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Creating systems that work: Principles of engineering systems for the 21st century

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The Royal Academy of Engineering promotes excellence in the science, art and practice of engineering.

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Creating systems that work: Principles of engineering systems for the 21st century

Front Cover: Courtesy of Transport for London. Reg. User No. 07/E/1737
The London Underground is a highly complex system, bringing together mechanical, civil and electrical engineering and the skills and efforts of the people who run it. But passengers see it solely as an efficient way of getting around London. The iconic map embraces all of that complexity in a model that tells a passenger all that is needed to plan a journey.

**Creating systems that work:
Principles of engineering systems for the 21st century**

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'When we mean to build,
We first survey the plot, then draw the model,
And when we see the figure of the house,
Then must we rate the cost of the erection,
Which if we do find outweighs ability
What do we then, but draw anew the model
In fewer offices, or at least desist to build at all?'

Bardolph, Henry IV, Part II, Act 1

NASA specified and developed, at great expense, a
ball point pen that Apollo astronauts could use in
space where gravity would not make the ink flow.
Russian cosmonauts used pencils.

Moral: specify what you want to achieve, not how to achieve it

Foreword

The challenges of the 21st century, from climate change to bird flu, can only be met by more effective use of science and technology, unless we want to go back to living in caves. Science provides the insight to understand the world around us; engineering uses technology to build the systems that meet our needs – energy, transport, food, health, entertainment and the rest. Those systems must work: do what they should and not do what they should not, do it on time and within budget, do it safely and reliably. These things do not happen by chance; they happen by design.

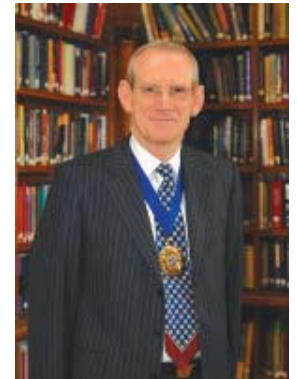
Engineering systems, and the problems that they seek to solve, are becoming more complex. It is not possible to design part of the system in isolation without considering the problem and its solution as a whole. This spans professional disciplines – it is not possible to conduct mechanical engineering in isolation from the other branches of engineering – and it reaches outside the technical domain to encompass the environment of the system. This includes not only the natural environment but also the human one – the relationships between the stakeholders and the legal and social framework within which the system must be built and used. We need Integrated System Design that looks holistically at both the need and the solution, and we need engineers who can *think holistic* to carry it out.

The Royal Academy of Engineering supports Visiting Professors in Integrated System Design, building on related schemes in engineering design and sustainable engineering. The guidance in this booklet will be a welcome support to their work in helping universities to develop the engineering curriculum for the 21st century, setting out some general principles and ways of thinking without prescriptively giving *the answer*. Engineering design, especially Integrated System Design, is an art as well as a science and our students will learn from the practical experiences of the Visiting Professors as much as the systematic approach set out here.

We can no longer afford the luxury of educating engineers purely in narrow specialisms. The UK's future prosperity depends on engineers who, as well as being expert in their own discipline, can contribute to team efforts that break down traditional silo walls. We need them in the design teams; equally we need them within the customer organisations for engineered systems. As manufacture and detailed design increasingly is conducted outside the UK, Integrated System Design remains the place at the top of the *food chain* where we can excel and create the greatest added value.

John Baxter FREng

President, Institution of Mechanical Engineers



Preface

Why should you read this document?

This guide is written for an audience that is familiar with everyday engineering language and concepts. We apologise to others for whom the terminology that we have used is not familiar, and we hope that the sense remains clear.

This guide will help you if you work in:

- **education** – both engineering students and those who are responsible for planning and delivering their education
- **engineering** – practising engineers and engineering managers who have to design and build systems that work within an increasingly complex and demanding business environment
- **business** – those responsible for specifying, procuring and operating systems that meet their business expectations, in the public or private sectors.

This is not a textbook, nor is it a recipe book. It does not tell you what to do. But it does offer insight into the challenges of building systems in the 21st century and a set of principles that might be incorporated into education and management.

Customers rarely want a *system*. What they want is a *capability* to fulfil effectively a business objective. The system, be it a building, vehicle, computer, weapon or generator, is usually only part of the means to deliver the capability – housing, transport, calculations, defence or electricity. Engineers are responsible for identifying with the customer the capability that is really needed and expressing it as a system that can be built and is affordable.

If the UK is to maintain and grow its strength in designing and building systems, we have to improve both the way that engineering is taught and the way that it is applied. We must produce and employ effectively engineers who bring to the design and implementation of projects:

- **creativity** – to devise novel, imaginative and effective solutions to the real problem and not to force the problem to match a solution
- **analysis** – using the tools and methods of mathematics and science, including the human sciences, to model and predict the behaviour of the interacting parts of complex systems
- **judgement** – using insight, experience and wisdom to reconcile the inevitable conflicts between competing demands and to align systems with customers' needs
- **leadership** – focusing on the right technical challenges & motivating others to succeed.

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Introduction

Context

A car is no longer simply designed by an automotive engineer. Neither is an accounting package designed by a programmer. Nor is a hospital by an architect or civil engineer. All three, like many other products and services, are *systems* incorporating a wide variety of technologies beyond the scope of a single specialist engineer.

Many stakeholders make demands. Society sets legal and regulatory requirements and less formal but equally important standards for acceptability. Suppliers of technology and materials need to know what is required and how to achieve it. The customer's business will have its own traditions and culture, as well as the need to work in the wider environment of society, including insisting that the product designer addresses the disposal of a product at the end of its life. The system must be sustainable – it must meet today's needs without making unreasonable demands throughout and at the end of its life.

These changes demand a different type of engineer with different skills. While it may still be appropriate for engineers to specialise in one discipline, they need in addition to appreciate how their specialism contributes to the bigger system. This involves not just appreciating what relevant technologies other specialists can offer to a project, but an understanding of, and ability to communicate with, the wider environment in which they operate.

Rising to the challenge

In order to stimulate the fundamental changes in thinking required, the Royal Academy of Engineering sponsors *Visiting Professors in Integrated System Design*, building on and complementing the earlier successful schemes for engineering design and sustainability. The VPs are engineers, with experience of designing and operating systems, who help university engineering departments. The aim is to inculcate into engineering courses the essential nature of systems and why every engineer needs today to have knowledge of what it means to design a system as opposed to a simple free standing product. Successful engineers need a system design background and culture, not

to be constrained by the boundaries of their own discipline. They must combine breadth with depth, flair with rigour, judgement with analysis.

This guide was written by engineers who have been responsible for designing and building major systems. It describes the nature of systems and their specification, construction, testing, use and disposal. The authors identified six general principles that encapsulate their experience; principles that work and set out the contextual framework for engineering in the 21st century. Not surprisingly, they align closely with the principles of sustainable development – sustainability, like capability, comes from thinking about the whole problem.

The principles are important:

- for **academia** – because graduates who *think systems* are in demand so universities must teach engineering fundamentals and how to apply them in complex situations
- for **business** – because integrated system design reduces cost and risk and ensures that the customers get the capability they need
- for **students** – because their future depends on being adaptable members of multi-disciplinary teams, able to distinguish the wood from the trees
- for **society** – because the challenges of the 21st century can only be met by customers and other stakeholders playing their crucial roles in demanding, specifying and operating systems that will work.



Electronics, mechanics, materials, ergonomics and aesthetics all contribute to making an excellent car – no one part can do it, and no one part can be specified or designed, without the context of the others

What is a system?

Emergent properties

Even apparently simple systems can have surprising emergent properties. Take for example a bicycle. The capability that the rider is seeking might be to travel safely and easily. Many technologies and skills like unconscious balancing have to come together for the capability to emerge. It would be hard to predict this from a drawing of a bicycle or even from the first experience of trying to ride one.

A system is a set of parts which, when combined, have qualities that are not present in any of the parts themselves. Those qualities are the emergent properties of the system. Engineers are increasingly concerned with complex systems, in which the parts interact with each other and with the outside world in many ways – the relationships between the parts determine how the system behaves. Intuition rarely predicts the behaviour of novel complex systems. Their design has to iterate to converge on an acceptable solution. That solution might not be what the customer originally envisaged – aligning expectations with what is achievable is an important part of the design of systems and the design engineer has to work closely with the customer and the other stakeholders.

Design is always hard – synthesis of technical expertise, insight and trade-offs combined with creativity are needed to make anything work – but complex systems bring additional challenges. If the emergent properties are hard to predict, simple design is no longer enough. Analysis, experimentation, modelling, prototyping, evaluation and testing are vital, all set in a framework that ensures that cost and timescales remain controlled.

The way that systems are built and used must also be rigorously controlled. The commercial, contractual and personal relationships have to be designed and managed along with the technology. And the system that emerges has to work, taking account of the strengths and weaknesses of the people who will use or even inhabit it. All this has to take place within the constraints of what already exists and what will exist when the system is built and operated, overlaid by the realities of finance and politics.

The challenges often lie deep in the system, far below its superficial structure. Less than half of the cost of a modern warship lies in the obvious parts – the hull and engines. The balance lies in the electronics – radar, communications and control – and weapons. It needs judgement, insight, creativity and diplomacy to weave a successful system out of its disparate parts.

Complexity arises in all engineering; it is not just restricted to aerospace, electronics and computing. Heathrow Terminal 5 is the largest construction project in Europe. It brings together hundreds of contractors in a highly interlinked sequence of activities to ensure that it is delivered on time, to specification and within budget. A car comprises thousands of parts, each of which has to work in conjunction with the others. The parts cannot be designed in isolation; each has to meet its specifications and be connected to and work with others. So, the specification of the engine has to take account of the mass and volume of the body, the body design depends on the market, the market determines the suspension characteristics for the right ride and the suspension has to be designed for the engine's mass and torque. Similar loops exist between the components within each of those major parts, and between components in different major parts. The car has

who told you big projects

go wrong?

Norman Haste, Project Director
Heathrow Terminal 5 (1996-2002)

to be designed as a system; the components tested against their specifications and then integrated into that system. The car itself is a sub-system which has to be integrated into the wider transport system that takes account of the needs of the owner, driver, passengers and society as a whole. Above all, if people do not want to own it or drive it, it won't sell.

Systems that work balance conflicting constraints. Some systems apparently have an over-riding priority. Transport systems carry people so must be safe, satellites cannot be repaired so must be very reliable. Safety and reliability are emergent properties that result from the interaction of all of the parts – hardware, software and the human elements. Safety or reliability cannot alone determine the architecture or how it is implemented; the train or spacecraft must be affordable, it must be useable, it must be in time to meet the stakeholders' needs. A perfectly safe train that costs so much that passengers choose to travel by car is no solution; a perfectly reliable spacecraft that is too heavy to carry a payload is no better.

Safety and reliability are examples of external constraints on a system, imposed by the environment in which it must work, that form the interface between the system and the rest of the world. Those constraints can change over the life of a system: new technology may permit improved performance, the customer may change its way of working, a competitor may emerge with a better solution, or a weapon may be countered by a new enemy capability before it is deployed. Successful systems are flexible and robust to changes in their environment.

How are systems designed?

The design of systems combines creative flair and rigorous analysis to ensure that they deliver the required emergent properties or, put differently, to manage the risk that they will not. It brings together two ways of thinking – building the right thing and building the thing right. Each contains risk; the risk whether it can be built and the risk that, if it is built, it will work as expected. It is just as necessary to manage the realisation of the system as to conceive the right solution in the first place; that is, to manage the process and the product. Project management, and the management of the contractual chain of suppliers, have as big an impact as the system design – successful system projects give adequate attention to all three.

Another way of expressing the two ways of thinking is that systems require the design to be both systemic and systematic: systemic in order to plan for the whole life of a system and all of its parts, including (especially) people; systematic to ensure that every design decision is based on evidence and reasoning that can be reproduced or revisited if the circumstances change.

Systems comprise people, processes and technology

A well-designed system does what it should and doesn't do what it should not

Design the project as well as the product

The way in which the individual design contributions are to be brought together is a vital part of the design. Take account of how the project will be managed, how the parts will be procured and above all, how the people, process and technology will interact.

Three levels of complexity

Level 1:

A sub-system, substantially within one engineering discipline and one organisation. Examples include a PC motherboard, a car gearbox, a sand filter for water treatment, air conditioning, the antenna for an aircraft radio and a secure encryption terminal.

Level 2:

A system that involves two or more engineering disciplines and/or requires two or more organisations to design, build, operate or maintain it. Examples include an electricity power station, railway signalling, a car, a waste water treatment plant, a hotel and a fighter aircraft.

Level 3:

A system of systems that impacts, or is impacted by, many disciplines and economic, social or environmental factors. Examples include the national rail and roads network, the NHS, military command and control, the telephone network and electricity supply.

Engineering disciplines are often defined within sets of unquestioned, and maybe unstated, assumptions and practices. Integrated system thinking is especially valuable when the design spreads across several disciplines that may not share assumptions. The scope and therefore opportunity for misunderstanding varies with the complexity of the system. In engineering teaching and business it has proved helpful to recognise three levels of complexity, described in the box.

The parts that make up a system rarely fail and, even if they do, the failure can often be predicted and accommodated. But serious failures can occur if there are unplanned or uncontrolled interactions between the parts. Good integrated design ensures that the interfaces between the parts are properly specified and hence their interactions are predictable and desirable. Defining and managing physical and organisational interfaces is a key part of designing systems.

What is changing?

Engineers have been building systems, without saying so, from the Egyptian pyramids through to Brunel's Great Western Railway. But the scale and complexity have changed; it is no longer possible for a single engineer to conceive and hold the entire project in his head. Brunel could personally design everything, from the Box Tunnel to the decorative scrollwork on the stations. Once that is no longer possible, a systematic and disciplined approach is needed to focus the efforts of a team of people. This need has become greater and the challenge harder.

The challenge of complexity is clearly close to the challenge of scale. The nature of engineering is also changing, driven by:

- **greater connectivity** in the problems faced by governments and organisations of all sizes. For example, solving the challenge of meeting the world's energy needs must take account of the finite capacity of the Earth's resources, international politics and climate science, as well as the technology of generating and distributing energy. The parts of the problem, and the solution, impact on each other and on other problems in complex, sometimes unpredictable ways. It is not enough to think just about this part of the problem, or even this problem, as failure often occurs at the artificial boundaries that have been created.
- **technological developments**, particularly obvious in the converging fields of communications, computing, bio-sciences and electronics but also in more stable fields of mechanical, civil, aeronautical and electrical engineering. Information Technology permits us to build ever more complex and connected systems which have the potential to solve

problems, but which can outstrip our ability to design and develop them with confidence. They and the tools used to analyse them encompass more than a single person's 'headful' of knowledge. They must be partitioned and managed by experienced people using sound principles. Team management is as important as technology management.

- **global competition**, which exploits connectivity and technology and in turn feeds consumer demand and a political desire for solutions. This is challenging global enterprises, companies and governmental organisations to create more complex products, systems and capabilities that operate across national boundaries.

As our lives become more complex, interconnected and reliant on potentially fragile systems, the consequences of failure become more severe. A Just-In-Time supply chain fails expensively if only one truck is delayed by a few minutes; one wrong-side signalling fault can cause a train carrying 500 passengers to crash.

Six principles for integrated system design

The parts have to be integrated into the whole – we use the term "Integrated System Design" to emphasise that this is more than just conceiving and building a part. Integrated system design encompasses a wide range of disciplines, skills and ideas. We have grouped them as six principles. These are not just theory; they have been pragmatically derived by experienced engineers with a long history of successful (and some unsuccessful) system projects. The six principles provide a pervasive framework for understanding the challenges of a system design problem and for educating engineers to rise to those challenges:

- 1 **Debate, define, revise and pursue the purpose**
- 2 **Think holistic**
- 3 **Follow a systematic procedure**
- 4 **Be creative**
- 5 **Take account of the people**
- 6 **Manage the project and the relationships.**

Integrated system design in practice

There are many examples of good or even great system design but they attract little publicity. When it's done well, design is transparent – there is little news value in a headline *Project delivered on time and budget, customer delighted*. The media, politicians and auditors naturally home in on what they perceive to be failures. We have tried to balance that by following the six principles with some examples of them in action in successful British projects.

Integrated system designers or system engineers?

There is a great deal of pointless and near-theological debate about system terminology. This guide is about designing integrated systems that work. There is a continuum, from a single discipline engineer who nevertheless has to work in a multidisciplinary team, through an engineer who designs integrated systems, to one who specialises in the system aspects and is called a system engineer.

This guide uses the term *integrated system designer* to include all of them.

Integrated system design anticipates difficulties, which gives confidence to tolerate greater uncertainty and risk. A well-designed system springs few surprises.

Principle 1: debate, define, revise and pursue the purpose

The system exists to deliver capability, the end justifies the means

What is a requirement?

A requirement is an unambiguous statement of the capability that the system must deliver. It is expressed in operational terms (what the system will do) rather than solutions (how the system will do it.)

The statement of a requirement must also define how it is to be tested – if it can't be tested or measured, it isn't a requirement.

No system is optimum for all parties - trade-offs must balance their conflicting demands

Wishes and dreams exist in isolation; requirements reflect the constraints of technology and budgets

Systems are created to satisfy a need. The expression of that need has to determine every step of the system's life, so it is essential to get it right. The need is codified as a set of *requirements*. Many people contribute to defining requirements, not just the customer who pays for it. "Stakeholder" is an over-used word but it is inclusive; we use it here to mean everyone who is materially affected by a system, including at least the people who specify, pay for, use and maintain it and who therefore should help to specify the requirements. Stakeholders rarely want a system; what they want is the ability to do something – what designers might call a *capability*. But it is often difficult for them to express that capability in terms of requirements. They more usually think in terms of candidate solutions – they might specify four wheel drive when they want off-road capability, or antenna gain when what they want is reliable communications at a specified distance. True requirements are based on a full understanding of what the stakeholders are seeking to achieve – the underlying needs, how the systems will be used and in what environment. Elucidating those requirements can be harder than engineering the system that meets them.

Iteration and the trade-off between the key parameters

Requirements have to be tempered by reality, firstly to establish that it is even possible to do what is asked and then to make a trade-off between the demands, most commonly between the three parameters of *cost, performance and timescale*. The constraints may not be compatible – the budget may not be enough for the performance that is sought, or it will not be possible to achieve the performance within the available time. The requirements emerge from an iterative process - the stakeholders say what is wanted and the design engineer explores how the laws of science and the available technology can meet it. The stakeholders contribute to iteration; it is usually hard to specify a requirement until a solution starts to emerge and the original "wish list" may have to be revised when confronted with technical and commercial reality and radical ideas for solutions can prompt the stakeholders to rethink the stakeholders' perceptions. The iteration has to flip between integration - how the parts work together – and partitioning – how each part is defined and built.

Risk – the fourth parameter

Risk is the fourth parameter that qualifies each of cost, performance and timescale. The system is not properly specified until the risk to each is understood, every risk is owned by the person who is best placed to manage it and strategies are in place to deal with contingencies.

Optimisation – effective or efficient?

The outcome of the trade-off is the *optimum* (or *least bad*) balance of all of the constraints. *Optimum* is not the same as *most efficient*. The most efficient solution (most economical in its use of resources) may not be the most effective (best meeting the requirement), especially when the consequences of minor failures are included. Efficient systems can be fragile.

The optimum system is usually not found by separately optimizing each of the components, especially when considering the *soft* properties of the capability, such as reliability, resilience, maintainability, availability, sustainability or safety. The optimum solution may be to use tried and tested components, because more efficient new technology brings extra risk.

Primary and secondary requirements?

If the set of requirements is complete and made up solely of true requirements (see the box *What is a requirement?*), they translate naturally into test and acceptance specifications.

There are no secondary requirements; requirements either reflect the capability or they do not. Stakeholders may start off hoping to "kill two birds with one stone" but a proper expression of the capability in terms of a set of requirements will determine whether the *nice to have* features are to be included. If they are, they become a requirement. If they are not, they should disappear from the thinking.

The end justifies the means

Take this statement at face value. It's not meant in its often pejorative sense of justifying unethical actions. Rather, the *means*, which are the system that is built, are only justified if they contribute to achieving an *end*, which is a capability. The system should include all and only those elements that are necessary to achieve the capability. Of course, this demands a set of requirements that capture every aspect of the capability.

Requirements first – and last

Ideally a complete and consistent set of requirements would be generated before designing the system. They would take account of all stakeholders and especially customers - the engineer has to see the world, and the system that is being designed, through the eyes of the stakeholders, which includes the people who will commission, own, use, maintain and dispose of it.

In practice, of course, life is never that pure. The requirements continue to be refined as the project proceeds. Although requirements are the touchstone for every decision throughout the life of the project, the purpose of the system might change over time, or a *nice to have* that was discarded early in the project as part of the design trade-off might be reinstated when circumstances change, either because the stakeholders' purpose has changed or because technology has now made it viable or even possible. Good systems build in adaptability.

CRINE - a business requirement

CRINE (Cost Reduction In the New Era) was the oil industry's project to reduce costs. The requirement was expressed in stark terms - to make North Sea production viable when the oil price fell to \$13 per barrel.

It's hard to remember that you were planning to drain the swamp when you're knee-deep in alligators

Traditional

No battle plan ever survives contact with the enemy

Field Marshall von Moltke

Recognising the need is the primary condition for design

Charles Eames

Requirements determine how the system will impact on its environment and how the environment will impact on the system

Principle 2: Think holistic

The whole is more than the sum of the parts – and each part is more than a fraction of the whole

Everything is connected to everything else

Leonardo da Vinci

An integrated system can only be satisfactorily designed by considering the system as a *whole*. That includes looking across all of the parts and along all of the timeline. The parts include all of the components of the system, the environment in which it must operate and the tools and procedures needed to build it. The timeline runs from the very first concept of a need through design, construction, maintenance and upgrade to the eventual disposal of the system at the end of its life.

Coping with change and failures

Creating successful systems is as much about anticipating what can go wrong as planning what should go right. Systems have to accommodate change – changing requirements or working environment, or new technology that renders old technology obsolete. They have to accommodate failures – component failures, human errors of operation or maintenance, organisational failures – by degrading gracefully and recovering where possible.

Start through to finish

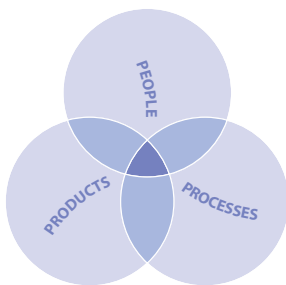
Holistic thinking is needed at the very start of a project, while the ideas are still fluid and easy to change. The influence of decisions made here can persist throughout the project. Good system design seeks an outline solution to *every* problem before committing to how *any* of them are to be solved. For example, there's no point in designing a clever new device if you don't also design a way of manufacturing it. That means both the product and the processes by which it will be built, tested and used have to work in the real world.

System design contributes in many ways throughout the project. The procurement and test specifications for the parts derive from the system design in the same way as their integration to make the complete system. System design even contributes to disposing of the system at the end of its life.

Impacts of the past and future

Few systems are built on a *green field site* and few requirements remain unchanged throughout a system's life. The legacy is part of the environment; it constrains the possible solutions but also brings experience and standards. Accommodating unforeseen future needs is hard to specify but is one of the requirements and may prevent narrow, short term thinking.

It's easy to change paper, difficult to change hardware, almost impossible to change minds.



Measure twice, cut once

The carpenters' rule

Boundaries

Systems have boundaries; without them, they cannot be thought of as systems. Everything that lies outside the boundary is part of another system. All systems are part of bigger systems, of a bigger whole. Hence one person's system is another person's sub-system. The boundaries have to be recognised, understood and managed. It might not be obvious where the system ends; this must be debated, iterated and decided. Where is the boundary of a car engine? Is a taxation policy that encourages the use of diesel or hybrid engines part of the engine system or one of the external constraints? Information flows both ways across that boundary; tax incentives for hybrids only emerge once the engine designers have shown that they are viable. Does the engine determine the tax policy or the tax policy determine the engine? Is that a boundary or part of the design? One of the first tasks when designing a system is to decide where to stop: what to take as a given and what to try to change.

In summary

So what is involved in *thinking holistic*? It means designing for the system's total life cycle – the whole system; the whole environment; the whole life; product, process and people. Thinking holistic starts with the concept of what the customer wants to achieve and ends with the disassembly and disposal (or reuse) of the redundant parts. It brings together all of the relevant disciplines at an early stage to ensure buy-in.

Integrated system design brings all of the parts of the system within a framework of the system boundary and it explores and defines that boundary, in space, scope and time.

*Big fleas have smaller fleas
Upon their backs to bite 'em
Smaller fleas have smaller fleas
And so ad infinitum*

Anon

*Manage integrated system risk,
exploit integrated system
opportunity*



Picture: Heathrow Terminal 5. Courtesy of BAA plc

Like a chain, a system is only as good as its weakest link

Principle 3: Follow a disciplined procedure

Divide and conquer, combine and rule

Allow time and resources for mistakes and rework – the man who never made a mistake never made anything

To create architecture is to put in order. Put what in order? Function and objects.

Le Courbusier

A good system architecture:

- defines all the elements, budgets, performance and capacity
- puts the interfaces between the elements where the interactions are weakest and integration and test is easiest
- aligns the technical and organisational interfaces
- is traceable - back to the requirements and forwards to the implementation
- designs for business continuity
- designs for integration, maintenance, adaptability and even dismantling (not everything that can be put together can also be taken apart)
- builds in fault tolerance - maintaining capability when components, sub-systems and especially people fail

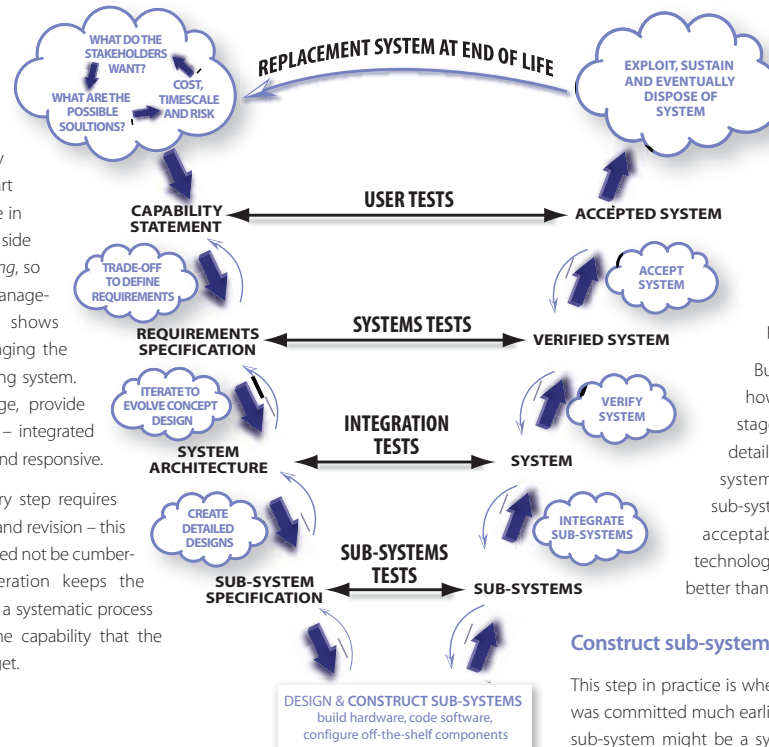
Systems that work do not just happen – they have to be planned, designed and built. There are many ways of formalising what is half an art and half a process; it's described here in terms of a V-diagram. The left hand side shows successive stages of *partitioning*, so that the task is broken down into manageable chunks. The right hand side shows successive stages of *integration*, bringing the chunks together to create the working system. The procedure must, at every stage, provide guidance and not be a strait-jacket – integrated system thinking must be adaptable and responsive.

Although this might look neat, every step requires creative insight and constant review and revision – this is far from a mechanistic process. It need not be cumbersome; planned and managed iteration keeps the creativity focused. Followed properly, a systematic process ensures that the project delivers the capability that the stakeholders need, on time and budget.

Partitioning

Partitioning starts by iterating with the stakeholders to agree the capability statement. The stakeholders and designer together explore what capability the stakeholders are trying to achieve, possible ways of doing it and the implications of each. There is no single starting point: the customer might have a clear idea of the essential capability or might be responding to an emerging technology. An attractive solution might be too expensive, a cheap one offer too low performance or the most cost-effective might have too much risk and uncertainty. A solution that is cheap to buy may be expensive to operate.

The capability statement is posed in terms of what the stakeholders want to achieve. This is translated into a requirements statement, which says what the system must do. It has to reconcile what the customer wants with what the laws of science and the norms of economics and commerce can deliver, within the constraints of the environment. Again there will be trade-offs which might lead to questioning whether all of the capability is needed or even achievable.



The system architecture is now developed. This is the high level design and is the *masterplan* for the project. It defines what each of the sub-systems must do and how they will be related to each other. It is comprehensive – human as well as technical sub-systems might be included – and it must show a credible way of building every element (what mathematicians would call an existence proof of a solution).

But the system architecture does not specify how each sub-system will work; that's the next stage, where each sub-system is designed in detail. Again there may be a need to revisit the system architecture, perhaps because the sub-system cannot meet its requirements with an acceptable cost or timescale or because new technology has allowed the sub-system to perform better than expected.

Construct sub-systems

This step in practice is where most of the cost is incurred (although it was committed much earlier, locked in at the earlier stages). And each sub-system might be a system in its own right and require its own version of this process.

Integration

There are now several stages of integration, testing at each of the levels. Each sub-system is tested against its specification, and the integrated sub-systems are tested to ensure that they collectively do what the system architecture envisaged. The performance of the system can then be compared with the requirements specification, and finally tested to ensure that it delivers the capability defined at the beginning by the stakeholder and the designer.

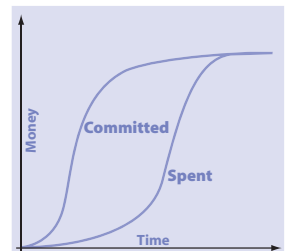
Death – or birth of the next system?

At the end of the system's life, it has to be dismantled, which is much easier if it was planned at the start. The stakeholders may still need capability, so there will also be a handover to maintain continuity between the legacy and successor systems.

Identify and manage uncertainty, keep room to manoeuvre within a stable architecture

In systems engineering, the expensive mistakes are made on the first day

Rechtin



The early stages of the project determine the spending in the later stages

Build a little, test a little

Augustine's laws

Don't cut corners – validate each step before starting the next

Minimise novelty, maximise use of proven sub-systems

Systems work because they're designed to work – the system architecture is the top level design

Principle 4: Be creative

See the wood before the trees

The best ideas might come as a bolt from the blue but remember what Edison said about putting them to work:

Genius is 1% inspiration and 99% perspiration – I never did anything worth doing by accident, nor did any of my inventions come by accident. They came by work.

All engineering is creative; it is built on a combination of visionary flair and rigorous analysis. But engineering integrated systems demands extraordinary creativity. The system designer has three basic roles:

- to work with the customer and other stakeholders to tease out and define the capability that the system must deliver, including making the trade-offs between cost, performance and timescale (and the risks of each)
- to create the top level design, or system architecture, and translate it into the requirements of each element
- to facilitate every stage – build, integrate, operate, maintain, modify and dismantle – of the system's life

This requires both innovative and conventional thinking – innovative to make the breakthrough that turns an impossible problem into a workable solution; conventional to maximise reuse of existing knowledge and components to avoid reinventing the wheel. System designers need to understand the entire problem, to look beyond its immediate boundary to identify the unexpected consequences, to look at it from all directions and everyone's point of view. Designers create the emergent properties, not just broker trade-offs.

They do not have to do this without help; there are many tools, processes and techniques that the designer can deploy.

Modelling and simulation

Designers use models of the system to make quantitative predictions of its behaviour – its emergent properties – as the architecture evolves. A model is an abstract representation that includes every aspect that will affect the system's behaviour and nothing else. Mathematics underpins system models. They are a quantitative representation using empirical or statistical data, although they need only be accurate enough for the task; a "back of the envelope" calculation can be adequate and is more transparent than a computer model.

A simulation is a dynamic model that allows people to be involved. Some are highly realistic - flight simulators for example can train a pilot to fly a new aircraft and explore conditions that would be too dangerous in reality. Others are more simple such as finishing sections of a wall with different materials to allow the customer to see what each looks like before choosing for the whole building.

Modelling and simulation are powerful tools to manage complexity. And they allow stakeholders to experience the look and feel of a system long before it is built, which creates buy-in, builds confidence and develops understanding.

Prototyping

A prototype can take many forms, from a bench "lash-up" to prove a particular point of uncertainty through to a full working model which, like a simulation, helps to achieve buy-in as well as to allow users to get real hands-on experience.

Where the system is destined for short production, and especially where it is a one-off, the prototype may become a deliverable and operable product. There is still room to make prototypes of parts of the system in order to demonstrate that critical solutions work and to allow the future users to influence the design.

The key aim of modelling, simulation and prototyping is the same - to have no surprises when the system is built, tested and used.

Budgets, trade-off and metrics

It is not possible to find the best system solution unless you know what *good* looks like. Part of the process of capturing requirements is to define a metric, sometimes called a figure of merit, that measures how closely a candidate design meets the goal. Suppose that the requirement is a fuel-efficient car; the metric might be miles per gallon or litres per hundred kilometres. The performance of different cars can be evaluated by calculating the metric for each.

Real system problems are much more complex, with many requirements that may be inter-dependent or even conflicting. It is often not possible to define a single metric that reflects all of the requirements nor simultaneously to optimise all of them; the designer has to use judgement and sensible thinking to find the balance that is *least bad*. This includes considering how robust the solution will be – *highly tuned* solutions can fail if there is only a small change, lower performance solutions may degrade more gracefully.

Once the metrics are defined, even if they are only very simple and crude, they can be used to perform trade-offs by making changes to the requirements and the system architecture and exploring the consequences. A system metric, such as cost, mass or reliability, may be divided between the sub-systems, giving each a budget to guide its designer.

The budget for a metric can be allocated to each of the major sub-systems so that each may be designed separately. But the allocation can change; trade-offs between sub-systems are effected by transferring budget from one that is achieving it easily to one that is more challenging. This may be a diplomatic as well as technical challenge if the trade-off is between sub-systems that are the responsibility of different companies or disciplines.

What if?

The system designer must remain flexible and be willing to say "what if the unlikely were to happen?," "what if we radically change the requirements?" These questions can be asked at every level, from the helicopter overview of the entire problem down to the deepest levels of the sub-systems. The models, simulations, prototypes and their underlying analysis are the tools that help to provide the answers.

A fool with a tool is still a fool

The more complex the problem specification, the more likely the solution proposed is incorrect

Aircraft reliability – an example of budgeting

The reliability target for large civilian aircraft is to have no more than one major accident every 10⁶ flying hours. It is assumed that 10% of the risk arises from airframe failure, so the airframe designer is given a budget of not more than 1 failure every 10⁷ hours. The airframe designer assumes that there are 100 independent critical sub-systems, each of which must therefore be designed to achieve a failure rate better than 1 in 10⁹ hours.

Concentrate on finding and managing the critical drivers – they might be mass for a spacecraft, speed for a racing car, transition for an IT system

Think creatively, laterally and logically – remember the aim is to deliver capability, not technology

Principle 5: Take account of the people

To err is human

Systems rarely go wrong – it's the people involved who do

People are part of a system; they're not just an external constraint. People have to build, install, operate or even inhabit, maintain and decommission a system. They may be called on to pay for it and to defend, challenge or tolerate it. People might be the most fallible element of a system, but their flexibility, inventiveness and intelligence might also be the only way to recover from an unanticipated system failure or from undesirable emergent properties.

The fundamental message to the system designer is to understand and take into account the human aspects of the system. If it is likely to have a large impact on the organisation in which it operates, treat this as part of the programme to be managed. The people who will be affected by, and who will affect, the system need to be consulted and engaged. And people behave differently in groups – what might work for an individual might fail when it has to meet the diffuse demands of a group of people, and what works in one organisation or culture might not in another.

Motivation

A system is not complete until it reflects the values and capabilities of those who designed it, those who made it and those who will use it

People respond strongly to signals that affect their personal wealth, safety or happiness. It is easy to include, by accident, perverse incentives that promote and reward damaging behaviour. Similarly, it is easy to reward short term behaviour at the expense of long term success.

Competence

Competence is sometimes defined as: *the ability to undertake responsibilities and to perform activities to a recognised standard on a regular basis and a combination of practical and thinking skills, experience and knowledge.*

Systems have to be designed to work with the competence that will be available. If there are not sufficient competent people, the system design has to include steps to train or recruit them. Investing in people is part of system development.

Quality

Quality isn't something you lay on top of subjects and objects like tinsel on a Christmas tree.

Robert Pirsig,
Zen and the Art of Motorcycle Maintenance

Quality does not exist as an absolute; it has to be seen in context. A thoroughbred race horse appears to be a higher quality animal than a camel, unless you are trying to cross a desert. Quality is fitness for purpose and lies very much in the eye of the perceiver.

The perceptions of everyone involved with the system must be managed and consistent. A stakeholder who does not share the requirements may be dissatisfied and create barriers to the system's success.

Whatever level of quality is appropriate – fit for purpose – it will not arise by chance. The designer has to define the level of quality that is needed and ensure that the other players can deliver it.

Ergonomics - design for real people

The people involved in systems are only human – they have all the weaknesses to which human flesh is prone. The system has to accommodate their limited abilities. This means both physical and psychological limitations – will the operator be able to reach the controls, will the maintainer be able to undo that screw, will too many false alarms cause the operator to ignore the real one, what is the attention span of a user, will users ever trust a system that they see as having been foisted on them?

Part of the system design is to identify the competence that will be demanded of all of the people involved in making the system work. For a big system, such as a programme to build nuclear power stations, it is necessary to assess whether the competence exists, either at all or in sufficient quantity. If it does not, the *system* includes training and personal development.

Ethics and trust

It's easy to say that engineers must do what is right but what is right to one person may not be right to another. Some issues are obviously contentious – building animal research laboratories or designing weapons is acceptable to some people and not to others. Others are less obvious – many technologies have more than one use and all engineering inevitably brings the risk that it will cause harm as well as good.

All that is true for any engineer; there are extra challenges for those who design systems. Systems have emergent properties that are hard to predict and have the capacity to do great unintended harm. Systems inevitably are defined, built and operated by teams of people. They collectively have to agree and share ethical standards. What's more, they must be seen to be ethical if they are to trust each other. Mission statements and corporate principles help but on their own they are not enough.

System designers are ethically answerable to those who will be affected by the system. There is a simple test: "would I be happy if my customer, a consumer or a journalist knew the basis of every decision made, and would they be satisfied that I had behaved properly?" If the answer to both questions is yes, then your decision is probably ethically sound.

Lastly, systems fail, that's a given, but well-designed systems fail safe and then recover. To learn from failures, and prevent them recurring, we need an open culture of inquiry and help, not blame and shame. NASA's experience with two Space Shuttle accidents taught the importance of listening to the engineers, not suppressing their uncomfortable views.

First we shape our buildings, then they shape us

Winston Churchill

A good idea is worthless until it is documented and shared – justify and communicate all trade-offs and decisions

If someone who will be affected by the system were to be sitting beside you when you take design decisions, would he be happy with what you have done?

People are at the heart of most systems; they may be both its weakest and strongest link

Principle 6: Manage the project and the relationships

All for one, one for all

Systems have to be built, not just drawn

Any major system is going to need a lot of people to specify, design, build, operate, maintain and dispose of it. They will be employed by different organisations, tied together formally by contracts or informally by a shared interest. They might not even meet; the person dismantling a system might not have been born when it was built.

Principle 2 *Think holistic*, was introduced with the words *An integrated system can only be satisfactorily designed by considering the system as a whole. That includes looking across all of the parts and along all of the timeline.* It is the formal and informal ties that make that possible. Many project failures have their roots in poor communication, within the project and outside it.

Design the project, not just the system

The system architecture should naturally lead to a sensible allocation of tasks – what is often called the *Work Breakdown Structure*. Ideally the interfaces between tasks that WBS allocates to different players should be as simple as possible, with the minimum interdependence. Where two sub-systems are inextricably bound together, it is better that they be treated as a single work package.

The system architecture should help to highlight the other systems that are needed – for example production and test systems to support development, and the training, maintenance and supply systems to support successful operation.

Politics or commerce may demand that a particular company or the industry from a particular nation performs certain tasks. These are just more constraints on system design – expensive if they do not align with the sub-system interfaces in the logic of the system design but nevertheless a fact of engineering life that has to be accommodated.

Project management

Only the simplest system projects can succeed without strong project management. Within the project boundaries it contributes the overall planning, cost control and progress monitoring. Externally project managers are responsible for continuous attention to client relations, value for money, engagement with stakeholders and subcontractors and the linkages to their companies' commercial legal and financial policies.

Project management and engineering design jointly drive and define the project lifecycle. They set out how the technical work is to be organised in stages, how risk is to be assessed and managed and how the elements of the system are incrementally tested and integrated.

Engineering, like politics, is the art of the possible

Integrated system design and project management are two sides of the same coin

The contractual chain – partners or adversaries?

Major system projects require flexibility to respond to changes of requirements or unexpected problems. It may be necessary to make trade-offs between sub-systems that are being built by different companies; those technical trade-offs cannot be separated from commercial trade-offs. Information has to be shared, both up and down the contractual chain.

A new model for the relationships between the players in a major system project is emerging. Old-style contracting saw each member of the contractual chain as an island, out to maximise his profits and minimise his exposure to risk. This *zero-sum* philosophy is being replaced by *win-win*. If the players cooperate, all can be better off. Instead of being adversaries, each trying to extract the greatest profit, they can be partners, each taking their share of a larger pot. Instead of the customer trying to offload risk onto the supplier, risk is allocated to the player best able to manage it. Open and honest project reviews allow all of the players to cooperate to anticipate problems and find solutions.

CRINE, the North Sea oil industry's programme in the 1990s, was one of the first examples of this approach, which succeeded because all of the companies worked together, sharing risk and profit. *Revitalising Construction*, more often called the Egan report, promoted it for civil engineering and has led to the emergence of the New Engineering Contract. Heathrow Terminal 5 is the leading example of Egan in action. MoD's *Smart Procurement* learned the lessons from CRINE and established Integrated Project Teams to bring together all of the stakeholders and create much greater openness between them and the contractors. This is being extended under the Defence Acquisition Change Programme to encourage through-life capability management, the approach that underlies this guide's six principles.

Partnership between customer and supplier is especially valuable for projects that cannot easily be separated from the customer's organisation. Systems and project boundaries are then notoriously difficult to pin down and manage, and success depends on mutual trust and teamwork. This requires a competent customer as well as supplier.

Allow time to think, plan and recover

Project managers often rush to do real work – start to build something tangible early on before definition is complete – in the mistaken belief that this demonstrates progress. Many system customers, including NASA, UK MoD and US DoD, recommend that 10-15% of overall project costs be spent on front end design and engineering of the system – though the pressure to show results means that it is rarely achieved. Similar resources are likely to be needed for commissioning and late rectification.

We must learn to live together as brothers or perish together as fools.

Martin Luther King

The only fault worse than getting the wrong design is persisting with it after you know (or should know) that it is wrong.

Understand the difference between those who benefit from using the system and those who benefit from building it – both want it to succeed but have different measures of success, which must be reconciled

You can't build an integrated system without an integrated organisation

Some examples of integrated system design in practice

Motor vehicle testing – the MOT test



Picture: Courtesy of Fox Motors Guildford

The national system for annual testing of all cars and vans, known colloquially as the MOT test, has traditionally relied on paper certificates. Apart from the security concerns – certificates may be stolen or forged – it was necessary physically to present the certificate to prove that the vehicle had been tested when renewing its Road Fund Licence (tax disc).

The Vehicle and Operator Services Agency, which runs the scheme, entered into a 10 year contract with a single supplier for the capability to record MOT test results centrally.

The supplier stripped back the requirements to the basics. Instead of trying to run the system on the computers already installed in the 18,300 registered test centres, it supplied each with a new basic computer and dial-up phone connection. At a stroke it bypassed legacy problems and the need to be compatible with the many different existing systems. Dial-up might be seen as old and crude technology, but the required data transfer rate is low and dial-up is available throughout the country.

The total cost of the system was £230M. It is successful and has transformed the administration of vehicle records. The cost is interesting; at around £12.5K per garage the marginal cost of a dedicated PC was negligible.

Key messages:

- buy a capability, not a system
- procure the entire system and its operation from a single supplier who integrates the system
- look for a simple, low-technology solution that is adequate, reliable and simple to install, maintain and use.

Military equipment

The armed forces procure and use some of the most complex systems, and subject them to the most demanding treatment. We have taken some elements out of several major military system projects to show how integrated system design has contributed.

Air defence in WW2. The air defence network, from the Chain Home radar stations through to the plotting desks in command centres and out to the dispersal bays on Kent's airfields, was a model of good integrated design. Its architecture was optimised to filter raw data up to those who could synthesise the strategic picture and then to delegate responsibility out to airfield commanders who could make the tactical responses.

ASTUTE submarine cost reduction programme. Submarines are especially complex – fit a nuclear power station and a 100-bed hotel inside a sealed and self-sustaining environment the volume of an aircraft fuselage, then add weapons, control and communications, then make the whole thing run quietly 100m under the sea. Cost reduction studies for ASTUTE started with revisiting the requirements to identify which were real requirements, which were “nice to have” and which were over-specified solutions. There are difficult trade-offs – a smaller hull costs less but the cost of squeezing in all the equipment rises rapidly once it becomes tight. Even the way that the submarine is built has a major effect – although building it in vertical sections adds cost because they have to be turned on their sides to be joined, the extra cost is more than offset by easier and cheaper assembly than with conventional horizontal construction. Above all, cost reduction needs an open relationship of trust between all players, so that the rewards of the saving are fairly distributed and motivate everyone to cooperate.

Tornado Combat Aircraft. Tornado was a tri-national programme that produced a total of 805 aircraft, on time and on budget, in six batches for UK, Germany and Italy. The Maximum Price was agreed at the outset and there was a programme of continuing cost reductions. Tornado subsequently formed the basis of export contracts. The success of the Tornado programme was a result of the holistic view taken from the start, recognising that the customers' needs would change over the life of the programme and that discipline, good engineering and project management were crucial.

Key messages:

- assign responsibilities to the people best able to discharge them
- ensure that requirements define what is needed (capability) and not how to deliver it (solutions), and recognise that the requirements will change
- look for novel solutions in a spirit of shared risk and reward.



Picture: Courtesy of BAe Systems. Copyright © 2007. All rights reserved.

Thames Water ring main

The London Water Ring Main is a system of gravity-fed tunnels constructed deep under London. It brings drinking water from Thames Valley treatment works into the capital.

Thames Water's designers started work on the project in 1985 and it was planned that the project would be implemented in two phases and would complete in 1996 and cost £250m.



Picture: Courtesy of Thames Water

Construction of phase 1 began in March 1986. At that time Thames Water would split projects into a large number of independent contracts based on specific engineering disciplines and manage the many interfaces between them. The Thames Water design staff invited competitive tenders for the separate parts of the system leaving no design liability with the contractors. Many delays occurred, mainly due to interface problems.

The 23 km of tunnels in Phase 1 were driven at an average rate of 158 metres per month. The programme ran late and significantly over budget, with some activities up 18 months behind schedule.

Phase 2 started in 1991. A modified tunnelling technique was used and all activities were treated as parts of an integral system. Thames Water placed two multi-disciplinary turnkey contracts, each covering tunnelling, shaft sinking, surface pipe-work, building works, electrical and mechanical plant and local control. This minimised interface problems between engineering disciplines. Target cost incentive contracts were used, promoting risk sharing and good cooperation between Thames Water and the main contractors.

Phase 2 consisted of some 33 km of tunnels driven at an average rate of 311 metres per month, almost double that of Phase 1. Phase 2 was completed 2 years early, well under cost and more than making up for the Phase 1 overrun.

Key messages:

- treat the problem as a system, bringing the disciplines together
- use cooperative rather than confrontational procurement.

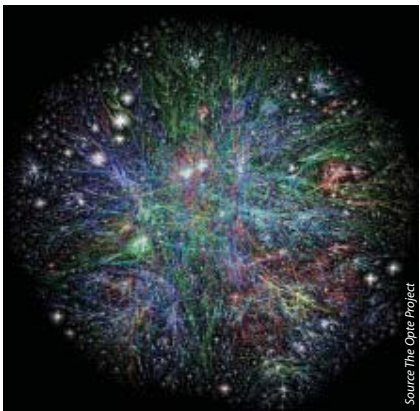
World Wide Web

The World Wide Web is all pervasive, accessible to much of the world's population. Its underlying technology is the internet, with a topology that looks like a Jackson Pollock painting with a chaotic pattern and no discernible structure – but this is far from reality. The internet is the most resilient and expandable communications system and it owes this robust structure to its founding concept that employed integrated system design.

In the 1960s the US Defence Advanced Research Projects Agency (DARPA) developed a resilient communication network that linked computing facilities at universities and research organisations for integrated military research. DARPA's system engineering mission was to create a capability that would be resilient to nuclear attack and that could expand easily. Throughout the 1970s and 1980s the net expanded rapidly with more academic institutions and commercial organisations being added under formal system management. E-mail and file transfer was developed together with standardised communications protocols to improve resilience and ease of use. The big breakthrough came in 1989 when Tim Berners-Lee, a British physicist from CERN, proposed a new protocol for embedding links in text. This protocol enabled the users to exchange information easily – the World Wide Web was born.

Key message:

- get the architecture right in the first place – robustness, scalability and flexibility will follow.



Source: The Opte Project

Above: A representation of the pervasive nature of the internet.

Each colour on this Opte map represents a region:

- North America – Blue
- Europe/Middle East/Central Asia/Africa – Green
- Latin America – Yellow
- Asia Pacific – Red
- Unknown – White

Arsenal's Emirates stadium

A stadium isn't just a place where fans watch football. It can form the nucleus of regeneration for an area, and become the focal point of a community through hosting events and providing employment for local people. Not only must a stadium make enough money to enable the club to compete at the top level, but it must also be designed for safe movement of crowds. It must also have adequate toilets, – an important part of the overall visitor experience and something that has to be considered at the design stage.



Picture: Courtesy of Scotland Aerial Photography.

For example, on the plaza of the Emirates stadium spectators are guided by colour-coded quadrants to lettered turnstiles where their ticket is read by a laser scanner, ensuring they only enter the correct zone. Upon entering the foyer areas, fans are immediately faced by food and drink counters that provide quick service, as well as an extensive number of toilets. The whole system is simple to ensure the efficient handling of the large crowds that will regularly use it.

The design team – architect + engineer – was appointed early in the programme and transferred to the main contractor to form an integrated design and build team. The main contractor's contract had two stages. The first specified a lump sum for preliminaries with a fixed percentage for overheads and profit and a rigorous deadline for completion.

Once the bulk of the almost 200 works packages were agreed the contract was converted to a Guaranteed Maximum Price. Many of the key sub-system packages still require substantial design. For example, the structural steelwork contractor was responsible for the design of connections and preparation of shop drawings, as well as detailing the cladding fixings. These details all require input from the design team to ensure the interfaces between packages run smoothly. Clarifying the design input and defining these interfaces reduced risk and made for an efficient construction process.

The stadium was completed two weeks early, having incorporated a significant number of the client's upgraded finishes on budget and the result is a stunning new landmark structure for football. The first game, the Bergkamp testimonial, was played on 22 July 2006 to a rapturous welcome from fans, players and media alike.

Key messages:

- conceive the stadium as a system that is part of its community, not just a football ground
- form an integrated team of architect, engineer and main contractor who work cooperatively and closely with the client throughout the programme.

What kind of people can design integrated systems?

Foxes, hedgehogs and T-shaped CV's

You can't engineer a complex system without managing it properly and you can't manage a complex system without understanding its engineering

Isaiah Berlin adopted the words of the Greek poet Archilochus to distinguish the intelligence of the hedgehog who knows one big thing from the intelligence of the fox who knows many little things. Most engineers are hedgehogs; they are experts in one discipline of engineering and they are vital – they are the ones who *get things right*. Conversely, most project managers (at least the good ones) are foxes; they need to know enough about a great many things to juggle all of the options and deliver on time, performance and budget.

The engineers who can design integrated systems, and especially those who specialise in that field and call themselves *systems engineers*, are neither, or rather they are both. The CV of a good designer of integrated systems has a T shape – broad knowledge about every aspect of the system and deep expertise on at least one part. The deep leg of the T is necessary for two reasons: without it the systems engineer does not command the respect of the hedgehogs who have to make each of the parts of the system work and does not appreciate the wider implications for the whole system.

Of course, it is soon not enough to have only one deep component of expertise. Successful design engineers know a lot about many things as well as a bit about everything, and they understand the stakeholders' world in which the system must work.

Formation of integrated designers

That combination of skills (and the attitudes that underlie them) is rare and conventional engineering education does not encourage it to emerge. The engineers who will lead the design of integrated systems – let's call them systems engineers – need:

- a sound basis in the science of engineering – the basic physics, chemistry and mathematics on which engineering is founded
- an analytical spirit, which seeks to model, understand, quantify and characterise problems
- creativity to find innovative solutions and not let the trees distract them from the woods
- an awareness of the many disciplines that impact on system design, from the different branches of engineering through law, commerce, management, logistics and politics
- strong communication skills to work with: the other engineers that are their peers; managers, financiers, customers and users; and the other trades and professions that make the system work (maintenance technicians, aesthetic designers, ergonomists, assembly workers ...)
- leadership to be able to carry their colleagues with them when they are right and to listen to those colleagues and learn when they are wrong.

It is the task of the systems engineer to choose the components and the interactions between them to achieve the desired emergent properties and to suppress those that are undesirable.

The systems engineer must understand the stakeholders' business. Integrated system design does not happen in isolation.

Those qualities can all be taught, as can an attitude that treats problems as beasts to be tamed, to be reined in by applying knowledge, models and context. But successful design engineers need something more – insight that lets them see the real problem and its solution and not be deflected by the surface detail. Everyone has some share of that insight and it can be encouraged and developed. We hope that this guide may contribute.

Teaching and the contribution of The Royal Academy of Engineering

Teaching systems engineering requires both theory and practice. The theory includes:

- techniques, such as mathematical modelling
- approaches to problem solving, including how to scope a problem on *the back of the envelope*
- behaviours, such as openness and sharing
- skills, such as listening, presentation and persuasion.

These are all transferable, applicable to a wide range of activities. For design engineers they are necessary but not sufficient; teaching integrated system design also demands that the students are exposed to the practice and experience of engineering real systems, experience that only comes from having done it, and especially from having made mistakes. Practising engineering designers carry the scars of their failures as well as the accolades of their successes. Not only do they have great wisdom to share but they also inspire students with the excitement of designing systems that work. Realistic design exercises, led by experienced engineers, provide a great introduction to real-world integrated system design.

That then is the rationale for the Academy's scheme to support Visiting Professors of Integrated Systems Design – bringing to the students engineers with the hard-won experience of building systems that work, and sometimes that do not.

Message – how should the UK improve its integrated system design skills?

System engineers or all engineers?

We have portrayed the engineers who design integrated systems as something different from other engineers, especially if they specialise as systems engineers. But every engineer has to understand the wider context of his or her part of the solution to a problem. Every engineer has to follow the same logical process to get from an abstract wish through to a working solution. And every engineer has to be able to work in teams, bringing together specialists from many different disciplines.

All engineers should *think systems*. It's one of the ways in which the UK must differentiate itself from the countries that are rapidly developing from leadership in manufacturing towards leadership in design.

Opportunities for action

The message set out in this guide highlights challenges and opportunities for: universities and their students, for the Institutions that guide engineering courses, for practising engineers, and the customers for and users of complex systems.

- Employers are crying out for more capable engineers – those that understand the fundamentals of their discipline and that have the personal qualities and professional skills to work in and lead integrated teams. The six principles that we set out here are not prescriptive but they do provide a framework on which to build. The Engineering Institutions have already moved a long way from defending professional silos but there is still opportunity to move further, by actively encouraging courses that teach both the fundamentals of a discipline and the ability to apply it to systems that span disciplines, and by recognising integrated systems thinking when awarding Chartered Engineer status. Students and universities have to move their thinking too, by lowering the barriers between departments and by offering and studying courses that cross those traditional barriers.
- Engineers who are already practising, including those senior engineers who guide their company's or organisation's policy, will have experienced the need to *think systems*. Their recruitment policies and professional development schemes need to reinforce that message.
- Customers and other stakeholders have also to understand that they should specify the capability that they need and not the way that they think that it should be delivered. They have to be flexible and above all allow the time and resources that are needed to make sure that their engineers build the right system as well as build the system right.

The European GSM cellular telephone system has swept the world because it was conceived and designed systematically using open standards shared by a group of clear-thinking companies.



Courtesy of Tomasz Pietryszak - istockphoto.com

Benefits to the UK

The benefits to the UK of an engineering education that teaches students to think systems are potentially massive, especially if coupled to engineering procurement that values such thinking. The Academy has, in a separate guide, developed ideas for engineering for sustainable development. It is no coincidence that many of them parallel the six principles that we have set out here. Engineering for sustainable development requires whole-life thinking and consideration of all of the implications of every decision; that's the core of systems thinking.

There is a wider economic return. The UK faces ever-growing challenge from low-cost, high productivity economies such as Brazil, India and China. They started by offering low-skill manufacturing capability, and have moved on to capturing important slices of product design. The UK has a chance to hang on to the very highest level design, by being pre-eminent at creating a sound system architecture out of a vague wish and at integrating a set of parts into a working system. This ensures global leadership and brings two important benefits:

- system skills are highly valued and attract the highest rewards – they're at the top of the engineering foodchain
- the systems that emerge will work, with consequent benefits to their users.

The benefits are pervasive. Integrated system design is a management philosophy that:

- brings clear thinking that looks at the whole problem and identifies the gaps and challenges before they become critical, informing both the management plan and the business case for a project
- identifies who owns every part of the problem and their interdependencies, leading to a disciplined and auditable process
- reduces risks and hence leads to lower cost and better performance.

And finally ...

The Academy hopes that this guide provides insight into the need for, and potential benefits of, improving the national capability for integrated system design and hence will lead to more successful British engineering projects. The guide gives some examples of success, drawn from mechanical, construction and electrical engineering for military and civil customers, involving hardware and software. All were successful because they followed the basic principles that it sets out. There are many others that could have been included but, sadly, there are too many examples of what happens when basic systems thinking is ignored or not applied. This guide will have achieved its aims if it helps British industry to have fewer of those in the future.

Benefits of integrated system design

An integrated approach brings:

- clear thinking to the whole problem
- creative and innovative solutions
- reduced risks and costs
- better performance
- defined ownership of responsibilities
- a constructive relationship between stakeholders
- identified gaps and priorities

all of which leads to:

- successful projects that deliver what all the stakeholders want