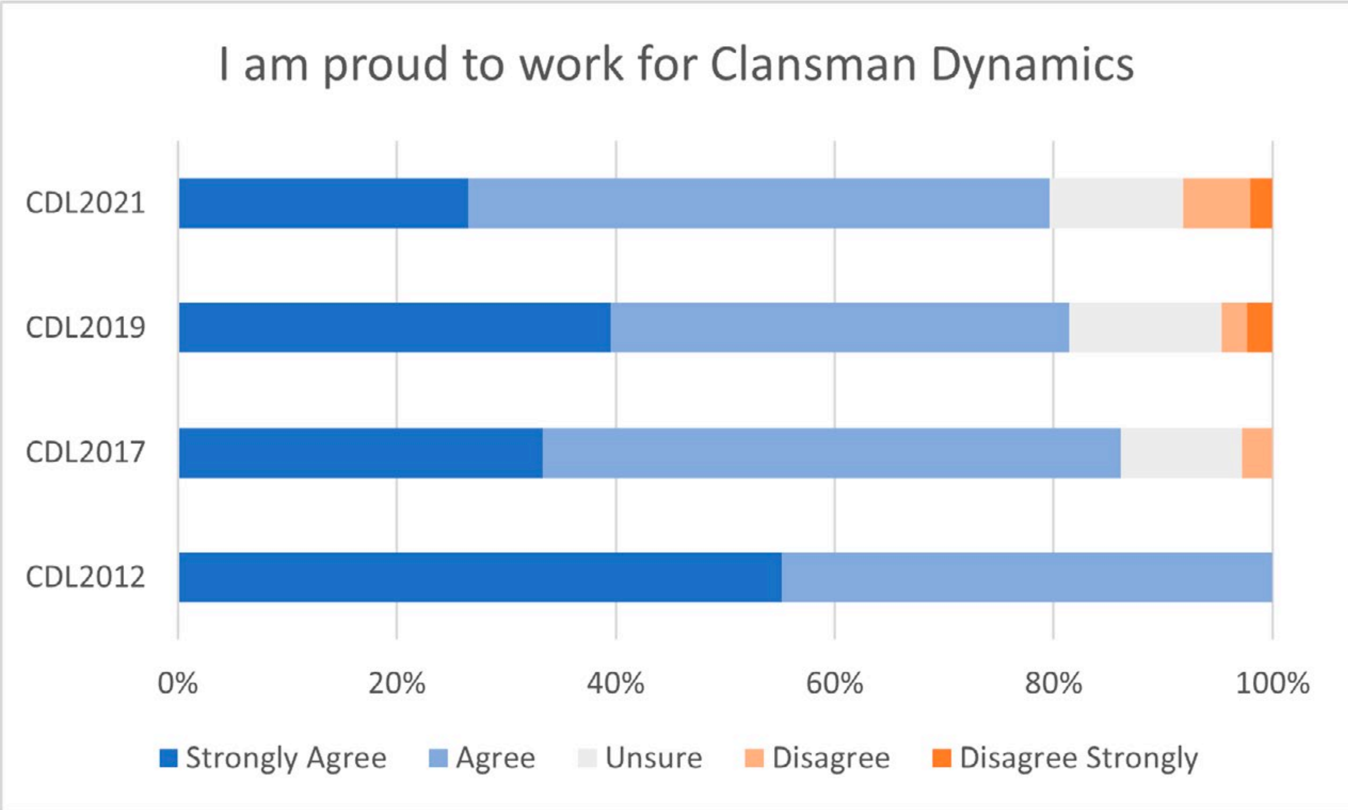
Short termism describes our inability in Britain to both plan and take a long term view; that is particularly relevant to engineering. I can't objectively comment on whether Clansman has been good or bad in this respect, but the comment of a trustee elected from the shopfloor at a Clansman Employee Benefit Trust meeting rang very true:

> *"We want our jobs to be here in thirty years time and we're worried that the strategy of the current managing director is not going to produce that."*

Yes, all employees are shareholders, but first and foremost they are employees who want long term jobs and they know (because so many have been paid off in previous jobs), that means continuous, long term product development and not short term profit taking – however tempting. So there is an intrinsic element in Employee Ownership that sustains long term thinking, which is great for engineering.

Societal and Exchange Rate Problems

Efforts have been made by governments to encourage STEM subjects, but insufficient numbers of students have come forward. Our three daughters were each discouraged from going into engineering by their teachers. Britain prefers to remember the William Morris of the Arts and Craft Movement and not William Morris the car maker who produced 27% of UK cars bought in 1939.



Many proclaim the need to increase UK exports. Try to imagine a well-run company with brilliantly designed products, carefully controlled costs and the best productivity which is then faced with a 20% revaluation of the £ in order to tame inflation. That is an impossible obstacle for an exporter. Until our economic policies reflect the need of serious exporting manufacturers (like Japan, S Korea, China, Germany did) we will remain a second rate industrial power.

Conclusion

I return to the wise words of Mausuru Ibuka and the lessons from the demise of Coles Cranes. Coles did not manage to have every aspect of its business in order and, despite excellent products, failed. Those cranes could still be being made – there is still an obvious demand for them. Employment costs in the UK are lower than for competitors in France, Germany and Japan – costs cannot be the excuse for the failure. A lack of collaboration was a key problem which I believe the radical change to employee ownership has addressed for the long term at Clansman.

The passion to put customers' needs first, to compete internationally, to innovate, to develop new processes, to keep all employees informed of the good and the bad news, to produce absolutely reliable engineering is very evident at Clansman, as the diagrams above show: the interests of all employees and shareholders are shared through employee ownership. The level of participation and expectation of answers to questions increased dramatically when just the structure of ownership of the company was changed.

Engineering companies can be started and can flourish in the UK if all collaborate with that passion. However the serious re-establishment of a significant manufacturing sector within the UK for a more balanced economy does also require big changes within society, education and government policies.

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The Institution of Engineers in Scotland

Great ships, solitary waves, and solitons

John Mellis

John Mellis has spent most of his career as a physicist, engineer and project manager working on optical telecommunication systems at the BT Research Laboratories in Suffolk. For many years he was also a Visiting Professor at the University of Sunderland. He now writes on the history of science, technology and medicine, and is the author of Scotland's Science (1550-1900) and Scotland's Science Next (1850-2022). He is a member of the British Society for the History of Science, and is a Fellow of both the Institution of Engineering and Technology, and the Institution of Engineers in Scotland.

Abstract

John Scott Russell was one of the foremost naval architects of his time. Born near Glasgow in 1808, he became a noted and popular lecturer, before moving away from academia to focus on industrial engineering. Among his many achievements, two stand out. First, the design and construction of the SS Great Eastern in collaboration with Isambard Kingdom Brunel. Second, the discovery and study of a strange wave phenomenon he acutely observed on the Union Canal near Edinburgh. Scott Russell's 'Wave of Translation', now known as Solitary Waves or solitons, turned out to have significance and application in many fields, including optical telecommunications.

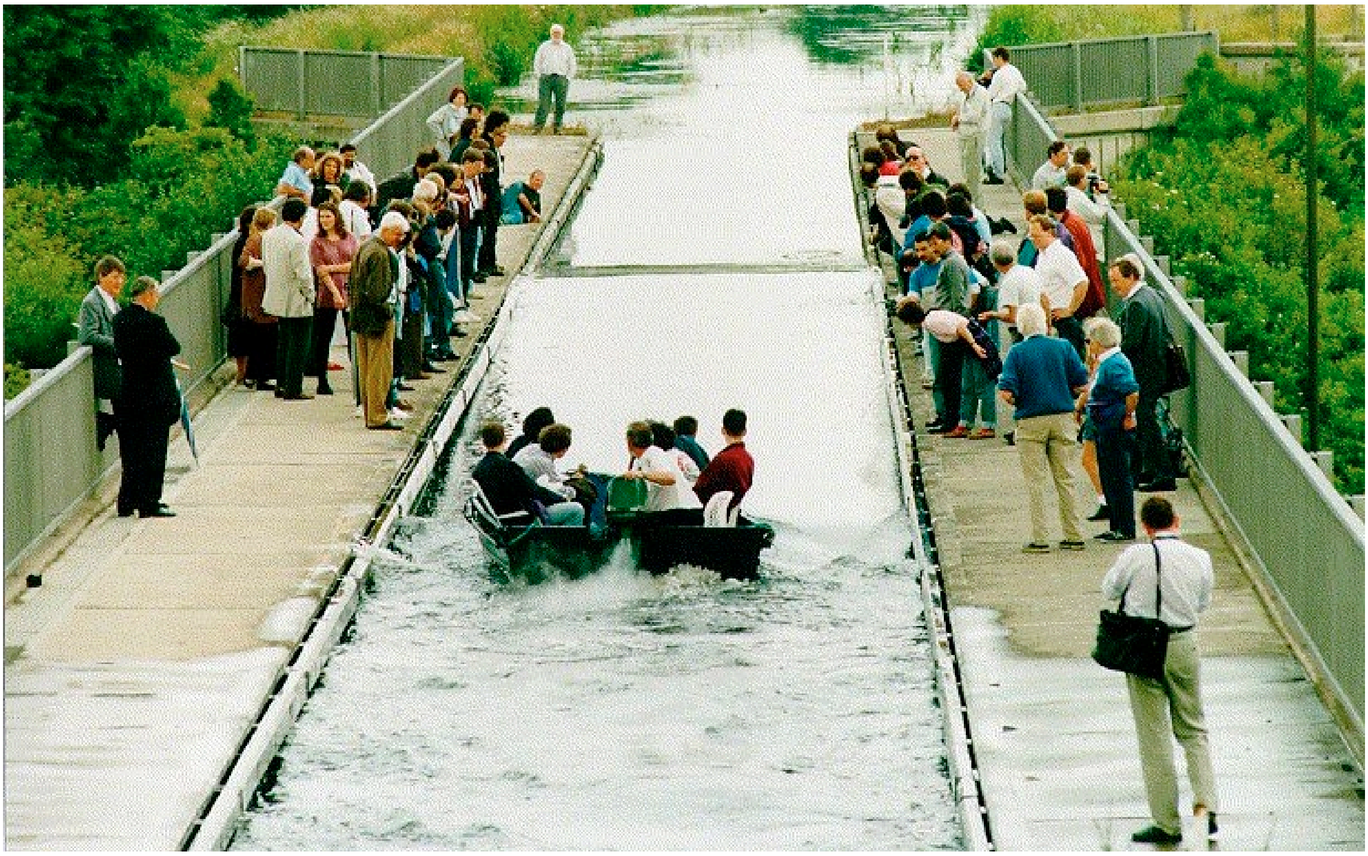
John Mellis

In 1851, the Australian Royal Mail Steam Company wanted ships that would make the journey from Britain to the Antipodes taking on coal only once, at the Cape of Good Hope. They turned to their chief engineer, the great ship designer of the age, Isambard Kingdom Brunel, creator of the largest ship afloat, the *SS Great Britain*, which measured 322 feet long, and displaced 3,675 tons[1]. In response, Brunel produced a specification for ships displacing between 5,000 and 6,000 tons. The company baulked at what they saw as the over-ambitious design. So instead, Brunel commissioned another design for two smaller ships from the well-known Scottish naval architect, John Scott Russell, which would still be able to carry enough coal to meet the requirement. Russell owned the respected and reliable Fairbairn ship-building yard at Millwall. Under the contract, two large iron-hulled mail steamers, the *Victoria* and the *Adelaide*, each carrying 200 passengers, were designed, constructed and launched successfully[2]. The *Victoria* won a prize for the fastest passage to Australia: 60 days, including a two-day stay at St. Vincent. By the spring of 1852, Brunel was wondering how to design a ship capable of sailing to the Far East, and back again, carrying all its own fuel. He began discussing plans with Russell for a truly enormous ship, over 600 feet long, and displacing more than 21,000 tons. It would become the *SS Great Eastern*.

Figure 1. John Scott Russell, engineer and naval architect

1 Brindle S (2006) *Brunel: the Man who Built the World,* Weidenfeld & Nicolson

2 Brown D K (2004), *Russell, John Scott (1808-1882)* Oxford Dictionary of National Biography https://doi.org/10.1093/ref:odnb/24328



Gathering of physicists and engineers recreating a solitary wave on the Scott Russell aqueduct in 1995

John Scott Russell was a naval architect and engineer. Among his many achievements, two stand out: first, the construction of the *SS Great Eastern* in collaboration with Brunel; second, the discovery of a strange wave phenomenon which has had many profound implications in the modern fields of fluid dynamics and optical telecommunications. Scott Russell was born the only son of a clergyman, Rev. David Russell, and Agnes Scott in Parkhead, now a part of Glasgow but then a local village. At the age of 12, he studied for a year at the University of St Andrews before enrolling at Glasgow University to study mathematics and natural philosophy, graduating when he was only 17 years old[3]. Encouraged by his old professor of geometry at St Andrews, he taught mathematics and science at the Leith Mechanics Institute, and at Edinburgh University, where his lectures were highly popular and so well-attended that *"when he commenced his second course of lectures, the classrooms of his former master and actual rival were rapidly emptied."* On the vacancy of the chair of natural philosophy at Edinburgh, due to the death of Sir John Leslie in 1832, Scott Russell (then aged 24) was temporarily elected to the post, pending the appointment of a permanent new professor. He was encouraged and invited to apply, but declined to compete with another candidate he greatly admired, the optical scientist David Brewster, who ironically did not get the job but later became Principal of St Andrews University. Scott Russell was in any case more interested in industrial applications, and moved away from academia. He briefly ran the *Scottish Steam Carriage Company*, which offered steam-car passenger transport between George Square in Glasgow and the Tontine Hotel in Paisley, until a fatal accident ended the service[4] It was while consulting for a company operating a passenger steam-boat service on the Edinburgh and Glasgow Union Canal, that John Scott Russell discovered a most amazing phenomenon.

In 1834, he was conducting experiments at the Union Canal near Hermiston to determine the most efficient design for canal boats, observing a boat being towed along rapidly by horses. When the boat stopped, the bow wave continued forward in a very unusual way. He described his discovery like this: *"I was observing the motion of a boat which was rapidly drawn along a narrow channel by a pair of horses, when the boat suddenly stopped—not so the mass of water in the channel which it had put in motion; it accumulated round the prow of the vessel in a state of violent agitation, then suddenly leaving it*

3 Brown D K (2012), *Russell, John Scott (1808-1882)* Oxford Dictionary of National Biography https://doi.org/10.1093/ref:odnb/24328

4 Petroski H (1998) *John Scott Russell*, American Scientist, Vol. 86, pp 18-21. https://www.jstor.org/stable/27856932

behind, rolled forward with great velocity, assuming the form of a large solitary elevation, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently without change of form or diminution of speed. I followed it on horseback, and overtook it still rolling on at a rate of some eight or nine miles an hour, preserving its original figure some thirty feet long and a foot to a foot and a half in height. Its height gradually diminished, and after a chase of one or two miles I lost it in the windings of the channel. Such, in the month of August 1834, was my first chance interview with that singular and beautiful phenomenon which I have called the Wave of Translation, a name which it now generally bears..." [5, 6] .

Scott Russell knew that in his 'Wave of Translation', which he also called 'solitary waves', he had observed something fundamentally important. He built an experimental tank in his garden to continue his studies of it, developing his observations of the strange solitary waves and measuring their key properties: stability and resistance to dispersion, so that they can travel over great distances; their high speed; and the dependence of speed on the width and depth of the water channel[7]. The wider relevance of Russell's solitary waves only became clear in the 1960s when scientists began to use digital computers to study non-linear wave propagation in fluids and in solid materials. It became obvious that many phenomena in physics, electronics and biology can be described by the theory of 'Russell's Solitary Waves' as they are now known in fluid dynamics, and of 'solitons' as they are called in the field of fibre-optics.

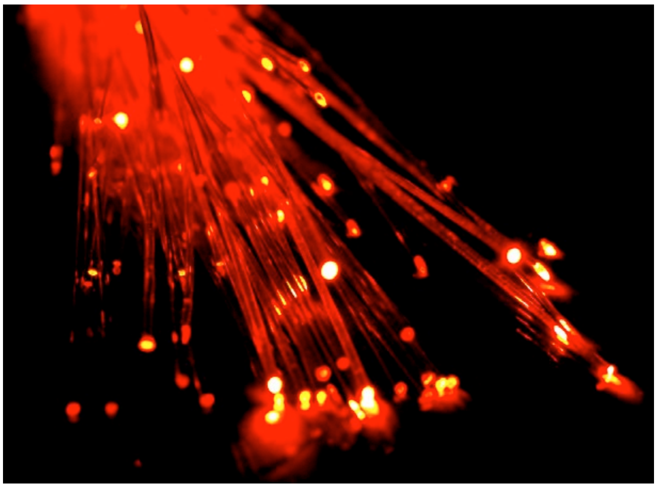


Figure 2. A bundle of optical fibres

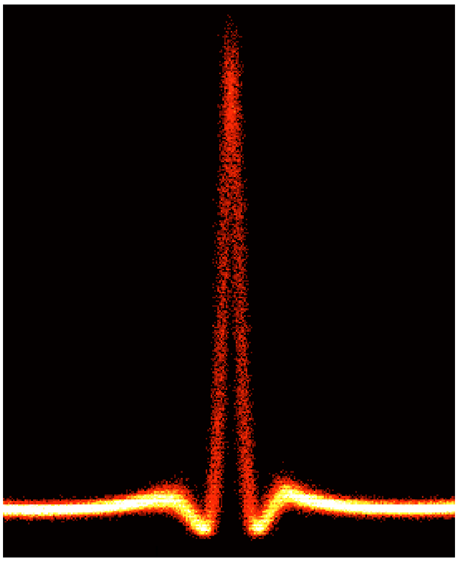


Figure 3. Temporal profile of a soliton at the point of maximal compression. K. Hammani et al. (2011)

Solitons especially caused great excitement in the fibre-optic communications industry. The qualities of solitary waves which intrigued Russell – the fact that they do not fragment, disperse, or lose strength over distance – prompted Akira Hasegawa at AT&T Bell Labs to propose in 1973 that solitons could exist in optical fibres if a sufficiently powerful light pulse exploited the non-linearity of an optical fibre's refractive index properties in exactly the right way to balance the dispersion of the pulse. Laboratory experiments confirmed that solitons could be used for ultra-high-speed communications where billions of solitons per second carry information down immensely long optical fibre links. For example, in 1999 the NTT laboratories in Japan demonstrated transmission of solitons at 10 Gigabits per second over a fibre-optic length of 180 million kilometres, and at 80 Gigabits per second over 10,000 kilometres. Recirculating solitons in tiny optical 'microresonators' have been used to generate a 'comb' of frequencies to incredibly high precision. Such frequency combs can be used to generate closely-spaced optical carriers with an immense combined data capacity – researchers have used 179 optical carrier frequencies to transmit 55 Terabits of data per second over a distance of 75 km – the equivalent of two million HD TV channels[8]. Optical frequency comb generation has become an important scientific tool, one that enabled the measurement of the spectral line wavelengths of

5 Russell J S (1884) *Report on Waves, Report of the Fourteenth Meeting of the British Association for the Advancement of Science*, York, pp 311-390 https://www.biodiversitylibrary.org/item/47344

6 Eilbeck, C (2013) *John Scott Russell and the solitary wave,* Heriot-Watt University, Dept. of Mathematics http://www.macs.hw.ac.uk/~chris/scott_russell.html

7 Russell J S (1885) *The Wave of Translation in the Oceans of Water, Air and Ether*, pub. Trübner & Co. https://archive.org/details/wavetranslation01russgoog

8 Landgraf, M (2017) *Optical communication at record-high speed via soliton frequency combs generated in optical microresonators*, at Phys.org https://phys.org/news/2017-06-optical-record-high-soliton-frequency-microresonators.html

hydrogen to an unprecedented precision of 1.4 parts in 10^{14} – for which Theodore Hänsch and John Hall shared the 2005 Nobel Prize in Physics[9]. John Scott Russell's acute observation of his 'heap of water' has had implications that have rippled far and wide indeed.

Back in the 19th century, Russell's immediate concern was in understanding how his wave of translation could be used to optimise the design of ships. He reported his original observation in a paper presented in 1835 to the Bristol meeting of the British Association for the Advancement of Science, and showed how the wave of translation could be used to reduce the water resistance to vessels moving fast in a restricted waterway. The interest was so great that Russell and Sir John Robinson, secretary to the Royal Society of Edinburgh, were appointed to carry on the investigations into the whole subject of waves, at the Association's expense. They reported back after two years, with three wide-ranging papers, including: *'On the Mechanism of Waves in Relation to the Improvement of Steam Navigation*', in which Russell described a new approach to optimising the design of ship hulls, which he called his 'wave-line' theory. In essence, this proposed that the profile of ship hulls should resemble the shape of the bow waves they created, with slim, concave bows shaped as sinusoidal curves to push water aside with minimum energy. This was a semi-empirical deduction, rather than a mathematically rigorous one, but it had a strong influence on subsequent hull design, as in the fast 'clipper ships' of the 1840s and beyond. Finding an entire hull shape to minimise water resistance was a problem that would be solved by William John Macquorn Rankine and William Froude many years later. Working at the Greenock shipyard of Thomson and Speirs, Russell introduced his wave-line designs to a series of vessels, including the *Skiff, Wave, Storm* and *Scott Russell*, followed by four fast Royal Mail ships, the *Teviot, Tay, Clyde* and *Tweed*. As well as their innovative, streamlined hulls, Russell introduced new structural designs for the iron ships, involving a system of longitudinal girders combined with numerous transverse bulkheads and a continuous iron deck; in effect, a box-girder construction conferring great strength and stiffness to the ships.

In 1836 Russell married Harriette Osborne, the daughter of Daniel Toler Osborne, an Irish baronet, and in the course of the next few years they had two sons and three daughters. His reputation as a foremost naval architect was established, and in 1844 Russell relocated his family to London, where he became engaged in a range of writing, editorial and engineering projects. He was invited by the Society of Arts to be its joint secretary, and helped to initiate its proposals for a Great Exhibition in what would become the marvellous Crystal Palace. In the aftermath of the Exhibition's great success, the dismantling of the Crystal Palace, and its reconstruction at Sydenham, in the south of London, the Prince Consort, Prince Albert, wrote that many difficulties had been encountered, and it was *"by dint of Mr. Scott Russell's tact, judgment, penetration, resource and courage, that obstacles vanished and intrigues were unmasked."*

Throughout his life Russell's main preoccupation remained firmly in naval architecture and shipbuilding, and in 1847, with partners, he acquired the Fairbairn shipyard at Millwall, and constructed the wave-line based yacht *Titania* for the English railway engineer Robert Stephenson, and *Adelaide* and *Victoria* for Isambard Kingdom Brunel and the Australian Royal Mail Steam Company. *Titania* enabled Stephenson to join the Royal Yacht Squadron, which had invited the New York Yacht Club's own wave-line based *America* to compete at Cowes for their Hundred Guinea Cup. In August 1851 *America* resoundingly defeated a flotilla of 14 British boats in the race that became the America's Cup. In the 'London Journal' a cartoon showed Queen Victoria asking which yacht came second, and being told *"Ah, your Majesty, there is no second."* A week later *America* raced *Titania* head-to-head in a battle of wave-line designs and won again. Russell acknowledged the victory graciously.

Meanwhile, ever ambitious, Brunel was hatching plans for his most audacious project yet. In 1852 he began sketching designs and calculations for an enormous ship capable of carrying its own fuel for an uninterrupted round trip from Britain to the Far East. In the finalised design the ship would measure 692 feet in length by 83 feet in the beam, displace 27,000 tons, and carry 4,000 passengers, 3,000 tons of cargo and over 10,000 tons of coal. To finance the project Brunel approached the Eastern Steam Navigation Company (ESNC) which had just competed unsuccessfully to win mail contracts to the Far East. Surprisingly, the beleaguered company accepted Brunel's bold vision and appointed him its chief engineer. To build the great ship, to be called the *Leviathan*, quickly became Brunel's major obsession and the ESNC's critical project. They invited tenders to build the ship, and received only one to build the whole ship, including engines, from Scott Russell's Millwall yard. Russell offered to build the hull for £275,200, with the paddle engines and boilers for £42,000 and the propeller screw engines and boilers for £60,000, sub-contracted to James Watt & Co. of Birmingham. This

9 Hänsch, T (2005) *Passion for Precision*, Nobel Lecture (2005) https://www.nobelprize.org/uploads/2018/06/hansch-lecture.pdf

total was a great under-estimate compared to Brunel's private estimate of £500,000 to build the whole ship. The sole tender was accepted but the project soon ran into problems.

Construction started well and with high quality outcomes. The hull embodied the well-established Russell philosophy of a wave-line form, longitudinal iron stringers and strong bulkheads. But the sheer scale of the ship required Scott Russell's company to hire the neighbouring Napier yard to accommodate the work, and Brunel's frequent design changes increased the costs. By 1856, J. Scott Russell & Co. were insolvent and the ESNC took control of the yards to complete the ship, now becoming known as the *Great Eastern*. In January 1858, she was eventually launched, after many issues and a fatal accident related to her huge size and weight. The construction had cost £600,000 to that point, contriving the difficult launch had cost £120,000 and another £200,000 was required for the engines and fitting out. The ESNC was forced into liquidation with huge losses for its shareholders, including Brunel, and sold the incomplete ship for £165,000 to a newly formed 'Great Ship Company'. Scott Russell had managed to resurrect his own business and won the contract to complete the fitting out. The *Great Eastern* sailed for the first time in September 1859 and almost immediately, a stopcock left accidentally closed caused an explosion which killed five stokers. Brunel, already terminally ill, died several days later and never saw his and Russell's 'great babe' at sea.

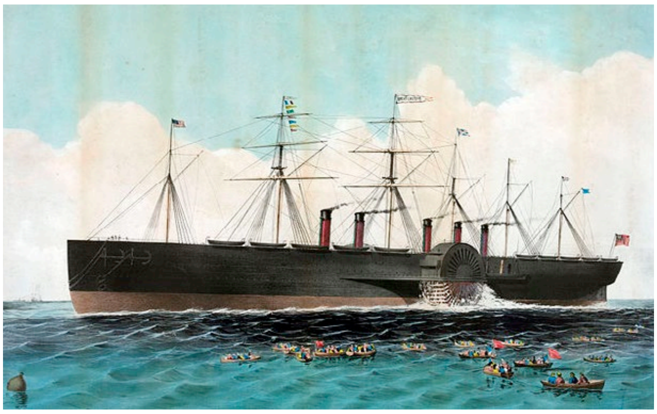


Figure 4. The S.S. Great Eastern. Hand-coloured lithograph by Charles Parsons

The *Great Eastern* was never a commercial success apart from her use in laying sub-oceanic telecommunication cables. But she was a masterpiece of pioneering design, too far ahead of her time. It would be another 49 years before a larger ship was constructed: the Clyde-built Cunard liner *Lusitania*. The first failure of Scott Russell's shipyard initiated a series of financial problems for him. Involvement in a business to supply guns to the American Civil War also left him heavily indebted and much of his property was sold. The bankruptcy of his son's shipyard on the River Taff in 1869 caused him further losses. Russell's later career was spent as a consulting engineer producing designs such as the Great Rotunda for the Vienna Exhibition of 1873, then the world's largest clear-span roof. He prepared some designs for the 1,000-foot span required for the London Tower Bridge, but while investigating potential ironworks for the project, he became ill and eventually died aged 74, in 1882.

In July 1995, an international group of scientists attended a conference on 'Nonlinear waves in physics and biology' at Heriot-Watt University, and gathered on the Union Canal near Edinburgh to witness a re-creation of Russell's famous first sighting of a solitary water wave. The occasion marked the naming of the new 'John Scott Russell aqueduct' which now carries the Union Canal over the Edinburgh City Bypass.

Picture credits:

Figure 1 Wiki CommonsL https://commons.wikimedia.org/wiki/File:Russell_J_Scott.jpg

Figure 2, Tyler Nienhouse https://commons.wikimedia.org/wiki/File:Red_optical_fibers.jpg /File: Red optical fibers.jpg CC Attribution2.0 Generic licence

Figure 3, K. Hammani et al (2011) https://commons.wikimedia.org/wiki/File:Peregrine_soliton_in_optics.png

from Peregrine soliton generation and breakup in standard telecommunications fiber, Opt. Lett. 36, pp 112-114.

Figure 4, Charles Parsons , Hand-coloured lithograph of the SS Great Eastern https://commons.wikimedia.org/wiki/File:Great_Eastern_painting_smooth_sea-2.jpg, public domain

Gathering of physicists, D Duncan, Department of Mathematics, Heriot-Watt University

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The Institution of Engineers in Scotland

Why Society Needs Engineers, especially Naval Architects, Marine & Ocean Engineers

Peter G. Noble

Peter Noble, FIES, is a naval architect and ocean engineer with a wide range of global experience across many sectors within the marine and offshore industries.
He is a Glasgow University graduate and started his career as an apprentice with a Clydeside shipbuilder.
His career has included positions with shipyards; ship and offshore design consultants; marine R&D development companies; major classification societies; and with an international oil company.
Peter is currently based in Texas where his work includes advising on ocean renewable energy and future marine fuels.
He continues to support student and young professional activities in naval architecture and ocean engineering through mentoring and advising on capstone projects.

Abstract

Firstly, the premise that engineering and technology are important and necessary parts of our human society and have been since the beginning of time; and secondly, the premise that, since we live on a planet that has approximately seventy percent (70%) of its surface area covered by water, there is an inherent need for development of technology and engineering solutions relating to the world's oceans.

Peter G. Noble

Engineering Ancient and Modern

In these times we engineers often seem to be on the defensive, with our professional work presented by the media and special interest activists as "grubby and even dangerous" while science seems to be championed as "pure and good". The reality, however, is that in the developed world we generally live safe, comfortable and rewarding lives due to the availability of technology while, in the developing world, engineers are responsible for bringing clean water, power, and transportation infrastructure that reduce infant mortality rates and increase life spans in places like India and China.

Unlike science, engineering and technology have been an integral part of human development from earliest times. Historically, tool-use has been considered a typically human behavior and the emergence of tool-use was considered an important step in evolution, even serving to delineate the appearance of the genus Homo. This is now a somewhat dated definition but it is still clear that our cave-dwelling ancestors survived and developed through the use of primitive technology. They did not, however, need to understand the science of combustion chemistry to use fire, only that its use allowed families to stay warm and cook their food; similarly, their need for transport drove the construction of log canoes without any understanding of the finer points of metacentric stability.

As human society developed, engineering and technology played an increasingly important role in advancing civilization. For example, the Egyptians built great pyramids to honor their Pharaohs around 2500 B.C. (and developed marine infrastructure to support these efforts); the Romans developed water supply and sewage infrastructure, central heating and an impressive network of roads, (including major defense systems such as Hadrian's Wall); and the Vikings designed and built ships which carried them across the stormy North Atlantic to Iceland and beyond, around 870 A.D. All these "engineering" feats were accomplished millennia before science was part of our regular lexicon.

While I stated earlier that engineers have not always had a good public image, in an encouraging turn of events, I read a recent Veracity Index poll of the most trusted professions and found that, at 87%, engineering is the second most trusted profession after nursing, 89%. Interestingly lawyers scored 57%, journalists 27% and politicians 12%. As an engineer I find this is quite encouraging but I am not sure that this easily translates into improving our societal or governmental systems.

The problem remains that there is a gap between what engineers do and their public trust recognition, and how engineers are projected by the media and how their value to society is often ignored by governments. At a governmental level engineers tend to be involved in reactive rather than proactive ways. For example, engineers may be called to investigate technical failures but are seldom asked to help in defining policy which has a technological component, (that is just about everything from policies relating to energy, to national security, to financial systems and to health care). This is of course not a new phenomenon. Plato stated it well ~400 B.C. *"Those who are too smart to engage in politics are punished by being governed by those who are inferior."*

In order to explore the premise that society needs engineers, it is useful to explore the status quo, particularly the relationship between engineering and science which I find to be poorly understood by many.

I have long held that a quote attributed to Theodore von Karam, the distinguished engineer and fluid dynamicist, succinctly describes the fundamental difference between scientists and engineers:

"Scientists seek to understand what is, Engineers seek to create what has not yet been."

And, in a more philosophical way the following quote from Carl Mitcham, Philosopher, Colorado School of Mines, further explains why we should value engineering:

"Design & Invention cause things to come into existence from ideas, they make the world conform to thought; whereas Science, by deriving ideas from observation and analysis, makes thought conform to existence."

Definitions

It may be useful to define science, engineering and technology:

Science can be defined as the intellectual and practical activity encompassing the systematic study of the structure and behavior of the physical and natural world through observation and experiment.

An all-encompassing but somewhat clumsy definition of engineering is that it is a process of inventing, innovating, designing, building, maintaining, researching, and improving structures, machines tools systems materials, components, processes, solutions and organizations. All this is achieved by utilizing creativity, ingenuity, empirical evidence, heuristic rules, practical knowledge, mathematics, economics, science, and social knowledge.

Technology is defined as the branch of knowledge that deals with the creation and use of technical means and their interrelation with life, society, and the environment, drawing upon such subjects as industrial arts, engineering, and science. Or a little more succinctly, technology is the sum of the ways in which social groups provide themselves with the material objects of their civilization. It is interesting to note that the definition of technology brings together human society and civilization with engineering.

In past years much technical discussion and professional education has centered around what has become known as the "Scientific Method". This can be described as consisting in systematic observation, measurement, and experiment, applying rigorous skepticism about what is observed, and leading to the formulation, testing, and modification of hypotheses. It is a systematic way to develop knowledge of our world.

Less referenced is the "Engineering Method", partly described in this Journal in its application to non-engineering activities in Iain MacLeod's paper *System Planning in Government and in Education.*

The engineering method (design) can be defined as a systematic approach used to reach the desired solution to a problem, remembering that as they seek solutions, engineers are answerable within a broad and diverse environment of actors and forces: socio-political, material, temporal, and financial.

To quote from the 2021 paper *"The Life and Legacy of William Rankine"* by Andy Pearson[1]:

> *"Rankine was the Regius Professor of Civil Engineering and Mechanics at the University of Glasgow … and for almost his whole tenure he fought vigorously to have engineering recognized as a degree subject in its own right."*

Although Rankine faced significant resistance from the university establishment, Glasgow did in fact start to award B.Sc. degrees in Engineering Science in the year of his untimely death 1872.

This has proved to be a significant step in engineering education, fulfilling Rankine's desire to reunite theory and practice by using science to help in solving real world engineering problems, a theme that runs as a recurring element through much his work.

Today, we have engineering schools around the world teaching engineering and awarding degrees in either Engineering or in Engineering Science, but we need to be careful, however, as engineering science and engineering are not the same thing. It should be noted that engineering science is but one of the tools that engineers use to solve problems. As stated in the earlier definition of engineering above, engineers use many tools including: creativity, ingenuity, empirical evidence, practical knowledge, mathematics, economics, science and social knowledge.

In the history of humankind engineering and technology, most often precedes science. Engineering and technology are not the children of science, but are more often the progenitors of it!

A prime example is from our own James Watt who developed the working steam engine and initiated the Industrial Revolution, decades before Kelvin and Rankine were able to articulate the laws of thermodynamics which describe why steam engines work. And, as a side note, today we still use steam to generate around 80% of all the world's electricity.

Further, after a recent visit to the Science Museum in Kensington, I left asking myself the question *"Where is the science in the Science Museum?"* On entering the museum, I saw the Energy Hall with wonderful examples of the work of the aforementioned James Watt and my further explorations brought me to space capsules, telescopes, microscopes and even to the Julius Totalizer Machine using for calculating betting odds at greyhound tracks. All of these and many more are examples of engineering and technological creativity, many of which were critical in allowing scientists to carry out their work of discovery. Without the microscope or telescope the scientific fields of biology and astronomy would have been slow to advance.

Scientists seek knowledge – Engineers find solutions

It is worth looking at the etymology of the words engineer and scientist: the word "scientist" first appears to have been used at the University of Cambridge in 1834 to describe a "cultivator of science, while the word "engineer" dates from

1 Pearson A (2021) *The Life and Legacy of William Rankine,* Proc. Intereantional Conference on Refirgeration and Air Conditioning, Institute of Refrigeration.

at least the late 1300s where it refers to a "constructor of machines".

Of course, looking at the Latin roots also helps us understand the role of engineers in society in that it is derived from the Latin words 'ingeniare' (to contrive, devise) and "ingenium" (cleverness).

Sir Francis Bacon, 1561-1626, has been styled as "the father of modern science", although he seemed to have had more respect for the engineers of his day, the smiths, masons and artisans, who practiced the mechanical arts, than for the scientist. He was driven in this work by a recognition that technology was advancing while natural philosophy (physics) had been stagnant since the time of Aristotle.

> *"Observe also, that if the sciences of this kind had any life in them, that could never have come to pass which has been the case now for many ages – that they stand almost at a stay…. and all the tradition and succession of schools is still a succession of masters and scholars and not of inventors or those who bring to future perfection things invented.*
>
> *In the mechanical arts we do not find this so: they, on the contrary, as having in them some breath of life, are continually growing and becoming more perfect. As originally invented they are commonly rude, clumsy and shapeless: afterwards they acquire new powers and more commodious arrangements and constructions….Philosophy and the intellectual sciences, on the contrary stand like statues."*

Bacon's description of the process of improvement built into the development of "mechanical arts" well describes the way in which engineering advances are made. Some may call this approach "trial and error" but I prefer to call it "continuous experimentation".

We can see this continuous experimentation taking place all around us since a key part is to gain feed-back to make improvements in products or systems. The cell phone growing from being a limited capability shoebox-sized wireless communication unit to being a powerful multi-function pocket-sized communicator/computer/camera/navigation device; or the ocean crossing container ship growing from a small 4000 TEU (Twenty foot Equivlaent Unit) capacity in the mid 1950s to today's 24,000 plus capacity giants are both good examples of continuous experimentation, with multiple generations of product being introduced in a relatively short time. These and many more cases illustrate Bacon's observation that "As *originally invented they are commonly, rude, clumsy and shapeless: afterwards they acquire new powers and more commodious arrangements and constructions…."*

This kind of engineering experimentation is different from scientific experimentation which is specifically designed to confirm or to reject new hypotheses. In engineering, continuous experimentation is a concurrent activity embedded in the engineering process. It is different in that it is carried out in parallel to the design and production of real products which in themselves are designed to fulfill the current requirements as best can be done with current knowledge, tools, budgets and schedules. Examination of the subsequent use of the developed product or process is the key part to the experiment. This in-service experience along with what was learned during the original design and construction, can then identify new opportunities for improvement in function, cost and schedule, which can be circled back to the design of the next generation of product or design.

Certainty versus Uncertainty

Scientists seek knowledge and certainty while engineers seek solutions and deal with uncertainty.

Some years ago, former US Secretary of Defense, Donald Rumsfeld stated:

> *"Reports that say that something hasn't happened are always interesting to me because, as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say, we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know. … and it is the latter category that tends to be the difficult ones."*

As engineers we spend considerable effort on understanding uncertainty and have developed methodologies for addressing it. Fifty years ago we tended to use design margins or factors of safety (factors of ignorance?) to address the uncertainty we encountered. For example, in naval architecture we would add an arbitrary corrosion margin to ship's hull plating to allow for a what we thought might be the reduction in plate thickness over the life of a vessel; or we limited the design stress in a pressure vessel to a percentage of the yield value of the material used for construction. Today we have reduced our levels of uncertainty by having developed better analytical techniques, such as finite element structural modelling, and computational fluid dynamics, that can give us a better understanding of the expected performance of our designs, although some level of uncertainty remains.

We have a whole range of tools that have been developed to assist in understanding and mitigating the risks associated with uncertainty, tools such as, Technology Readiness Factors, Risk Matrices, Hazard Identification, HAZIDs, and Hazard and Operability studies, HAZOPs.

Engineering science has provided useful tools in understanding uncertainty and in many cases reducing it, but in the end the engineer must also use creativity, ingenuity, empirical evidence, practical knowledge, mathematics, economics, and social knowledge, to develop safe, practical, cost-effective designs.

Engineering for the Oceans

One of the areas of engineering which may have more uncertainty, that is, the known-unknowns and unknown-unknowns, is the field of engineering for the ocean. Our planet might better be named Ocean rather than Earth since it is largely covered by water, and much of it remains unexplored and undeveloped. The second part of the paper will examine our current areas of naval architecture, marine and ocean engineering where present and future technology will be deployed.

The importance of the planet's oceans and seas cannot be overstated:

~ 70% of the earth's surface is covered by water
~ 80% of the world's population lives within 250 km of the coast
~ 90% of the world's trade moves by sea
~ 100% of life as we know it depends on water

For as long as humans have taken to the sea, ships and other craft have served as a means of material and technological exchange and have embodied the culture that has produced them. The materials to build a ship reflect the ability to procure resources; the construction process reflects the ability to organize labor, and the construction techniques define the level of skill and technology available. Even the size of a ship is indicative of the risks that a society is willing to assume.

The *Pesse* log-canoe, now on display in the Drents Museum, Assen, Netherlands is believed to be the world›s oldest known boat. Carbon dating indicates that the boat was constructed during the early Mesolithic period between 8040 BC and 7510 BC, which places it firmly in the Stone Age.

To examine true shipbuilding, defined as the construction of large marine craft using manufactured component parts, however, we need to look to the southeast corner of the Mediterranean. While there is no precise date for when the building of ships began, the current archeological evidence suggests that it was in the early Bronze Age which began around 3,000 BC.

The earliest known physical example of a large vessel is the funerary boat discovered in Egypt in 1954. This ship, known as the Khufu ship, was almost certainly built for the second pharaoh of the 4th Dynasty of the Old Kingdom. It is the oldest, largest and best-preserved vessel in the world from antiquity. It measures 43.6 m (143 ft) in overall length and has a beam of 5.9 m (19.5 ft) and demonstrates a level of ingenuity and practical skill which are foundational in the design and construction of any waterborne craft.

The development of ships seems to have spread along what we might call the Maritime Crescent, with initial developments in Egypt, and then spreading along the eastern end of the Mediterranean through the Levant and into modern day Turkey and Greece.

From that time forward, ships and marine transportation systems have been an essential element in the development of civilization and this has led to those who design and build ships, be they shipwrights, naval architects or marine engineers being seen as important.

John Adams, 2nd President of the United States of America. recognized the importance of naval architecture as a step towards a more refined degree of civilization in a letter to his wife Abigail Adams (May 12, 1780):

> *"I must study politics and war, that our sons may have liberty to study mathematics and philosophy. Our sons ought to study mathematics and philosophy, geography, natural history and* ***naval architecture****, navigation, commerce and agriculture in order to give their children a right to study painting, poetry, music, architecture, statuary, tapestry and porcelain."*

And less than 100 years later the Scottish naval architect and engineer John Scott Russell, described the almost super-human attributes that a naval architect must possess in his massive treatise "The Modern System of Naval Architecture", published in 1865

> *"A naval architect should be able to design, draw, calculate, lay down, cut out, set up, fasten, fit, finish, equip, launch and send to sea a ship out of his own head. He should be able to tell beforehand at what speed she will go, what freight she will carry, what*

qualities she will show in a sea, – before it, athwart it, against it, – on a wind, close hauled, going free, – what she will stow, and carry, and earn and expend. On his word you should be able to rely, that what he says, that his ship will infallibly do."

Today, the role of the naval architect has been extended beyond the traditional role of ship designer into the broader field of engineering for the ocean space. But the need for the multi-facetted skill set described by Scott-Russell over 150 years ago has not diminished although the range of engineering projects has moved far beyond ship design and construction.

The oceans present challenges and opportunities to accommodate the ever-increasing needs of the world's population for expanded services and resources in areas such as:

Trade and Transportation

- current fleet of ships >1000GT is ~54000 vessels with a combined deadweight (cargo capacity) of ~2.1 million tons.
- Total cargo transported ~ 10.7 billion tons of which 28% was oil.
- Rapid changes in, ships fuel – (low or zero carbon): autonomous and unmanned systems; digital twins etc.
- Advances being made in port technology and ship design and construction.

Energy

- Offshore oil accounts for about 29% of all production world-wide in waters from a few meters deep to over 3500m deep.
- Offshore wind energy production, both bottom fixed and floating, is increasing rapidly in some parts of the world.
- Wave, ocean thermal and tidal energy sources are at early stage of development with prototypes already developed.

Food

- The oceans are an important food source. ~ 185 million tons of fish and seafood, both wild caught and farmed are produced per annum, which represent about 15% of all protein consumed. By comparison, global annual production of beef is ~130 million tons.
- Further the UN estimates that ~58 million people make their living from fishing and mariculture and the global fishing fleet numbers ~4.6 million craft.

Living Space & Working Space

- While a large percentage of the world's population live in coastal areas, many actually live in low-lying or below sea-level areas where engineering has made that possible. The Netherlands, Singapore and Venice are examples of engineered solutions. Engineers need to continue to develop recovery of coastal lands and protect existing land from rising sea levels.
- Future floating cities are already being proposed.
- Floating plants for oil production, nuclear power production, data centers etc. are already with us and other similar opportunities will appear.

Mineral Resources

- Current seabed mineral extraction includes diamond mining and tin dredging.
- New developments include the exploration for and development of deep-seabed mineral resources such as manganese nodules that contain amongst other material, copper, nickel, titanium, and rare earth oxides.

Recreation

- Recreation is an important part of human existence and the ocean provides many opportunities from lying on a sunny beach, to swimming in the ocean, taking a cruise, sailing, surfing, fishing etc. It is estimated that there are currently ~30 million recreation craft in the world.

While there are without doubt exciting opportunities ahead for those who choose to work in the broad field of ocean engineering, we must take care.

Modern civilization has not always shown much restraint in the use of technologies which make engineering our environment or extracting resources from the earth or ocean easier. And new developments will make it even simpler to build, harvest, drill, mine or fish in ways that may not be sustainable.

The choice, however, is not between taking these risks and taking no risks. Rather, the choice is about judging those risks against the capacity to lessen any harm being done to our oceans, while providing benefit to society in general. It should be recognised that the capacity for good will always increase as new technologies develop.

That is our challenge in engineering the future of our oceans and our planet!

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The Institution of Engineers in Scotland

System planning in government and in education

Iain A MacLeod

Iain MacLeod is a retired Professor of Structural Engineering. He was IES President 2012-14

Abstract

Over thirty years ago, I posed myself this question: “What are the processes and guiding principles that support the success of professional engineering outcomes?” I needed answers to that question to inform research work in computer aided design and also to help students to develop their professional competence. My quests for answers has continued over the years. I have re-phrased the question to be more generic: “How are successful outcomes achieved in situations of complex uncertainty?” and I use the term system planning to represent the processes and principles. I offer here some answers to the question.

Consideration of the wide use and success of system planning in society, raises two further questions: First: “Why do we allow politicians to go ahead with strategies aimed at solving problems of very high complexity that have not been subject to system planning?” Second: “Why is learning for system planning not a main activity in education?” In the paper, I provide some thoughts on the second of these questions that may also provide some answers to the first.

Iain A MacLeod

1. Introduction

I define *system planning* as ‘methodical achievement of outcomes in situations of complex uncertainty’. Such outcomes can be in relation to a wide range of situations such as the creation of a physical system – for example an engineering product, the creation of a process – for example a business process, or a change in a state of affairs – for example reduction in the use of fossil fuel. The fundamental aim is to make the future better than the past. Box 1 gives examples that illustrate the principles.

Use of the word ‘system’ implies a systematic approach to the development and use of processes and to the use of ‘systems thinking’ where the performance of systems and of their parts is taken into consideration.

Some of the important features of system planning are shown in Figure 1 and are briefly explained in Section 2

Abiliity to plan and think strategicaly, i.e. to do system planning, stands beside communication methods and manual dexterity as a characteristic that distinguishes *homo sapiens* from other animals. When it is successfully used to address situations of high complexity and high uncertainty, it is one of the most intellectually demanding of all human activities.

While examples of successful system planning are widespread in engineering, in medicine and in business, we also see many situations where the principles are neglected. In particular, governments seeking to address major global issues such as environmental degradation and inequality often fail to use system planning principles – Section 3.

Education should seek to ensure that learners in all disciplines – and particularly those who aspire to hold responsible positions in society – develop system planning skills.

Box 1 Examples of how outcomes are achieved

1. Intended outcome: Have food in your house
Sue and Jack Brown have well-paid jobs. The cost of food is not important to them and they do not worry much about nutrition. To stock up on food, they go to a supermarket, select items as they walk along the aisles, pay, and go home. They keep the process as simple as possible. It is mainly tacit.

Claire and Joe Green are on a tight budget. Before starting to shop, they prepare a list of items to purchase and decide to shop around to get better prices and to take account of nutritional value, fair trade, animal welfare and sustainability. For each purchase, they look carefully at options in relation to these issues. After doing their shopping, they keep a record of their purchases and use this information in making future decisions when buying food.

The Greens are much more explicit and systematic about their shopping as compared with the Browns. This makes their process more complex and, since low cost and high quality are normally competing requirements, it raises the level of uncertainty about choices. They work as a team to seek to ensure that the food in their house is well suited to their preferences. They adopt system planning principles such as being explicit about objectives, doing options analysis and keeping records to inform future purchasing decisions.

2. Intended outcome: Put a man on the moon
In the 1960s, the USA committed about 2% of its Gross Domestic Product for a period of 10 years to the strategic objective of putting a man on the moon. Many interconnected systems had to be designed and implemented. They were all carefully tested. The parts were tested; the systems were tested; unmanned flights were carried out. The levels of uncertainty, complexity and risk were of a very high order. There was deep collaboration: the intellectual capital of the nation was harnessed to the task. People with high levels of competence and leadership were recruited, e.g. in political administration (James Webb) and in technical/project administration (George Mueller)[1]. There was deep commitment to achievement of the goals.

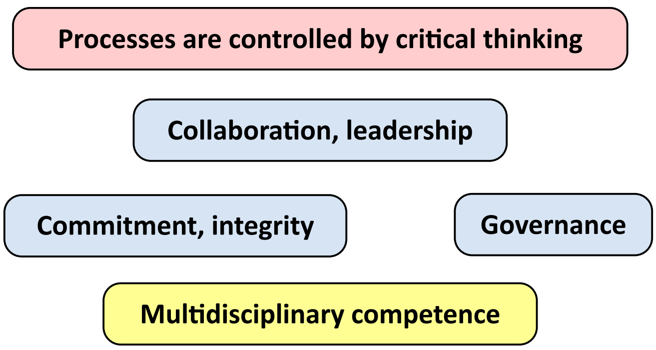


Figure 1 Typical features of system planning

2. Features of system planning

In a system planning situation there are no fixed rules. Processes need to be customised to the context, not all of the features listed on Figure 1 may be relevant but other features may need to be addressed.

Critical thinking

Critical thinkers constantly seek to identify and use principles that will lead to successful outcomes. Ethos is defined as 'the principles and attitudes that are associated with a particular type of activity'. In a previous article I implied that critical thinking is the overarching ethos for system planning[2].

1 Johnson S B, The Secret of Apollo, Johns Hopkins University Press, 2006
2 https://eit.engineers.scot/index.php/Critical_thinking

A crucial principle is the adoption of a reflective, contemplative ethos where questions are posed, responded to and which result in appropriate actions. Those involved review, consult, challenge, expect to be challenged, are sceptical about all information, avoid preconceptions and bias and are prepared to change their minds on issues.

Other guiding principles in a system planning ethos include:

1. Test all proposals to the extent that is appropriate in the context.
2. Adopt a systems approach where the behaviour of the system and of its parts are addressed.
3. Adopt a holistic approach where all relevant issues are addressed.
4. Define the objectives in terms of what is to be achieved rather than how it is to be achieved.
5. Identify guiding principles and state them clearly.
6. Look widely for advice but be wary of bias in what is received.

In team working, the principles should be made explicit so that everyone involved in the process can adopt them[3].

Process control

A process can be viewed as what is done to transform a set of objectives into outcomes. Controlling a process means taking action to ensure that the process achieves the objectives – mainly by posing questions about its efficacy with the intention of seeking to improve it.

A *procedure* is an established process with fixed steps.

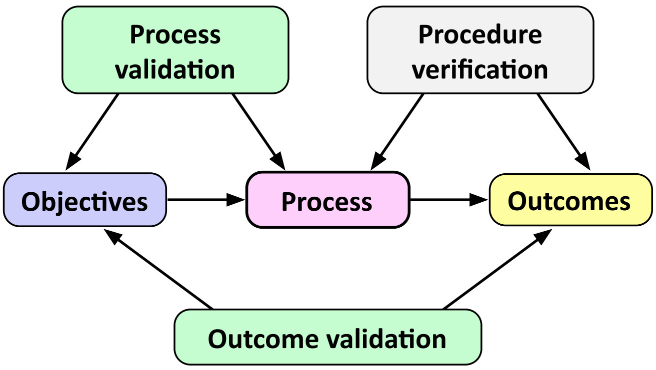


Figure 2 Validation and verification

Validation and verification, see Figure 2, are important actions in process control

Process validation is to seek answers to questions such as: 'Is the process capable of satisfying the requirements? Is this the most appropriate process in the context?' *Outcome validation* is to seek answers to the question: 'To what degree do the outcomes satisfy the objectives?'

Procedure verification is to seek answers to the question: 'Has the procedure been correctly implemented?' This question is used after the process has been established as a procedure.

In determinate situations where processes are predefined, process validation is not normally required. When working with the inherent uncertainty of system planning, process validation is of great importance because, since every situation is different, a procedure that worked in one context may not be suitable in another apparently similar situation.

Risk control

While the purpose of system planning is to achieve good outcomes, a fundamental strategy for doing that is to to take action to prevent unsatisfactory outcomes – i.e. to control risk. As well as using formal risk control methods, reflective questioning, that is a main feature of critical thinking, can be viewed as a strategy in risk control. For example, it is often wortwhile to pose 'What if?' questions.

Problem solving processes

Two basic problem solving strategies[4] are: bottom-up and top-down.

In bottom-up, one uses rules to synthesise a result. For example, in mathematics a quadratic equation such $ax^2 + bx + c = 0.0$ can be solved using the expression:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

For top-down, one proposes options and tests them for suitability. For example, for a differential equation such as

$$a\frac{d^2y}{dx^2} + b\frac{dy}{dx} + c = 0.0$$

3 Macleod I A, *Leadership and ethos in complex problem solving*, IES Journal, Vol 158, 34-37, 2019 https://library.engineers.scot/files/original/1abcc4e75de630d47cd1f08c61304860.pdf

4 Macleod I A, *To Engineer*, Institution of Engineers in Scotland, 2017, https://engineers.scot/office/resources/publications/to-engineer.pdf

there is no formula that will result in a solution: one has to guess a solution and test whether or not it is valid. Top-down is a searching process.

In problem solving, situations are either determinate or they are not determinate. *Determinate* implies that there is at least one outcome that can satisfy the objectives precisely, where logic alone is sufficient for the assessment of solutions. For example, the solution of a quadratic equation is determinate. On the other hand, in a situation that is *not determinate*, there are no outcomes that meet the objectives precisely and acceptance of an outcome has to be based on judgement, requiring the use of logic plus evidence. The term 'not determinate' does not imply that the matter cannot be resolved. It does imply that there will always be uncertainty about the suitability of outcomes.

The problems that are addressed in education for mathematics and science, are predominantly in situations that are determinate and for which bottom-up solutions are feasible – such as the solution for the quadratic equation; whereas in system planning, the contexts are not determinate and top-down is the only feasible strategy.

Use of the top-down strategy in system planning

Three basic stages in the top-down strategy are shown in Figure 3.

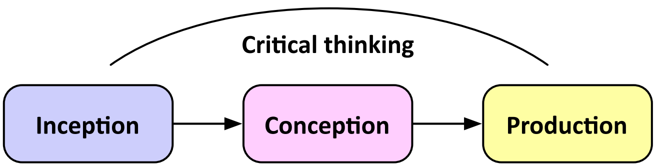


Figure 3 Basic stages for the top-down strategy

The stages are defined as:

I	Inception –	Define the strategic objectives
C	Conception –	Devise courses of action to achieve the objectives.
P	Production –	Implement the courses of action to achieve the outcome

In Figure 3 Critical thinking is shown as an overarching concept that integrates the stages and supports the systematic nature of the work. A fourth stage in often added to the list to represent feedback. For example 'outcome validation' in Figure 3 can be thought of as a stage but it is important not to treat the stages as being clearly bounded. Forward consideration of later stages, and feedback to previous stages, are very imporant features of the critical thinking ethos.

As an example, suppose that the objective is to create a building. In Figure 4(a) the *project process* is the overall process to achieve the outcome. 3 stages/subprocesses for the project process are shown:

- The strategic objectives (Inception) are in the form of a client brief.
- The outcome of the design stage (Conception) is information about what the building will be.
- The building is created at the construction stage (Production)

Each of the stages involves use of the top-down strategy. For example, the design stage (Figure x(b) for a building starts (Inception) by developing the client brief into a project brief that defines the requirements (the objectives and constraints) for the building. This is followed by a concept design stage (Conception) where a range of design solutions are considered leading to a decision about the general form of the building. Then the drawings and specifications for the building are prepared (Production). This output becomes the input to the construction stage that is also subject to the top-down strategy.

Figure 4 demonstrates the *recursive* nature of the top down strategy where sub-processes, e.g. the design process, is part of the project process but also has its own ICP stages.

The basic stages in the top-down strategy are relevant in all situations because they follow logically from the need to test proposals. But every time the strategy is used, it will be different – because the situation to which it is applied will be different.

The stages are given different names; normally more than 3 stages are defined and the boundaries between the stages tend to be flexible. For example: clinical psychologists use the names: "Assessment, Formulation, Treatment and Evaluation" for the stages in their treatment process; in quality circles (for example in ISO 9001[5]), the names of the stages are: "Plan, Do, Check, Act".

The process does not always follow directly through the stages because feedback loops, triggered by critical thinking, can occur at any point.

Making well-informed judgements

Proposals for action are normally made on the basis of judgements that should be informed by logic and evidence derived from testing.

5 ISO 9001:2015 Quality Management Systems

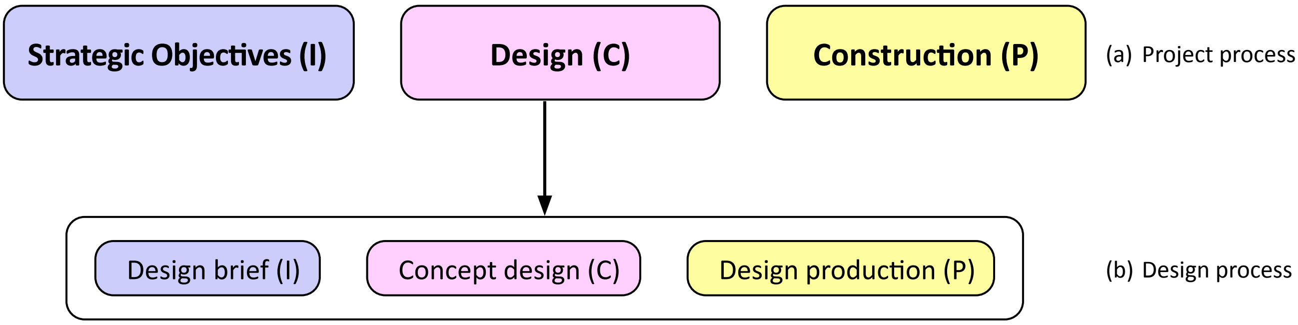


Figure 4 Processes for the creation of a building

Making an untested proposal for action, i.e. jumping to a conclusion, is strictly avoided.

The suitability of a judgement depends on the quality of the information available and the quality of the methods used in making the evaluation. Good judgements are critically dependent on good information.

Multidisciplinary competence

The range of disciplinary skills that are drawn on to address complexity is another very important feature of successful system planning. This applies especially to the key members of the team.

Collaboration, leadership

A fundamental principle for successful system planning is that, because of complexity, it is unlikely that one person will have all the necessary expertise and the work is normally carried out by multidisciplinary teams. That the team works in harmony, is crucial to the achievement of successful outcomes.

Autocratic managers make independent decisions, prefer not to consult with others and seek to marginalise those who challenge their decisions. Collaborative leaders seek consensus from the team. They expect their ideas to be challenged by others.

By failing to take advantage of the intellectual capital of the team, use of an autocratic style of management increases the risk of unsatisfactory outcomes as compared with a collaborative approach.

Being able to work together and to lead teams that focus on achieving the project objectives, are special skills that are best learned at an early age.

Commitment, integrity

Commitment to the goals of a project implies that one puts aside considerations that are not consistent with the goals. For example, it is normal for people to be inhibited about admitting to mistakes, to prefer to tell senior colleagues what the latter want to hear rather than the truth or to be biased towards actions that serve their own interests. Such thoughts cannot be banished from one's mind, but in system planning, positive action should be taken to prevent them from adversely affecting outcomes.

Integrity is the degree to which one acts in accordance with ethical principles. Maintaining an ethical stance in all activities is crucial for a fair society.

Wise Governance

Governance represents the processes by which decisions are made and implemented. Responsibility, authority, accountability are core issues in governance.

A key principle in governance is that when acceptance or rejection of proposals is the responsibility of senior management or of a client, changes to proposals generated using system planning should only be made on the basis of further proposals that have also been thoroughly tested.

3. System planning and government decision-making

In November 2020 the UK Government issued a press release[6] that stated "PM (Prime Minister) outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs."

Although many would have been involved in preparing the plan, the press release infers that the Prime Minister formulated the plan. He had, for example, the authority to

6 https://www.gov.uk/government/news/pm-outlines-his-ten-point-plan-for-a-green-industrial-revolution-for-250000-jobs

change a target date in a draft plan to his own preference without being required to justify the change. Government ministers are expected to make decisions in this way but it is highly inappropriate that they should do so.

Energy planning involves complex technical and safety-critical risks, where the consequences of error can be dire. Is it acceptable that a person with no qualifications or experience in the matter has authority to act on untested proposals? In most professional contexts such decision-making would be considered to be unacceptable. For example, suppose you have a serious medical problem. Would you prefer to be treated by a lawyer or by a team of highly competent medical people? It would be absurd to make the former choice but major decisions are made in politics on the basis of proposals from people who may lack even basic training in the subject.

When the Ten Point Plan was issued, it was not backed-up by reference to reports that demonstrated the feasibility of meeting the emissions reduction targets. If such studies were not carried out, the Plan was not based on system planning methods.

The appropriate strategy for major government decisions is to separate the responsibility for making major proposals for action from responsibility for deciding whether or not proposals be accepted. The proposals for action should be formulated by a multidisciplinary team. Acceptance (or rejection) of major proposals should normally done by ministers or by Parliament. They are elected to make decisions about the allocation of resources. Making decisions based on proposals made by specially appointed bodies would not reduce the authority of the Government or of Parliament, but it would reduce the risk of unsatisfactory outcomes.

Such a process is used by government. For example, proposals for the Queensferry Bridge over the River Forth were prepared by a multidisciplinary design team led by government staff. The proposals were approved by the Scottish Parliament. It was obvious that, due to the technical complexity and safety-critical nature of a long-span bridge, government ministers would not feel competent to force changes to the specification. Energy planning should also prompt that reaction. Indeed, all actions by government should be based on system planning principles.

A main role of government is to mould the future to the needs of citizens and of the environment. Action by governments has the greatest potential to address issues such as environmental degradation, inequality, resource depletion and climate change, that are characterised by very high levels of uncertainty, complexity and importance. In the absence of system planning by governments, the likelihood of success will be significantly compromised.

The adoption of a system planning ethos would provide an opportunity to reduce the democratic deficit in Parliament that stems from the executive power of ministers. Before deciding on proposals, the Government would seek responses from the public to documentation explaining the logic and evidence that had been used. Such public scrutiny would significantly improve accountability.

4. System planning and education

In order to learn for system planning, it is necessary to carry out project work. Later in this section, I suggest that the level of project work in seconary education and in university education is low. Therefore learning for system planning is not a core activity in education.

Ability in system planning is is crucially important in society and is an innate feature of healthy human brains (see Box 2) that artificial intelligence is not close to mimicking. Why is it not well-nurtured in UK education?

According to Donald Schön[7], in his 1982 book *The Reflective Practitioner: How professionals think in action*, all professions had to make an unsatisfactory compromise to gain academic recognition. He wrote (p21):

> *"According to the model of Technical Rationality – the view which has most powerfully shaped both our thinking about the professions and the relations of research, education, and practice – professional activity consists in instrumental problem solving made rigorous by the application of scientific theory and technique."*

Schön's argument was that the professions had to accept that university learning would be based on the principles of technical rationality but he noted (p39) that:

> *"Increasingly we have become aware of the importance of complexity, uncertainty, instability, uniqueness, and value-conflict – which do not fit the model of Technical Rationality."*

Although scientific theory can help to make professional practice more rigorous, use of such theory is only one of the strategies used in professional decision making.

7 Schön D, 1984, The Reflective Practitioner: How professionals think in action, Basic Books,

Box 2 *Homo sapiens* and the frontal lobes of the brain

We often compare ourselves to animals in a superior and arrogant manner. This notion is simplistic and overlooks various superior skills that animals possess in relation to their human counterparts. Such skills have evolved over many years to assist them living in the wild: for example superior sensory capacities, such as an advanced sense of smell or hearing, which far outstrips our own.

Nevertheless, our broad capacity for complex problem solving and intellectual functioning is certainly superior to other animals. There are complex neurological reasons for why this is the case, but one of the areas that is proposed to set man apart from other animals is in the frontal lobes, located at the very front of the head. The structure and function of the brain in animals is surprisingly similar to our own, but one distinct difference is that our frontal lobes are far larger than other animals. The frontal lobes govern complex behavioural interactions, and cognitive processes, including planning, advanced problem solving, social processing, and the governance and control of our impulses. When we drink alcohol, the functions of the frontal lobes are stunted; we lose the ability to logically appraise our surrounding and there are no "brakes" to control our impulses. We have been blessed with the capacity to assimilate and process complex information, and we need to harness this ability in a manner to benefit individuals and communities alike.

M Albiston, clinical psychologist, Personal communication, November 2022.

An educational programme that focuses on technical rationality does not address the range of skills needed in professional practice.

Presumably Schön was writing about the situation in USA. I do not have information about education for professions in the UK apart from engineering where, as I now explain, the philosophy behind the early degrees was undoubtedly based on Technical Rationality – as defined by Schön.

Engineering Education in the UK

In the nineteenth century, William Rankine, the Professor of Engineering at Glasgow University and first President of IES, struggled to get agreement by the University to offer degrees in engineering. In 1872, he accepted a proposal for a degree in engineering science[8]. The University would not allow the practice of engineering to be included in the curriculum. It is unlikely that the term 'Technical Rationality' was used to justify this arrangement but the study of science was deemed to be suitably rigorous whereas the study of engineering practice was not. This was the view across the UK university sector but it was seriously misguided. Progress in UK engineering education was held back for over a century by this philosophy because:

- System planning, the fundamental issue in engineering practice, requires intellectual activity of the highest order.
- Use of science is only one of the techniques used by professional engineers.
- Learning the science in the absence of how to use it is like going to piano lessons and finding that there is no piano on which to practice.
- Learning to *use* the science in practical situations provides purpose. People tend to be better motivated to study when the purpose of what they are doing is evident
- Attitudes that are important in system planning are best developed from the earliest practical age.

Based on the recommendations of a 1980 UK government report[9], learning for engineering practice became a requirement for university degrees in engineering. All UK university engineering courses now incorporate project work in the curricula.

8 Small J The Institution's first president, IES Journal https://library.engineers.scot/files/original/ca6500f8c480535a5f97d7c48d30597d.pdf

9 Engineering our future HMSO, 1980

School education

'Capacities' intended to be developed via Education Scotland's Curriculum for Excellence[10] include:

- Apply critical thinking to new contexts
- Develop informed, ethical views of complex issues
- Evaluate environmental, scientific and technological issues
- Make reasoned evaluations
- Assess risk and make informed decisions
- Work in partnership and in teams
- Take the initiative and lead

These capacities are in strong alignment with the features of system planning discussed in Section 2. In order to develop such capacities, it is necessary to work on projects. Project work is the essential context for learning for system planning. Most projects have potential for learning to develop system planning skills.

Primary school

Apart from disciplinary competence, the system planning skills listed in Figure 1 are strongly dependent on ethos, i.e. on attitudes. Attitudes tend to be easy to establish when young and it is therefore preferable to start to learn system planning skills from an early age, i.e. in primary school.

Project work is already a feature of primary school learning. Day to day tasks can be used for practice – see Box 1. Older pupils can be introduced to methods of working with uncertainty at low to medium levels of complexity. They can learn to be critical thinkers, to be explicit about objectives, to do options analysis, to measure/assess outcomes and to reflect on how situations might be improved. For example[11], a primary school head teacher required her senior pupils to make a report on the suitability of the layout of their school to be used for briefing an architect for a new school. This is a very good example of learning to reflect about a situation that was within the experience of the pupils.

Secondary school

The breakdown of learning in secondary schooling into subjects with clear boundaries and the focus on knowledge acquisition makes it difficult, but not impossible, to introduce project work Having a subject that involves only project work not tied to particular subjects would be worthwhile. There are design subjects in the Scottish secondary school curriculum that are related to engineering and to art but the principle that design is part of a wider process in the achievement of successful outcomes needs to be more fully addressed. Overall, the level of project work in secondary education appears to be low.

The need for STEM (Science, Technology, Engineering and Mathematics) learning is widely promoted. When discussing the objectives of STEM, it is common to link it to 'key skills' such as critical thinking, problem solving, creativity, teamwork, i.e. to the skills needed for system planning. However, learning in the STEM subjects tends to be focused on knowledge acquisition and the solution of determinate problems (as discussed earlier) with little opportunity to develop system planning skills.

For example, traditional learning in physics covers predictive modelling, i.e. mathematical representations that can predict behaviour of physical systems. Predictive models are always approximations and it is often very important that the model adequately represents the real behaviour of what is being modelled – see, for example, Box 3.

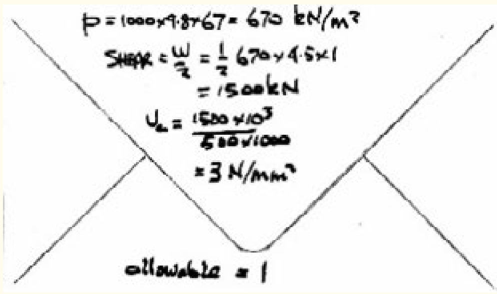
Traditional learning tends to lead to a mindset that the use of science is determinate, i.e. that it leads to outcomes that can be accepted on the basis of logic alone: where the answer is either true or it is false. In system planning, most processes are not determinate: there are no 'correct' answers and judgement is needed. Box 3 describes a situation of this type where the predictive model should have been validated against the requirements. It is very important to learn to be reflective about the suitability of models in use, i.e. to have experience of making judgements about models. Learning of this type should be incorporated into existing subjects.

Many learners have difficulty in accepting the uncertainties involved in making judgements: they prefer determinate situations where there is no ambiguity. While the use of science, in engineering and in medicine, for example, is of incalculable value, students need to learn (a) to work with the underlying uncertainties when they use science and (b) to operate successfully when science is not available for predicting behaviour.

10 Education Scotland https://www.education.gov.scot/Documents/btc4.pdf, 2009

11 MacLeod I A The discipline of critical thinking, IES Strategy paper, 2020, https://www.engineers.scot/office/resources/publications/discipline-ct.pdf

Box 3 The Sleipner Platform collapse



In 1991, the construction of a North Sea oil recovery platform was nearing completion in a Norwegian fjord. Following a loud bang, the structure sank to the bottom of the fjord. The designers had, for the first time, used a 3D predictive model of the whole structure. The root cause of the failure was identified as a simple fault in the specification of the model. A simple back-of-an-envelope calculation (right) would have identified the error. There were no injuries or deaths but the cost of the failure was of the order of $700m

System planning, as defined in this paper, is relevant to STEM situations and to situations that are not directly related to STEM and is therefore relevant to all learners.

University education

Some university courses have significant proportions of project work. For example in architecture, 50% of the curriculum is design studio work; all engineering degrees involve design project work. Most university students undertake a individual 'final year project' but I think that it is fair to conclude that the proportion of project work across university curricula is low.

A strategic objective of all universities should be that students develop system planning skills via multidisciplinary project work. That objective can be addressed at a course level, at a faculty level and at a university wide level. Some universities, e.g. the University of Aalborg in Denmark, have a significant proportion of the curriculum devoted to 'project-based learning'. The Engineering Council require that degrees in engineering involve multidisciplinary design project work.

5. Conclusion

System planning, the methodical achievement of outcomes in situations of complex uncertainty, is in common use across the spectrum of human activities, but a large sector of the population does not seem to understand how it is done or why it is needed. This is a serious flaw because we all need to work together to address global and local threats to society and to the environment. The root of the problem lies in education that should be structured to help people to develop the underlying skills but we cannot wait for education to catch up on that. The need, for example, for people in government to adopt system planning methods now, is manifest.

I cannot think of a more worthwhile objective in society than to ensure that when people seek to make the future better than the present, they know how to go about it in a professional manner.

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Science of Cracks: Fracture Mechanics

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Erkan Oterkus

Abstract

Although we may not always recognise it, cracks are important part of our daily lives. Cracks are also very important in the discipline of engineering. We can make predictions about whether cracks will initiate in a particular structure, when and which direction that they can propagate, with at what speed that they can propagate, if they will branch or not, and if they will stop or not once they propagate. The scientific field which focuses on cracks is named as "fracture mechanics". In this paper, a brief history of fracture mechanics is given starting from its early days. Then, some important concepts of fracture mechanics are highlighted such as fracture modes, stress intensity factor and energy release rate. Since numerical tools are widely used for engineering analysis, several numerical techniques developed for fracture analysis and implemented within finite element analysis framework are discussed. Finally, an emerging approach, peridynamics, is briefly introduced and its applications for different material systems, loading and environmental conditions are summarised.

1. Introduction

In many cases, we don't want cracks to happen and when they emerge, we don't feel happy about it. For example, if we accidentally drop our fancy glass cup on the floor, it will be fragmented into pieces within a second and we cannot use it anymore (Figure 1(a)). In some other cases, we need cracks to achieve something that we can enjoy. For instance, if we want to eat a chocolate bar, we first need to create a crack to open the package. The chocolate bar has been designed to make it easy to crack it into regular pieces (Figure 1(b)). Then, when we move the chocolate bar into our mouths, we create cracks with our teeth to split the chocolate bar to be able to swallow it.

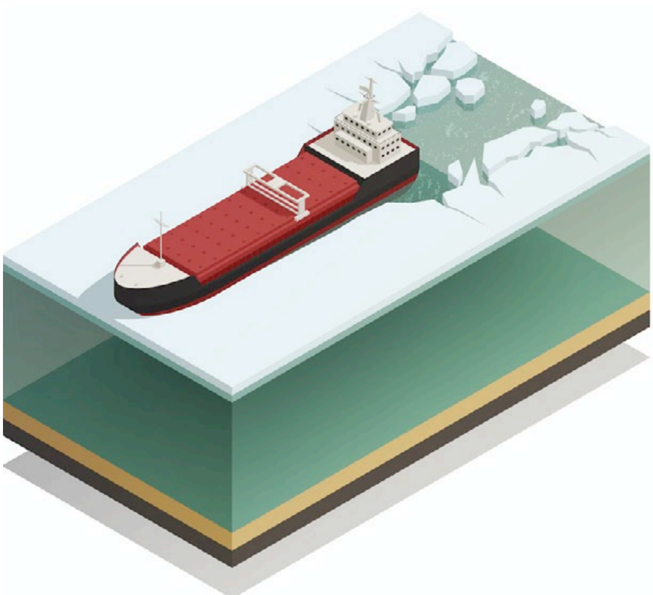
(a) Fragmented glass

(b) Opened chocolate bar package

Figure 1 Cracking in daily lives

Cracks are also very important in the discipline of engineering. Again, in many cases, we don't want cracks to happen and we try to take actions to prevent them because if they occur, they can result in catastrophic consequences such as failure of an airplane engine, ship hull cracking, explosion of a pressurised tank, etc (see Figure 2(a). In some cases, we also try to create cracks to achieve good outcomes such as cutting of metals in manufacturing process, breaking ice in arctic with icebreakers for the ship to continue its operation, etc (Figure 2(b)).

(a) Engine failure



(b) Icebreaker

Figure 2 Cracking in engineering applications

Cracks are natural features that occur as a result of physical and chemical processes. As engineers, we can make predictions about whether cracks will initiate in a particular structure, when and which direction that they can propagate, with what speed that they can propagate, if they will branch or not, and if they will stop or not once they propagate. The scientific field which focuses on cracks is named as "fracture mechanics".

2. History of Fracture Mechanics

The history of fracture analysis of structures goes back to Leonardo da Vinci and Galileo (Timoshenko, 1983). Based on his own experimental results, da Vinci concluded that the strength of a beam is inversely proportional to the its length. After da Vinci, Galileo also performed similar experiments and ended up with similar conclusions.

In order to analyse the deformation of materials and structures under external loading conditions, the French polymath Augustin-Louis Cauchy (1828) developed a mathematical framework based on the concept of 'continuum mechanics'. For this, he assumed that a structure is composed of a continuous distribution of infinitely small volumes called 'material points'. He made an assumption of locality of interactions between material points, so that only points which have direct contact can interact with each other. He introduced the important parameters of strain and stress to describe the behaviour of each material point. While the strain parameter describes the change in size and/or shape of the material point, the stress parameter represents the intensity of internal forces in the structure. Stress and strain parameters can be related to each other through a constitutive equation:

$$\boldsymbol{\sigma} = \boldsymbol{D}\,\boldsymbol{\varepsilon}$$

where $\boldsymbol{\sigma}$ is the vector of stress, $\boldsymbol{\varepsilon}$ is the vector of strain and $\boldsymbol{D}$ is the constitutive matrix.

The constitutive equation incorporates the basic assumptions for the stress-strain behaviour of the material. For example the behaviour of a linear elastic isotropic material can be described by two material constants: Young's modulus and Poisson's ratio. Based on the model of material behaviour, the stress-strain relationship for the whole structure can be defined in the form of partial differential equations of equilibrium. These equations are nowadays solved numerically to give the displacements, strains and stresses in the structure. Such output is used to assess the potential for fracture at different states of loading. Cauchy's continuum mechanics formulation has been one of the great successes of engineering and has been used to analyse numerous complex problems of engineering.

After the expansion of railroad construction during 1800s, fatigue damage started becoming a concern since unexpected cracks emerged in locomotive axles after being in operation for some time. The reason was not clear at the beginning, and it was suspected that the main reason for the cracks was a change in the microstructure of the metal under stress. William Rankine, the first President of IES, was commissioned to investigate the cause of the failures. From examination of several failed axles, he noted that there was no significant change in the microstructure, but made the observation that having straight angled corners where the axle changed shape appeared to exacerbate the formation of cracks. In 1843 he recommended the use of rounded corners in castings (Rankine, 1843) This was a remarkably insightful observation. In the 20th century, failures of the Comet airliner were attributed to the lack of rounded corners in the window holes in the fuselage (Withey, 1997)

Jean-Victor Poncelet (1826) used the term 'fatigue' for the first time by describing the fact that metals can get "tired" when they are under repeated action of tension and compression loadings. It was found that structures which are subjected to cyclic loading condition can fail as a result of fatigue damage. Fatigue is still one of the most common and dangerous damage mechanism for structures in operation such as ships, airplanes, trains, etc.

A A Griffith (1921) made significant contributions to fracture mechanics. Rather than using strength-based concepts, he introduced a new failure criterion based on the First Law of Thermodynamics. According to this criterion, for a crack to be able to propagate, the strain energy change should exceed the surface energy of the material to create a new incremental crack surface. He demonstrated the validity of this criterion by performing fracture tests for glass specimens. Although this discovery has made significant impact to the field, the proposed criterion did not show reasonable success when applied to metallic structures. It was then concluded that Griffith's criterion is limited to brittle materials for which insignificant plastic deformation occurs at the crack tip. Materials like metals can show different fracture behaviour known as "ductile fracture" including significant plastic deformation and should be represented with a different criterion.

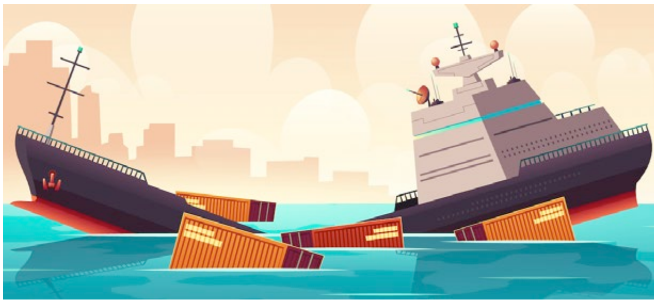


Figure 3. Cracking problem in ships[11]

Fracture mechanics attracted more attention after World War II. During World War II, "Liberty ships" were manufactured in the U.S. using the then novel method of welding rather than riveting. This significantly reduced the manufacturing time that was especially critical during the war period. Although this was an important achievement, cracking problems arose in these ships after a short period of time and some of them split into two (Figure 3). This problem motivated researchers and scientists to investigate the causes of the cracking. Amongst these, G R Irwin at the Naval Research Laboratory in U.S. extended Griffith's approach to metallic structures (Anderson 2013) by taking into account the energy dissipation due to plasticity at the crack tip. He also introduced the concept of energy release rate. During these years, there was also significant development in the analysis of fatigue damage. Cyclical test loading for fatigue was introduced early in the twentieth century. Specimens are repeatedly subject to repeated stress levels to produce stress vs number of cycles (S-N) curves. These are widely used but provides information about the time necessary for the structure to fail due to fatigue damage. Paris-Erdogan (1963) introduced a new equation which can describe how a fatigue crack can grow in a structure under cyclic loading, which has been named as Paris-Erdogan law. Since then there has been significant achievements made in fracture mechanics field and there are still many questions to be answered and explored. Detailed information about the history of fracture mechanics is given in Timoshenko (1983).

3. Important Concepts of Fracture Mechanics

In fracture mechanics, it is assumed that a fracture can occur in three independent modes of fracture (Figure 4). Mode-I or opening mode, is related with a condition that the loading is trying to open a crack. Mode-II or shearing mode, is related to in-plane shear loading which causes crack surfaces to slide on each other. Mode-III or tearing mode, is related to out-of-plane shear loading, describing the tearing behaviour. In a real scenario, a crack can be subjected to one of these fracture modes separately or a combination of them which is called mixed-mode condition.

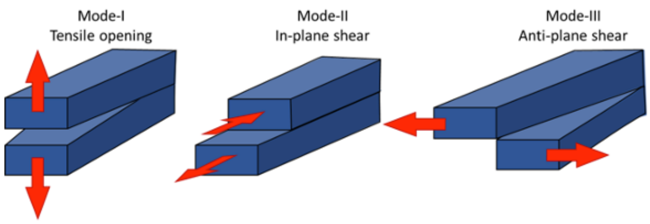


Figure 4. Three independent modes of fracture

It is not always possible to solve the equations of Cauchy's classical continuum mechanics by using analytical techniques i.e. by direct solutions of the differential equations. Such solutions are limited to particular geometry, loading, material type and boundary conditions. The Airy stress function is widely utilised to obtain analytical solutions. Williams (1957) determined a suitable Airy stress function by defining a polar coordinate system to analyse the stress field around the crack tip. According to this model, the stress field is inversely proportional to the square root of the distance from the crack tip and varies as a sine function depending on the orientation of the location of interest with respect to the horizontal axis. Moreover, the stress field is dependent on a constant which varies depending on the fracture mode.

The constant parameter defining the stress field in the Williams solution is called the "Stress Intensity Factor" (SIF) which is a very important parameter in fracture mechanics. SIF mainly depends on the geometry, location and orientation of the crack, material type, boundary conditions and loading. SIF values are defined for different fracture modes in handbooks. Cases that are not included in the handbooks can be calculated by using a numerical technique, such as the finite element method (FEM).

As mentioned earlier, an important outcome of the William's solution is that the stress field is inversely proportional to the square root of the distance from the crack tip. As a special condition, if stress values are to be calculated at the crack tip, they converge to infinity since the distance value takes a value of zero at the crack tip. This causes an illogical condition that even for a very tiny load, very large (infinite) stresses can occur at the crack tip. If such condition were true, then all cracks would propagate regardless of the loading that they are subjected to. In reality, for cracks to propagate, they should be subjected to a certain amount of loading. Therefore, this particular condition makes the use of a stress parameter questionable for making decisions about the safety of structures. Instead, energy based parameters such as energy release rate or J-Integrals are widely used along with material parameters such as critical energy release rate and fracture toughness.

4. Numerical Techniques for Fracture Mechanics Calculations

In addition to analytical solution for the equations of continuum mechanics, there are numerical techniques available and widely used in both industry and academia. Amongst these, the finite element method (FEM) has become a standard numerical tool available for structural analysis. Despite its success, Cauchy's continuum formulation and associated numerical techniques have encountered difficulties for certain problems of interest. One such problem is the analysis of cracks and their evolution. This is mainly because of the emerging discontinuities due to cracks which makes the partial differential equations invalid along crack surfaces since partial derivatives cannot be defined due to discontinuity in the displacement field. To overcome this problem, various solution strategies have been proposed.

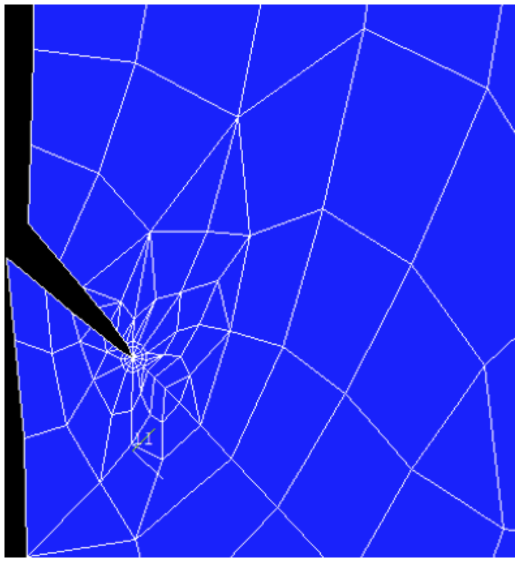


Figure 5. Finite element modelling of cracks with special crack tip elements

Traditional FEM is not suitable to analysing cracks. To improve its capability for this purpose, several approaches have been proposed. Special crack tip elements have been introduced by modifying standard finite elements that cannot capture infinite stresses (singularity) at the crack tip (Barsoum 1976). These special elements (Figure 5) are suitable for calculating stress intensity factors at the crack tip, but they do not adequately simulate crack propagation. To simulate propagation, "remeshing" techniques have been developed (Wawrzynek and Ingraffea 1989). After determining the condition that a crack should propagate by satisfying a particular failure criterion, the solution domain is meshed again by considering the new crack surfaces. Although this approach can be suitable for some relatively simple cases, it is usually considered as a tedious process since the remeshing process is a time consuming part of finite element analysis.

Another important development was the introduction of cohesive elements (Hillerborg et al. 1976). Cohesive elements can be considered as a series of springs and their behaviour is described by a traction-separation relationship. Cohesive elements are normally added along and between the boundaries of traditional finite elements. Once a stress value in a cohesive element reaches a critical strength value, the element starts to indicate damage and can completely fail once a critical separation is exceeded.

Once the element fails, cracks naturally propagate along the failed cohesive elements. Therefore, there is no need for remeshing of the solution domain. Although cohesive elements remove the necessity of remeshing, since cracks may need to propagate along directions other than element boundaries, cohesive elements may suffer from mesh dependency problem. To overcome the mesh dependency problem, extended Finite Element (XFEM) has been introduced with the capability of splitting traditional finite elements if crack needs to propagate inside the element domain(Sukumar et al. 2000) Although XFEM brings the advantage of resolving the mesh dependency problem, other challenges may be encountered such as crack surface detection especially for 3-Dimensional cases.

5. A New Approach for Fracture Analysis: Peridynamics

As an alternative approach, a new continuum mechanics formulation, peridynamics has been introduced by Silling (2000). According to this new continuum mechanics formulation, the equilibrium equation of each material point is represented by using an integro-differential equation rather than a partial differential equation. Since the peridynamic equation does not contain spatial derivatives, it is always valid regardless of discontinuities. Therefore, it becomes very suitable for the analysis of crack problems. Another major difference between peridynamics and Cauchy's continuum formulation is the non-local interactions between material points. In peridynamics, rather than limiting interactions to nearest neighbours as in Cauchy's formulation, all material points inside an influence domain, horizon, can interact with each other in a nonlocal manner. The size of the horizon is a length scale parameter which can also be used to describe non-classical material behaviour mostly seen at small scales. Therefore, peridynamics can be utilised for the analysis of both large scale structures such as ships, airplanes, buildings, etc. and small scale structures such as graphene sheets, carbon nanotubes, etc. used for advanced technology applications.

Although peridynamics has its own material constants, there is no need to perform additional tests to determine these constants. Instead, existing material parameters based on Cauchy's continuum mechanics formulation can be related to the peridynamic material parameters.

Analytical solution of peridynamic equations is usually not possible and numerical solution techniques are utilised. For this purpose, meshless methods are generally used. As opposed to mesh-based discretisation as in finite element analysis, the solution domain can be discretised into small regions and each small region can be represented by a point located at the centre of that region. Then, these points can interact with each other by defining a spring (bond) between them if they are inside the horizon of each other (Figure 6).

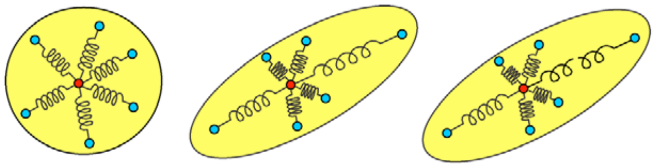
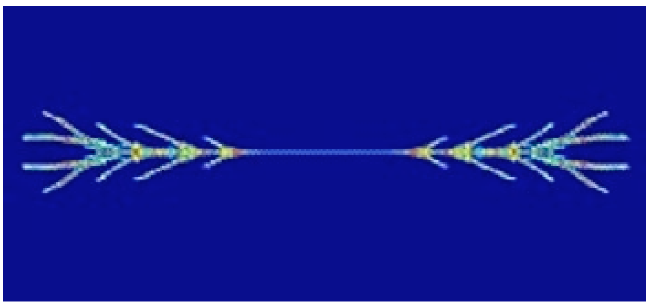
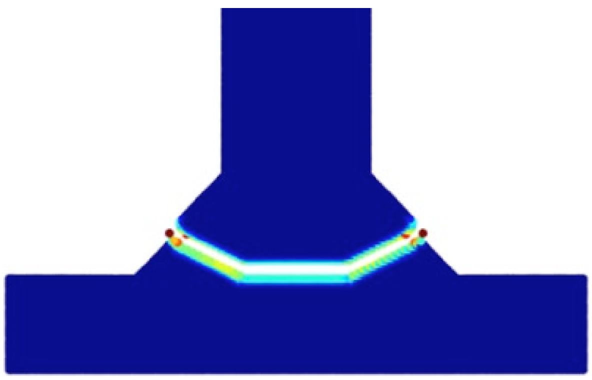


Figure 6. Peridynamic interactions between material points inside a horizon and failure of an interaction

The definition of failure in peridynamics is relatively more straightforward with respect to other existing techniques. For brittle materials, failure of an interaction (bond) between two material points is defined in a way that if the stretch of the interaction exceeds a critical value, then the interaction is assumed to be broken. Critical stretch parameters can be related to fracture toughness or critical energy release rate of the material. Since critical energy release rate corresponds to the energy required to create a unit crack surface, peridynamic representation of this can be achieved by breaking all interactions passing through the same crack surface. Therefore, by equating the critical energy release rate to the energy required to break all interactions passing through the crack surface allows determination of the relationship between the critical stretch and critical energy release rate.



(a) Crack branching (Madenci and Oterkus (2014)



(b) Fatigue cracking of a welded joint (Hong et al. 2021)

Figure 7. Peridynamic simulation

There has been significant progress on peridynamics especially during the recent years. It has been used to analyse crack propagation in different material systems such as metals (Amani et al. 2016), composites (Oterkus and Madenci 2012), concrete (Oterkus et al. 2014), ice (Vazic et al. 2020), etc (Figure 7). It has also been shown that the Peridynamic fatigue model (Nguyen et al. 2021) can show superior characteristic with respect to SN curve approach and Paris-Erdogan law with the ability to predict all three phases of fatigue, i.e. fatigue initiation, fatigue crack growth and final failure. Peridynamics can also be used to predict different corrosion mechanisms including pitting corrosion (De Meo and Oterkus 2017) pit-to-crack transition (De Meo et al. 2017), hydrogen embrittlement (De Meo et al. 2016) and corrosion fatigue (Karpenko et al. 2022).

The application potential of peridynamics is enormous since many engineering applications can suffer from different types of damages. As an example, a major electronics company used peridynamics for failure analysis of electronic packages, i.e. enclosures for electronic devices – as shown in Figure 8 (Oterkus et al. 2014).

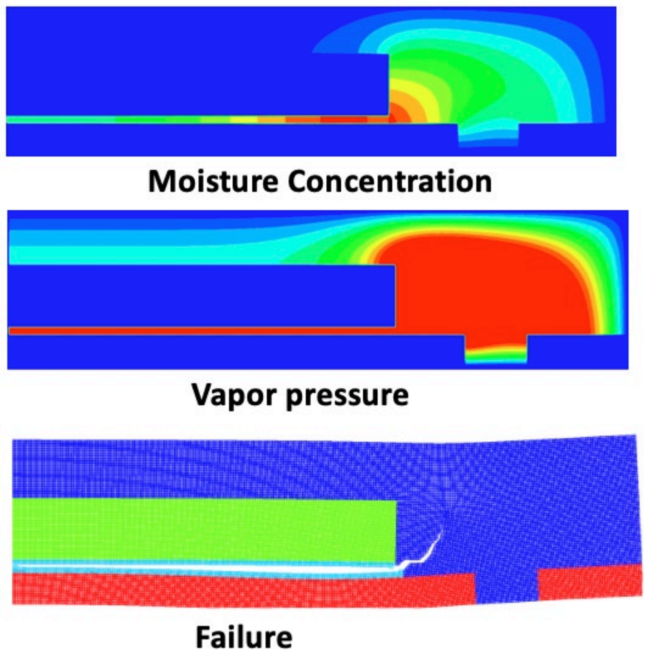


Figure 8: Peridynamics for failure analysis of electronic packages

6. Conclusions

Prevention of cracks in structures that will lead to failure is a critically important task in the design of structures. The paper has shown that the science of crack prediction has been under continuous development for over 200 years. Such technology has undoubtedly prevented many structural failures. Recent developments have potential to improve the science and hence to improve ability to prevent failures.

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Energy Benchmarking

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Abstract

This article summarises the lessons learned about energy benchmarking over the last three years, as developed in a series of studies on the cold storage logistics business. The results were presented as papers at international conferences in Canada, Scotland, Japan, Macedonia, Norway and England The article uses real data from live sites to illustrate the various advantages gained by pursuing this goal and explains how to add this capability to an existing facility. The possibility of using similar techniques in other sectors is briefly discussed.

Andy Pearson

Introduction

Nowadays everyone says that energy efficiency is one of the most important metrics in their business. With gas and electricity prices reaching record heights it is clearly a key topic but many people don't seem to know what to do about it. It is relatively easy to tell whether someone is really interested in the energy performance of their facility. All that is needed is to ask them whether they sub-meter their electrical consumption so that they can tell which parts of the system are using the energy that they are buying. Without this level of granularity the only thing that people can do, faced with rising energy bills, is despair. With this information it is possible to construct a cost-saving plan, often without much capital investment.

Information is critical to the success of any benchmarking activity. Ideally, the information should be gathered automatically and stored for long-term analysis of trends and developments. It should be easily verified to provide a sense check on the numbers presented and should not be affected by occasional gaps in the recording caused for example by power outages or component downtime. It should be delivered to the plant supervisor and key decision makers in an easily understood format, preferably graphically, but the raw data behind the graphs should also be available for more detailed analysis if required. Modern industrial refrigeration systems already are equipped with sufficient computing and storage capacity to do this.

Defining the Metric

For logistics warehouses it is appropriate to calculate the energy consumption per volume of the cold store over a defined period. This is known as the Specific Energy Consumption (SEC). It is common to use full year energy because the business tends to be seasonal and the system performance is somewhat dependent on the ambient. This gives a measure of energy per volume per year, in units of kWh m^{-3} y^{-1} which is sometimes abbreviated to kpma (short for kiloWatthours per cubic metre per annum). If the warehouse includes a lot of automated conveying and sorting equipment then the SEC metric will tend to be higher for a given volume and conversely if the building is relatively tall the metric will tend to be lower. If the facility includes a processing capability, for example a blast freezing service in addition to product storage and marshalling, then the SEC for the whole facility will tend to be higher and more variable, depending on the amount of processing handled, but in this case with access to the freezer throughput it is possible to segregate the process

energy use from the logistics energy use to create more meaningful metrics for both parts of the operation.

Benchmarking

There are three key elements to a benchmarking programme. It should be possible to track a facility's performance over time to judge whether it is improving or declining. It should also be possible to compare the facility under examination with other facilities operated by the same owner or even competitors' facilities. It should then be possible to use recorded data to predict the direction of travel of the trend in order to assess the benefit of taking early action to improve performance and to assess the financial benefit, if any, of action already taken. Each of these aspects of benchmarking is considered here.

Individual facility performance

The construction of a database of facility performance is simple. It only requires that energy use data is recorded in a consistent way on a regular basis and presented in a meaningful format to aid useful analysis. Submetering of the total electrical use is essential. Ideally, each main user of electricity in the system should have its own power meter and there should be a power meter for each functional unit too. For example, a system with three glycol chillers each with two compressors should have a power meter for each compressor and also one for each chiller including auxiliary loads such as condenser fans or drain line heater tapes. It is not necessary to add power meters to resistive loads such as heaters or smaller inductive loads like fans and some pumps, however there may be some advantages in monitoring their use, for example using a current sensing relay to indicate when they are on and allocating a factor based on the current drawn to apportion the total power use. This data should be recorded at least once a day, at the same time. Often the midnight boundary is used for this, where the data recorded is the aggregate of kWh consumed in the previous 24 hours. This requires some form of aggregation of the power meter reading, but this is easily done by counting pulses from the power meter if it is enabled with that facility. If data storage capacity is not a constraint then there will be some advantage in storing more frequently. Half-hour periods are quite common, resulting in 48 readings per data point per day. The important point about this self-referencing benchmarking is that it can only be done over a period of time, so it is essential to be regular and consistent in the method of data capture, otherwise a valid comparison will not be possible. If a major work element is being planned, for example, a compressor overhaul or a condenser replacement, then the benchmarking should be started as soon as possible, preferably several months before the work starts. This will enable the performance benefit to be assessed and might also highlight errors in the execution of the work element, as discussed later in one of the case studies.

To account for the full energy consumption it is necessary to add together the energy use for each sub-system that serves the space. For example, a cold store served by four independent units will probably not equalise the running hours of the four units within a 24-hour period. It is necessary to consider the energy used by all four and divide it by the total store volume. However, this makes it more difficult to pinpoint the cause of any higher levels of SEC that are identified. The historic data in this case should therefore also record which of the units were running so that comparisons can be made between different operating patterns. The same principle applies to a central plant with several compressors. There can be large differences in efficiency between compressors so the correlation of lead/lag arrangement and SEC can help to identify more efficient methods of running and can pinpoint additional maintenance requirements.

Comparison with other facilities

It can be extremely helpful to know how a facility is performing in comparison with similar installations. This is where the SEC is necessary. The store volume for this calculation should include all refrigerated spaces (for example, chilled loading docks and anterooms) but should not include workshops, offices and welfare facilities. There are two schools of thought on what should be included in the kWh figure. On the one hand, there is a case for saying that the whole site is relevant, so this figure should include workshops, forklift charging, office lighting, vehicle wash facilities and so on. This can be valuable, and it is often stated that the refrigeration plant will typically be 70% of this figure so it can serve as a proxy for refrigeration consumption. On the other hand, if meaningful conclusions are to be drawn about the refrigeration plant performance, then it is better to focus only on electricity use that is directly related to the provision of cooling, for example, compressors, condenser fans and glycol pumps, but not forgetting fan peripheral heaters, drain line heaters and other ancillary loads.

To date, the accumulation of SEC data across the industry has been rather haphazard. Various academic studies have gathered data on a piecemeal basis in different countries and an app is available in the UK to allow users to calculate their own SEC or sign in and compare their SEC figure with other app users (all anonymously). These early steps have shown that even this crude level of comparison can be a useful motivation for the improvement of performance but since they rely on having a year of data the ongoing benefit once the initial assessment has been made is less powerful. However, there is an opportunity for an industry body to step forward and offer a data collation service to the market so that any analysis can be made with a higher degree of confidence that the information presented is on a truly comparative basis.

Predicting Specific Energy Consumption

Both of the methods presented above require the accumulation of information over time. This does not need to be labour intensive as the SEC can be calculated knowing only the annual energy use and the volume of the building. However, if it represents the previous year's performance then it will be of limited value for the assessment of performance improvement initiatives. If it is necessary to wait a year to see the consequence of a maintenance intervention then the influence of the message will be severely diluted. Firstly, the work that produced the improvement will only be a distant memory and secondly, many other changes will have occurred which mask the true effect of the intervention. It is therefore necessary to be able to make an assessment of the effect on the annual figure without waiting a year for the result. In order to be able to do this it is necessary to understand how energy consumption varies with the seasons. For some facilities, perhaps surprisingly, the answer is "not much". This might be a good thing, or it might not. For example, if the refrigeration system is well controlled and well maintained and the building is protected from excessive heat load or moisture ingress then the energy consumption might be low throughout the year. On the other hand, if the refrigeration system is set to maintain a high head pressure in all weathers, then the energy consumption might be high throughout the year. Seasonality might also be produced by variations in product throughput. For example, a fruit storage plant will have busy spells shortly after harvest and then long periods of much lower load, or a meat freezing facility might be subject to large variations in the quantity of product handled. If an annual pattern can be established, then it can be included in the prediction method. If not, then predictions can still be made but might need to be linked to product information or else the forecast will tend to be less accurate.

Best Practice

Several studies of "best practice" around the world showed the surprising result that the relationship between cold store size and best energy consumption did not seem to be related to the local weather conditions. For example, a paper presented by an Australian contractor at the International Congress of Refrigeration in Montreal (Jensen, 2019) showed several examples of best practice installations across the east coast of Australia from Cairns in the north to Melbourne in the south. In the same conference session, the results of a UK study were also presented (Pearson, 2019). The curves for best practice in these two studies, developed without any correspondence between the authors, were almost identical. Further analysis of European and US data indicated that the same metric could be applied in those regions too.

The preferred metric, the Specific Energy Consumption, is given in equation 1

$$SEC = E/V = 15500V^{-0.63} \quad \text{Eq. (1)}$$

Where E is the energy used per year, in kWh and V is the volume of the warehouse, in m^3.

It can be seen that the best practice for SEC is a function of store volume only. The reasons for the convergence of performance around the world were explored in more detail in subsequent studies. In a paper presented at the Gustav Lorentzen conference in 2020, hosted by Kyoto, but held online (Pearson, 2020) several additional factors were considered. These included wind speed, wind direction and wind gust speed as well as ambient air temperature and solar gain. No strong correlation was found with any of the parameters for a store with a reasonably good specific energy consumption rating. It was concluded that the features of a building in use that define it to be "best practice" have the effect of dissociating the energy performance from external factors such as weather. There are many ways that this plays out in practice. A best practice facility will be kept in good physical condition, with attention paid to the quality and condition of insulation and door closures. The incoming product will be temperature controlled to ensure that additional load is not transferred to the building when it should be handled elsewhere and the refrigeration plant will be kept in good repair and controlled to provide efficient operation, for example, by allowing the compressor discharge pressure to be as low as possible under all weather conditions.

To date, there has been no definitive study on the effects of wind speed, wind direction, wind gust speed ambient air temperature and solar gain on bad practice facilities. It is likely that the factors that cause energy use to be much higher on these sites will be very varied and will require a high level of commitment from the site management to address them. There is no easy solution to bad practice.

Case Studies

The following case studies are drawn from subsequent publications in the same thread of research and development, listed under "Additional Reading".

Individual facility performance

The individual performance can be measured in a spreadsheet or app and plotted against various recognised performance standards including ETSU's best practice curve from 1994 and the averages from a European study. Output from a typical tracking app is shown in Figure 1.

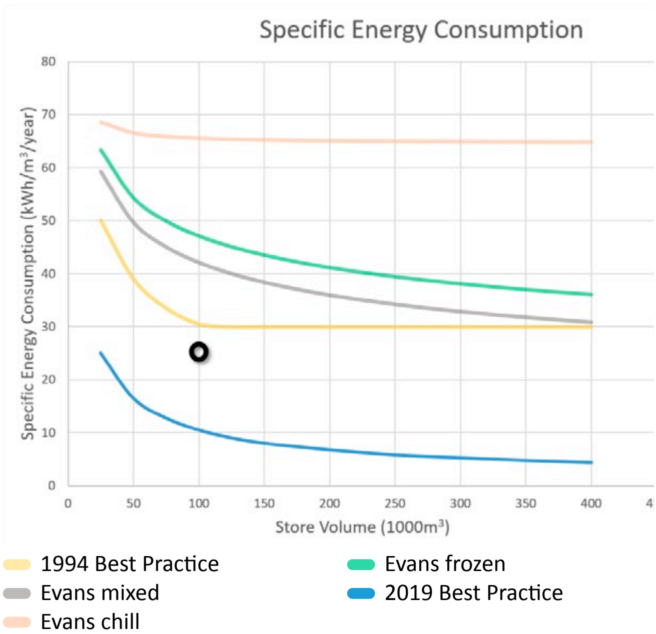

Figure 1 – Benchmarking of a cold storage facility showing SEC plotted against Store volume

Figure 1 shows a data point for a coldstore of 100,000 m^3 with an annual energy consumption of 2,400 MWh, giving a rating of 24 kWh m^{-3} y^{-1}. Note that a 25,000 m^3 store consuming 600 MWh per year would have the same SEC rating, but would lie on the best practice line since the smaller store size removes the economies of scale associated with a large facility. This method is best suited to stores of 50,000 m^3 or larger. Although this facility is higher than the best practice benchmark set in 2019 it is still not too bad – less than half the SEC of the average across Europe for frozen stores.

Comparison with other facilities

The individual methodology shown above can be extended to include other facilities within the same company, or across other companies. A typical example is shown in Figure 2.

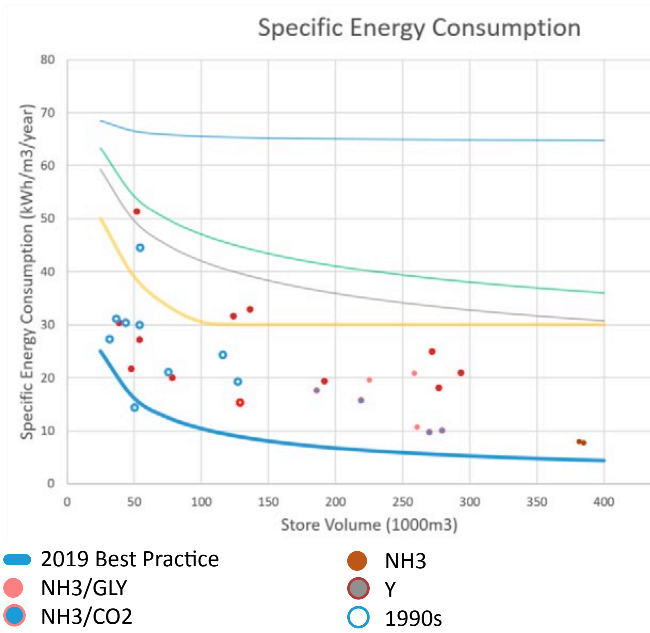

Figure 2 – Comparing SEC across different sites and different decades

This shows that even in the 1990s it was possible to exceed the best practice benchmark that had been set, with one store even managing to exceed the 2019 benchmark. It's interesting to note that the excellent performer in the 1990s was the first ammonia low-pressure receiver system installed in the UK. The scattering of sites across a wide range of sizes and system types shows that the 2019 benchmark is a good indicator of excellent performance. It can be said that any system lying between the blue and yellow lines is in the "good performance zone". Even here, there may still be scope for significant improvement.

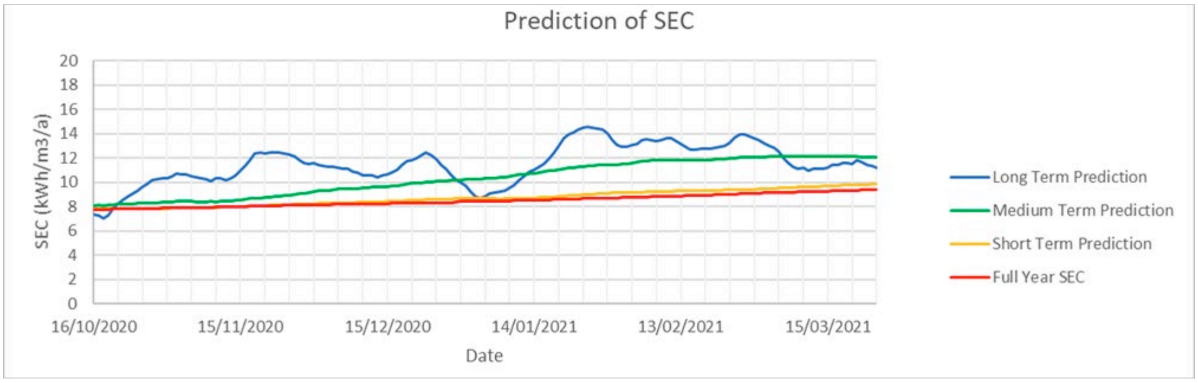

Figure 3 – short, medium and long-term predictions of SEC from a cold store site

Predicting specific energy consumption

The data presented here shows an unusual level of variability in the predictions over time, caused by the activity that was happening on-site at the time.

The red line in Figure 3 is the annual SEC data based on the previous 365 days' energy readings. The blue line is the prediction based on just 10 days of readings. During this period, from October 2020 to April 2021 a second chamber was being commissioned on the site, with all traffic to the new room passing through the original cold store. The blue line shows that energy use was much higher than previously through November and December. This was due to the initial commissioning and pull-down in temperature of the new chamber. The downturn around the end of December is because the construction site closed for a two-week break at Christmas. The upturn after Christmas is because commissioning and pulldown activity restarted, followed by a period of loading stock into the new facility. By the end of March, when this process was nearly complete, the long-term prediction was heading back towards the previous levels and even the medium-term prediction was beginning to turn around.

The operator on-site using this benchmarking system can choose to follow the graph, looking to see whether the blue line is above or below the red line as an indicator of the health of their system. The first group of numbers are from the start of the commissioning period at the beginning of October. The numbers are all relatively close, with the blue value being the lowest, indicating that the energy trends on site are downwards, thanks to a policy of ongoing improvement. One month later, at the beginning of November, the red value has hardly changed, but the blue value has risen from 7.18 to 10.48. This indicates that if the energy use continued at that level for a year, then the annual bill would be 50% higher, however, in the context of the building activity on-site this jump is understandable and expected to be short-lived. The final set of values in Figure 4 are after a further six months, once the building is fully commissioned and stocked. Although the full-year value is now high, and the medium-term (green) prediction is even higher, the blue value has dropped right down and is even lower than it was at the start of the building programme. This indicates that the store is now operating even more efficiently than it was before.

Of course, the real value of this capability is not in tracking what is happening during a building project. If a maintenance intervention is proposed in order to achieve an energy improvement then the long-term prediction (the blue value) will give a meaningful indication of the effect of the work within a few days of its completion. As time goes by the medium – and short-term predictions, if they follow the trend set by the blue value, will confirm that effect. On the other hand, if through wear and tear the performance of the system is somewhat compromised, the shift upwards of the blue line will indicate the need for some further investigation long before the adverse effect of the change is apparent. This could save almost a full year of higher running costs if appropriate, effective remedial action is taken quickly.

An example of adverse performance of a work package is the replacement of a large screw compressor, which ought to have produced an improvement in SEC performance. Instead, the system performance was evidently worse. Detailed investigation of the new compressor showed that it was marked with the required volume ratio but in fact, the wrong internal component was fitted and so it was operating inefficiently. Without SEC prediction this situation could persist for many months before it became evident and might never be discovered.

Conclusion

The days of judging cold store performance by considering only whether the room is cold enough to satisfy the QA inspectors should be ancient history by now. Temperature compliance should be a given, but the question of whether it is achieved efficiently or not is still difficult to answer. There is a need to develop a desire for energy compliance alongside the temperature compliance regime. In this regard, any form of regular record keeping and analysis will be beneficial because it helps to create a picture of normal operation. This is helpful in justifying plant improvement initiatives and also in quickly identifying when something changes for the worse.

Basic benchmarking is not expensive to implement but it can be costly to make good use of the data collected. The use of automated dashboards and analysis calculators may seem to be a more expensive path but often these initiatives pay for themselves in the savings earned and even when there is no obvious immediate improvement made, they can be considered to contribute to the financial security of the client organisation by demonstrating unequivocally that performance remains good and highlighting opportunities to make it even better.

In principle the same technique can be applied to other sectors such as commercial office buildings, production lines and even the domestic market but very careful consideration of the denominator in the specific energy consumption metric is required, particularly where human behaviour is a more significant factor. For production sites the production throughput is an essential element of the measure, but additional details may also be required. For example if the product is tubs of ice cream to be frozen the size of tub and possibly also the type of icecream may have a bearing on the performance, so need to be recorded and correlated with the energy data. For an office building it is common to use floor area as the denominator but this alone is insufficient to give a useful comparison between sites. Work patterns, amount of office equipment in the space and even the type of work being done need to be considered. Solar gain will also be an important consideration for an air-conditioned office, but it is arguable that the heat gain from insolation will have been designed out of a best practice facility through good building arrangements and the use of shading. In the domestic setting it is common to see houses rated by the number of bedrooms but this is too crude a measure to give meaningful comparisons. The habits of the occupants in both the commercial and domestic settings are also a significant factor, perhaps the dominant one, and certainly more significant than in the logistics sector. This rather gives the lie to the idea of a "net zero carbon" building – it can only be zero carbon", that is to say not causing the emission of any additional carbon dioxide to the atmosphere, until it has been occupied. From then on the emissions, or lack of emissions, will primarily be driven by the behaviour of the occupants. Energy efficiency becomes a question of motivational psychology and behavioural change rather than engineering.

Acknowledgement

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Celebrating the achievements of David Boyle

Andy Pearson

Andy Pearson was President of IES 2020 to 2022

I recently set out to investigate the life and work of Scots-born engineer David Boyle. He is included in an elite group of 65 eminent figures who are accorded a short biographical note in "A history of refrigeration throughout the world" by Roger Thévenot, published by the International Institute of Refrigeration in 1977. Note that 10 of the group of 65 are Scots, or worked in Scotland, including Dr William Cullen, Sir John Leslie, Lord Kelvin, and two former Presidents of this Institution, Professor William Rankine and Mr Alexander Kirk. Boyle was inducted into the Scottish Engineering Hall of Fame in October 2022, joining Kelvin, Rankine, Kirk and Clerk Maxwell, but it always seemed to me that he was quite different to the rest of Thévenot's group.

Thévenot wrote that Boyle "designed an ammonia refrigerating compressor (patented in 1872)" and "at the end of 1872 he built the first ammonia compressor in New Orleans". Noting that 2022 was the 150th anniversary of this achievement I set out to find out more about this little-known and enigmatic figure.

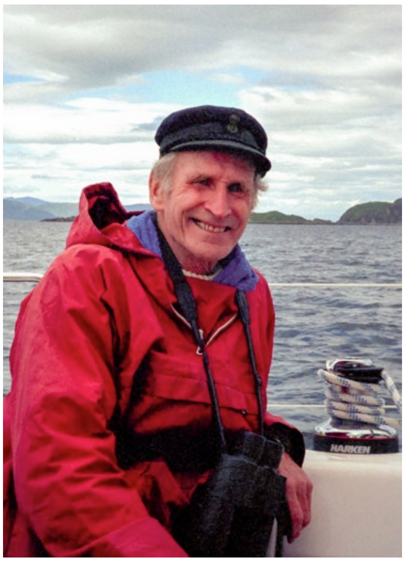
He was born in Johnstone, Renfrewshire in 1837, where his father owned the grocer's shop on High Street. David rebelled against his father's desire that he too should become a grocer and so he emigrated to the United States at the age of 21 with his younger brother James. During the Civil War the brothers were conscripted into the Confederate Navy but towards the end of the war, while living in Demopolis, Alabama, David noted that the supply of ice for cold drinks was erratic in price and availability. The ice was typically harvested from lakes and rivers in the northern states and he concluded that local manufacturing of ice could be a very profitable business. He later stated that his vision had been to make enough ice for "the whole of Demopolis", a town of about 1,200 people.

He doggedly pursued this vision for the next ten years, including the grant of a patent on "Improvement in Ice Machines", issued in 1872. However this text doesn't give any detail of the compressor used and doesn't mention ammonia so it's not quite the landmark achievement suggested by Thévenot. Reading around this topic I discovered that others had tested ammonia compressors before 1872, including French chemist Charles Tellier and American engineer Francis De Coppet. David and James Boyle had designed and built an ice making system using an ammonia compressor but they didn't get it running until the spring of 1874, not in New Orleans but in Jefferson, Texas. Encouraged by this success David relocated to Chicago to establish a production facility for their machines and it was James who applied for a patent on the novel aspect of their compressor, the poppet valves used to let gas in and out of the cylinder of the compressor. This application was filed on November 24, 1875 but James died just five days later, leaving his widow, Theresa, and his business partner, Thomas Rankin, to manage the patent process. This patent, "Improvement in Gas Liquefying Pumps" was granted on March 21, 1876 after Rankin had successfully responded to some queries from the patent examiner in December 1875.

Meanwhile David Boyle continued to develop his business in Chicago, initially working with the Crane Brothers Company to get machines manufactured and then setting up his own business, The Boyle Ice Machine Company, which successfully proved the technical superiority and commercial viability of the ammonia compression system for refrigeration. This created a surge of activity with many manufacturers in America and Europe following Boyle's lead so that, although he had initially been very successful, his business was overtaken by larger concerns and by 1891, having merged with a competitor in 1884, was finally closed down.

My conclusion to this fascinating investigation was that, although his achievement was not as popularly described and 1872 wasn't a particular highlight, David Boyle's success in establishing ammonia refrigeration systems as a viable business sector is undoubtedly worth celebrating.

Alexander Moncrieff Mitchell Stephen



March 5th 1927 – October 5th, 2022.

Alexander (Sandy) Stephen was the seventh generation and last survivor of the shipbuilding dynasty to run Alexander Stephen and Sons Ltd, at Linthouse on the Clyde.

In his book *Stephen of Linthouse*, written in 2015, Sandy charted the decline of the Stephen's yard with candour and humour. He appeared on television in " Scotland's Story", "All our Working Days and 'The Men who built the Liners' and gave insightful lectures on the shipbuilding industry.

Sandy was born in Glasgow on 5th March 1927. He was the second son of Sir Alexander Murray Stephen and his wife Kathrene Paton Mitchell. He was educated at Cargilfield and later Rugby School. After service in the navy, he went up to Trinity Hall, Cambridge in 1948, gaining a Mechanical Sciences Tripos degree.

As a second son, he decided to join the family firm ignoring warnings from his father that life as a shipbuilder would bring him nothing but trouble! After gaining experience in other yards, and at sea with the Anchor Line, he joined Linthouse as a junior manager in 1953.

The Stephen shipbuilding business started in Northeast Scotland in the 18th century, moved to Glasgow in the 19th century and was established at Linthouse on the Clyde in 1870. By 1953 it was a medium sized yard employing around 4,000 people.

With air travel expanding and the company facing fierce competition from abroad, Sandy, as Sales Director, struggled to get orders. Attempts at modernisation caused crippling labour disputes amongst the many trade union bodies involved and post war, the cost of materials was rising. In 1968 the yard was incorporated into Upper Clyde Shipbuilders which went into liquidation three years later. The engineering and ship repair business continued until 1978.

He was deeply concerned about the effect of the yard's closure on the employees. Sandy supported the Preshall Trust providing aid and activities for people in need in the Govan and Linthouse areas.

He was a member of the Institute of Engineers and Shipbuilders in Scotland becoming President in 1983-85. Sandy was responsible for securing the future financial stability of the Institution during his tenure as President. He became a Trustee of the Scottish Maritime Museum in Irvine where he was instrumental in moving the famous engine shop from Linthouse to Irvine and recreating it for future generations.

Following in the family tradition he was on the Mastercourt of the Hammermen, in the Glasgow Trades House being Deacon in 1977-78.

After 1968 Sandy took on other business interests including becoming a director

of Murray International Investment Trusts and Scottish Widows. He founded Polymer Scotland, a small civil engineering business, in 1972 which he successfully ran until his retirement in 1992.

Sandy was a gifted sportsman, but it was his skill as a yachtsman for which he will be most

remembered. He was renowned for his success in Dragon class races and in 1968 his yacht Sou'wester, came fifth in the Olympic Trials.

Sandy was a Patron of Scottish Opera and assisted several charities including the West and Central Scotland Region of Riding for the Disabled. He was a Governor of the Glasgow School of Art, raised funds for the RNLI, was an Elder of Balfron kirk and Preaces of the Sons of the Rock in Stirling.

Sandy moved his family from Renfrewshire to Ballindalloch, a large baronial house in 1972. Using his skills as a naval architect he demolished 25 rooms and created a more manageable house with beautiful gardens which he used frequently to raise funds for Scotland's Garden Scheme.

Throughout his life Sandy's ability to cope with adversity was extraordinary. At separate times, he, and his wife Sue Thomson, whom he married in 1954, faced the unexpected cruel loss of three daughters. He survived major cancer surgery in 1998 outliving his prognosis by more than two decades.

Sandy leaves a unique perspective on the Clyde Shipbuilding and a lasting testimony on how to weather the storms of life and seize each God given day.

He is survived by his wife Sue, their son, three granddaughters and a great grandson.

Obituary Carlo Dinardo

5th July 1939 – 6th July 2022

Carlo Dinardo (Italian DiNardo) was born in Italy in July 1939, the first child in a large family, two months before the outbreak of World War II. His home village, Ceppagna, lies 20 miles from Monte Cassino, where the Allies conducted a long battle to clear their way to Rome. It was perhaps what Carlo saw in local affected buildings and in nature that persuaded him to declare, at the age of five, that he wished to be an engineer. This bold ambition was neither early nor easy in attainment. At the age of 11, his uncle, living in Scotland, invited Carlo's father to travel there to help him run the shop floor of Askey's ice-cream wafer factory. Carlo, his mother and his then two siblings travelled to Airdrie to begin a new life there in 1950.

This was a dramatic change from life in rural Italy, to post-war austerity in North Lanarkshire. Carlo did well at School leading to success at Coatbridge Technical College, opening up the path to engineering. He won a mechanical engineering traineeship in London in 1955, although gained his first engineering job with the firm of "Square Grip" in Glasgow offering him training in both structural and civil engineering which he sought and preferred. He complimented his studies with evening classes in mathematics at the Andersonian Institution,which became part of Strathclyde University in 1964. Carlo's site experience was gained on the Hamilton Bypass, which he much enjoyed. In Glasgow's Park Circus Business area, aged 18, he met Irene Niven from Helensburgh, who was to become his wife. They married in 1962, setting up home in Bearsden. Three years later in 1965, Carlo qualified as a Chartered Engineer in both Civil and Structural disciplines. He also became a Chartered Highways Engineer.

This was the beginning of a rapidly expanding career based on Carlo's ability, drive, ambition, and hard work, together with the solid support provided by Irene. Carlo set up his consultancy business, Dinardo & Partners, in 1969, first in Park Circus but moving in 1973 to Mirren Court, Paisley, where the DP office is today. This business expansion coincided with a happy family extension. Irene and Carlo's first daughter Karen was born in 1965. She like her younger brother Mark followed their father into the family business, Karen also following in his footsteps to become the first female President of the IESIS. Carlo's youngest, Lorraine, is a medical Doctor. Carlo was a very proud and devoted grandfather to Keir, an engineering graduate, and to Zoe a medical student.

In 1976, at the early age of 37, Carlo became a Fellow of both the Civil and Structural Engineering Institutions and a Chartered Highways Engineer. In parallel, his business had by then spread to offices throughout Scotland and then to London and Bristol, reflecting his wide-ranging interests in a large variety of structural and civil engineering design projects. These included contracts related to industrial, commercial, residential and hotels. In addition his consultancy business spread into Conservation projects notably at Fort George, and his patented design for Float – Out Bridges attracted design awards and Government plans in Singapore. Other overseas ventures also met with success in Hong Kong, China, and Nigeria, his 23 storey Hotel design built in earthquake zone, Fuzhou, PRC, in the 1980's, in collaboration with the Hong Kong / Chinese Team.

While Carlo was first and foremost a family man, his energy and outgoing temperament also saw him active in the major Engineering Institutions. Not the least of these was his involvement in the Institution of Engineers and Shipbuilders in Scotland. He was a long serving Member on the IESIS Council, and the President 1999 – 2001. As President he helped organise the production of the Millennium Commemorative Volume, "Mirror of History "published by IESIS in the year 2000.

He also enjoyed serving on the Education Committee of the IStructE, and on the AACE Scottish Committee.

In addition to his professional interests he took his civic responsibilities seriously. He was a member of the Trades House, the Incorporation of Cordiners, and of the Glasgow and Paisley Hammermen. He was also a patron of the Arts, annually supporting the Glasgow Art Exhibition at the McLellan Galleries. He was in addition a member of the Royal Glasgow Institute of Fine Arts and of the Paisley Art Institute, and when time permitted he indulged in hobby painting himself. He also had a long and keen interest in education and served as a Westbourne School Governor. For relaxation he was above all a keen golfer.

He and Irene had only just returned from Florida when sadly he suffered an aneurysm and died in hospital in Glasgow, the day after his 83rd birthday. He was a distinguished and successful Engineer and a man of warm friendships. He is greatly missed.

Tony Slaven

David K Harrison

6th March 1954 – 11th December 2022

Members have been shocked to hear of the untimely passing of Past President David Harrison.

David was a popular President and member of the Institution.

David served his apprenticeship at Fodens Ltd in 1970, some of his experiences and observations were documented in his Presidential Address (2008). After completing his apprenticeship David went on to study at the University of Manchester, gaining his degree, then his masters and finally his PhD. Once qualified David taught at the University of Stafford for several years before moving to Glasgow Caledonian University in 1994 as the Assistant Head of the School of Engineering. He went on to hold many leadership roles within the School. David managed a wide range of collaborative projects with colleagues and students as well as a diverse group of manufacturing companies. His research interests were primarily concerned with improving overall manufacturing competitiveness in companies via Optimised Design, Computer Aided Design, Computer Aided Manufacturing and advances towards Computer Integrated Manufacuring. Through his involvement with European projects he built up strong links with fellow academics in several European countries forging relationships that led to many research breakthroughs.

David's prestigious academic track record included over 500 publications, 85 PhD supervisions and numerous external PhD examinations. In 1995 he was awarded the Rector's Medal of the University of Mining and Metallurgy, Krakow, Poland, for his work in promoting international co-operation.

David was also a key figure in the Engineering Professors Council since its formation in 1994 and had served as Secretary for more than ten years – a position he held until his passing on 11th December 2022. He held a respected position on the Board and had been an active member of multiple committees.

David joined the Institution of Engineers in Scotland in 1995 and contributed greatly to the running of the Institution, serving on Council for several terms before becoming President in 2008 (2008-2010). David supported the Scottish Engineering Hall of Fame initiative, started in 2011, which celebrates the contribution and achievement of Scottish engineers. He was particulary delighted when some of the unsung heroes of the profession were recognised. In his Presidential Address David was able to document how the tremendous changes in engineering manufacturing over a 40 year period had been enabled by developments in Computer Aided Design.

David was a key figure in promoting the Institution to students and encouraging many to join. He started the 'University Lecture' which brought professional engineers to the university to give talks to students.

He also helped to forge closer links with other organisations, particularly the Hammermen of Glasgow. He will be greatly missed by members.

David is survived by his wife Gill, his two daughters Fran, Christine and three grandchildren.

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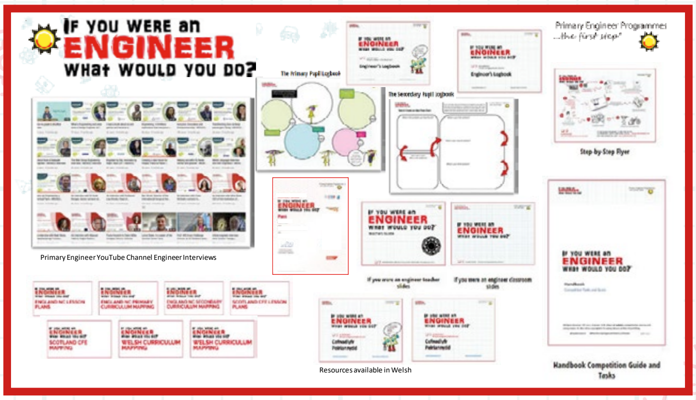

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