

Intelligent buildings

SYSTEMS ENGINEERING FOR THE BUILT ENVIRONMENT

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The engineering of complex systems is a mature discipline in aerospace and defence. Drawing on those domains, the UK Royal Academy of Engineering developed a set of principles to guide engineering education and to influence the procurement and management of major projects. The principles, and the approach to design that underpins them, operate well in other domains. Intelligent buildings require similar whole-life thinking and trade-offs to find optimal solutions to the complex problems that have to be solved to deliver the benefits of 'intelligence'. The RAEng's six principles apply to the design, construction, use and eventual disposal of intelligent buildings just as they do to a weapon or spacecraft.

INTRODUCTION

There are at least as many definitions of 'systems' and 'integrated system design' as there are people who practise it. For this paper we define a system to be:

a set of parts which, when combined, have qualities that are not present in any of the parts themselves

and we use the term 'integrated system design' since 'systems engineering' is more appropriate to the aerospace and defence domains.

What does 'a system' mean in practice? A trivial example is the system of a battery, two wires and a bulb. Light emerges when they are brought together, but is not a feature of any of the components alone. Such qualities are the emergent properties of the system. All systems have *emergent properties* that can be desirable

or undesirable, often both at the same time. For example, the system made of three major sub-systems – cars, roads and drivers – has the desirable emergent property of transport and the undesirable emergent properties of pollution, noise and accidents. Integrated system design seeks to predict the emergent properties and to manipulate the design to give, so far as possible, the desirable ones without the undesirable.

Society increasingly demands capabilities that can only be provided by ever more complex systems, in which the parts interact with each other and with the outside world in many ways. Those relationships determine how the system behaves and must be studied, analysed and modelled; intuition rarely predicts the behaviour of novel complex systems. Integrated system design is the way that engineers manage emergent properties. It is a mature discipline and an explicit stage of major projects in the

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aerospace, defence, telecommunications and software industries, where it is more commonly called systems engineering. The design and construction of intelligent buildings applies similar thinking to the built environment.

CONTEXT FOR THE BUILT ENVIRONMENT

The UK's Royal Academy of Engineering has published guidance for creating systems that work, intended to inform both the formation (education and training) of engineers and the practice of specifying, designing, procuring and operating complex systems (Deasley and Elliott, 2007). It comes from the aerospace and defence sector; this article examines how its principles might be applied to the conception, design and construction of intelligent buildings. Similar principles have been advocated before, in the Egan report (DETR, 1998) and subsequently by Blockley and Godfrey (2000), but this paper seeks to show that those principles have a more universal applicability.

Some of the greatest thinkers on the built environment have the basic premise of integrated system design that the system exists to meet a human need. Le Corbusier described a home as 'a machine for living in' and Frank Lloyd Wright defined 'organic architecture' as architecture that is appropriate to its time, appropriate to its place and appropriate to man. He defined 'appropriate to its time' in technological terms – using current materials and methods; 'appropriate to its place' seeks to be in harmony with the natural environment, a philosophy that we might now call sustainable; and 'appropriate to man' is a reminder that the building's first mission is to serve people. Integrated system design can provide the rigour and tools to ensure that the machine is fit for living and that architecture is organic.

PRINCIPLES OF INTEGRATED SYSTEM DESIGN

The guidance identifies six basic principles that were developed in the aerospace and defence sectors:

1. **Debate, define, revise and pursue the purpose** – *the system exists to deliver capability, the end justifies the means.*

We build systems because someone needs what the system can do. If we forget that, we are engaged in art, not engineering; the result may be beautiful but it is not useful and that is the touchstone of good engineering. Everyone may have a general idea of the purpose, but it is unlikely to be agreed in detail, there may be more than one view and it may change as the project proceeds. The agreed and evolving purpose provides the rationale for the compromises that are the heart of good design. The proper balance between cost, performance and timescale, or between speed, comfort and cost, is not an absolute – it depends on the stakeholders' needs. Without a clear understanding of those needs, there is no way of locating the proper balance point. Even safety is part of the trade-off; the perfectly safe vehicle would never move.

2. **Think holistic** – *the whole is more than the sum of the parts and each part is more than a fraction of the whole.*

'Holistic' may sound like it belongs in a New Age pamphlet but it sums up the need to see every design decision in the context of the wider system. Good system design needs an outline solution to every problem before a detailed solution to any of them. The holistic view looks at the whole life cycle of the system, from concept through to disposal, and it looks at the interaction between the parts and not just the parts in isolation.

3. **Follow a disciplined procedure** – *divide and conquer, combine and rule.*

Designing systems is creative, imaginative and holistic but it is not anarchic. Good system design follows a systematic procedure that starts from an abstract concept of the capability that the stakeholders would like and breaks it down into the specifications of the parts to be built. It then brings those parts together, tests them against the specs, integrates them and tests again, repeating until the entire system meets the requirements.

4. **Be creative** – *see the wood before the trees.*

All engineering is creative, built on a combination of visionary flair and rigorous analysis. Creative solutions do not have to be wholly novel; some of the most successful systems are based on creative exploitation of proven technology, the technology that is appropriate to the time. Engineers model and simulate to understand how systems will behave and they constantly ask *what if* – ‘I know how this system is supposed to behave but *what if* there’s a power cut, operator error, poor maintenance, user who doesn’t read the manual, exceptional weather ... ?’. Answering these questions requires a clear view of the system in the round and not just a detailed knowledge of some small part, however important that part might be.

5. **Take account of the people** – *to err is human.*

People are a vital part of any system. They may have to build, install, operate or even inhabit a system, and they may have to pay for or defend it. Their flexibility may be both the greatest weakness of the system and its best hope for recovery when something goes wrong. Good system design takes account of the people involved, both their weaknesses and strengths, and works with them.

6. **Manage the project and the relationships** – *all for one, one for all.*

Many different people and organizations contribute to creating a successful system. They might be bound formally by contracts or informally by a shared interest. They might be close colleagues or they might never meet – the person dismantling a system might not have been born when it was designed and built. Relationships within a project are crucial – the most successful projects are built with a spirit of partnership rather than confrontation.

diagram should take but all will agree on the essential features:

- Defining what the stakeholders want is an iterative process. They may not be able to articulate what they want and, even if they could, their demands have to be aligned with the available and affordable technology.
- Stakeholders’ demands have to be translated into specifications for what to build, paying special attention to the interfaces between elements of the system. Elements are likely to be designed, built and tested separately, by different people or different companies, and the interface specification defines the environment for their element.
- The elements must be combined and tested as a system, after testing each alone.
- The process must take account of the entire life of the system, from initial concept through to disposal.

The first three of the six Principles concern issues that would easily be recognized as within the domain of engineering. Principles 4 to 6 are perhaps surprising, because they are about human behaviour and relationships. The Academy’s Guidance includes many aphorisms and quotations to emphasize its arguments; two of those are ‘You can’t build an integrated system without an integrated organization’ and ‘Systems rarely go wrong – it’s the people involved who do’. These underpin two important messages from systems engineering. The first is that the organization that delivers the system has to be designed and nurtured just as much as the system itself. The contractual and human relationships within the team are vital. The second is that those people will fail – they may make mistakes or errors of judgement or may even be deliberately obstructive. Systems engineering addresses human and not just technical issues.

THE PRINCIPLES IN PRACTICE

Figure 1 shows a systematic procedure, as demanded by Principle 3 but which also underpins all of the other Principles. Engineers will argue for eternity on the exact form that this

APPLYING THE PRINCIPLES TO INTELLIGENT BUILDINGS

The model in Figure 1 splits neatly into two types of activity, both of which are needed to create

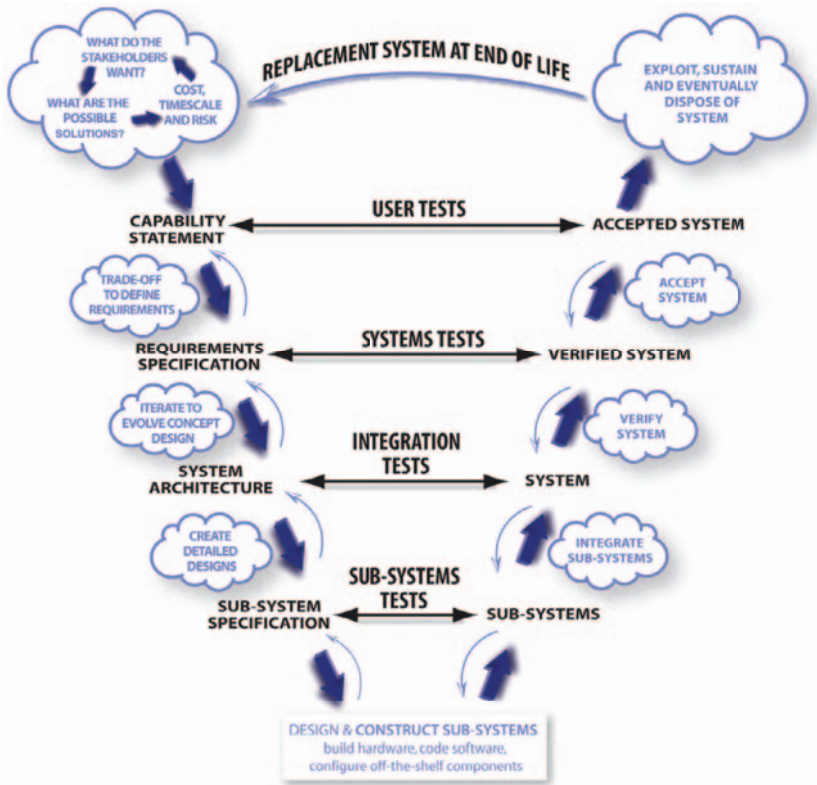


FIGURE 1 A systematic procedure

a successful system. The left hand side of the V is analysis and decomposition; its purpose is to ensure that the system development ‘does right things’. The right hand side is synthesis and integration; its purpose is to ensure that the development ‘does things right’. Both sides have a role in the development of intelligent buildings and both sides bring challenges.

DOING RIGHT THINGS: THE LEFT HAND SIDE OF THE V

The core of the left hand side is capturing the requirements and breaking them down into specifications. An intelligent building cannot be specified and designed in isolation – ‘intelligence’ is not an abstract quality, like beauty it lies in the eye of the beholder. More prosaically, an intelligent building is one that is ‘fit for purpose’

but what is the purpose and who defines it? What is the scope of the left hand side of the V?

One of the most obvious opportunities to introduce intelligence is a commercial building such as a rented office, which should be the solution to the need to provide a place to work. If the building includes features that make the people who work in it more productive, such as better lighting and ventilation, improved communications or calmer acoustics, it should allow its tenants to earn more and that in turn should be able to be captured in higher rent.

It is easy to illustrate this with figures. A good quality office may attract a rent of between £100 and £1000 per square metre per year (or even more in West London). Let’s take £250 as typical. The total area required by each employee is around 25 square metres, including

a share of common spaces such as reception, corridors and meeting rooms, making the annual cost of renting space to be around £6000 per employee.

The value to the tenant depends on the nature of his business but we can indicate a lower limit. The value added by the employees must exceed the cost of employing them or the business is not viable. The total cost of employing a professional who might use such an office is typically at least £100K per year, including salary, overheads, pension and benefits. The value to the employer will therefore be at least £100K. An intelligent building that made the employee 10% more productive is worth at least an extra £400 per square metre to the tenant; enough to pay additional rent or running costs that would cover a 50% increase in the cost of construction and still leave room for both developer and tenant to share an improved profit. The challenge is for the developer to understand the true needs of the future tenant and translate those needs into the requirements for the design and construction of the building.

The designer has to engage the full range of stakeholders from the start, both to get their input into the design and to ensure that the economic benefits of the more productive building are appropriately distributed. Future tenants have to see the long-term benefits of being part of the team. Holistic thinking breaks down when short-term considerations dominate the thinking of one or more of the players. For example, property developers proposing a block of apartments were offered a connection to the local authority's Combined Heat and Power system less than 100 metres from the site. This would have provided low-cost heating and cooling forever. The developer turned down the offer because the capital cost was greater than underfloor electric heating and he (probably rightly) believed that future purchasers would consider only the purchase price and not the running cost of the apartments.

So how do integrated system design's six principles apply? Principles 1 and 2 are crucial. If

you don't know the true purpose and don't think holistically about who will use it, then you have little hope of delivering an intelligent building. Principles 3 and 4 also apply. The designer must be creative, to find the ways in which engineering can add value to the purpose, and must be rigorous and systematic to avoid the whole exercise being little more than *feng shui*. Intelligent buildings are all about taking account of people, both as users of the buildings and in the relationships that allow the users to express what they need and the developers to capture the greater value, so Principles 5 and 6 apply both while the building is being developed and when it is in use.

In the 1970s a science research department of Cambridge University moved into a new building. The researchers found nowhere to store materials, spare equipment or even documents. When accepting a prestigious award for the building, the architect complained that it was ruined by the untidy tenants. Where was the intelligence in that building?

DOING THINGS RIGHT: THE RIGHT HAND SIDE OF THE V

The statement in 'Creating systems that work' that 'You can't build an integrated system without an integrated organization' was mentioned earlier. Major systems, including intelligent buildings, are too complex and too large for one organization to design, build, maintain and operate. They work in teams, bound together by contracts and unwritten shared understanding where the contract is silent, ambiguous or incomplete. The challenge is to design the team so that every member's *responsibilities* align with his *interests* and those responsibilities collectively militate for success. The crucial design step is to characterize the scope of the right hand side and therefore of the team conducting it, just as the scope of the left hand side has to encompass all stakeholders interested in defining the requirements of the project.

Integration is both horizontal and vertical. Horizontal integration is the process of aligning the

interests and actions of all of the organizations and people involved currently in the project. It moves beyond the idea of a contractual chain, where companies higher in the chain instruct those lower down and the client, at the top of the chain, instructs the principal contractor. The relationships are more like partnership, in which 'we' have a problem when something goes wrong. Two examples from other industries:

- The North Sea oil industry underwent a revolution in the 1970s when the price of oil fell and production was no longer viable. Companies across the industry cooperated in the CRINE project to develop new ways of working and new contractual relationships that share risk and reward. The cooperative relationships reduced costs below the falling prices.
- The UK rail industry after fragmentation established System Authorities (later called System Interface Committees) to bring together all of the companies concerned with problems that arise at the interfaces between them. The most important addressed the wheel/rail interface, a complex scientific and engineering problem that required a substantial collective research programme and joint action.

The Eden project and the construction of Heathrow T5 show that the built environment can share this thinking, which is Principle 6 of the guidance. However, there are many examples where the overall goal – a successful project – has been lost under the pressure for completion. It is all too common for the M&E contractor, whose work gives effect to much of the intelligence in a building, to be squeezed between an over run of the construction phase and a high-profile public opening.

Vertical integration takes account of the total life of a building, from concept through to adaptation for a new role or, if that is not possible, demolition. It requires cooperation between people who are widely separated and may not ever meet. The building has to be conceived for operation and maintenance as well as ease of construction and performance. The technical services have to be capable of being operated by the maintenance

staff – a complex building management system is of little value to traditional janitors, it needs a skilled contractor. Principle 5 of the guidance recognizes the limitations of the people involved. More indirectly, the handover between the construction team and the operations and maintenance team must be planned and properly resourced, allowing sufficient time even if the construction phase is late. The end of a building's life is an even more distant thought. Sustainable buildings can be adapted to a new role at the end of their life but, if that is not possible, demolition might be necessary. How many buildings now cannot be easily dismantled because their structure was post-tensioned? Building life is becoming shorter – a senior civil engineer recently told the author that he knew that he was getting old because two of his projects have been demolished and one listed.

The message is clear – intelligent buildings are as much a consequence of intelligent procurement as of intelligent design.

SUCCESSFUL INTEGRATED DESIGN OF INTELLIGENT BUILDINGS

'Intelligence' when applied to buildings is assumed to refer to function. An intelligent building meets the needs of all of its stakeholders. It is easy to overlook aesthetic considerations, but those too should be part of the needs. The Basilica in Lille is an outstanding example, where the building has evolved over more than 100 years and the final stage, the west front, is a masterful construction in stainless steel, marble and glass that blends beautifully with the rest. The building's aesthetics reinforce its function; it encourages worship. The west front also epitomizes Frank Lloyd Wright's concept of 'appropriate to its time'. Compare this with the practice of setting aside a small percentage of the budget for a public building for art. Several European countries have ugly steel bridges with, bolted on half way across, a platform for a challenging and thought-provoking statue. Aesthetics should not be (in that case literally) a bolt-on, they are an intrinsic part of the design. There is an old engineering maxim: 'if it looks right, it probably is'.

But in the end, beauty is about function. An example of an intelligent building is the David Young Academy, designed to create an environment that helps learning. One of the pupils summed it up: '*it feels quite bright even on a rainy day*'. Teaching and learning are never easy but a positive and supportive environment helps. The building is more than just an enclosed space to keep out the weather; it has become a 'machine for learning'.

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