Big ideas BAE Systems Engineering Resource Pack

Big ideas are engineered

A resource for schools

INCOSE International Council on Systems Engineering

2150 N. 107th St., Suite 205 • Seattle, WA 98133-9009 (USA)
Phone: (206) 361-6607 or (800) 366-1164 • FAX: (206) 367-8777
Email: info@incose.org
World Wide Web URL
http://www.incose.org

To: Teachers reading the “Big Ideas: BAE Systems Engineering Resource Pack’’

8 July 2005

Dear colleague:

SYSTEMS ENGINEERING CASE STUDIES FOR SCHOOLS

The International Council on Systems Engineering (INCOSE) is delighted that BAE Systems has taken the step of making these case studies available, in order to raise awareness of systems engineering amongst young people in schools. It is important that young people, and crucially their teachers, are helped to understand more fully how systems thinking and systems engineering impacts upon everyday life. We would encourage you, their teachers, to make use of the resource in the classroom and hope that it will inspire more young people to pursue careers in engineering, and systems engineering in particular!

Professor Heinz Stoewer
President
INCOSE

Paul Robitaille
President Elect
INCOSE

Acknowledgements page

At BAE Systems

Richard Hamer
Education Partnerships Director BAE Systems
richard.hamer@baesystems.com

Project co-ordinators

David Barlex
Nuffield Curriculum Centre

Torben Steeg
Systems and Control consultant

Desk Top publishing

Jo Oladejo
Nuffield Curriculum Centre

Design concepts

Dave Mackerell
devised

Participating Schools

Broadlands School
Bristol

City of Portsmouth Boys School
Portsmouth

Devonport High School for Boys
Plymouth

Westcliffe Girls High School
Westcliffe-on-Sea

Carr Hill High School
Preston

Lytham St Annes High Technology College
Lytham St Annes

The following individuals made a significant contribution to these materials

David James	Educational Consultant
Andy Hughes	Segway HT advisor
Amanda Pearce	Loughborough University
Allan Seabridge	BAE Systems
Russell Davison	Losing power case study
Michael Dean	Losing power case study
Robert Eato	Losing power case study
Ben Foster	Losing power case study
Richard Gould	Losing power case study
Michael Hartley	Losing power case study

BAE SYSTEMS

Contents page

BAE SYSTEMS

Welcome to Big Ideas, the BAE Systems Engineering Resource Pack.

The aim of the Big Ideas resource is to provide you with a set of resources and approaches that will enable you and your pupils to use systems thinking to enhance the design & technology curriculum, to provide an appreciation of the work of systems engineers and develop an appetite for pursuing a technical career involving systems engineering.

The pack has **three main sections.**

- **First, there is "Systems teaching".**
This provides a detailed treatment of the ideas needed for teaching a systems approach and how the Welsh Joint Education Committee GCSE Design & Technology in Systems and Control can be taught using a systems engineering approach. There is a feedback section to allow you to ask the author questions about systems teaching and thinking.

- **Second, there is "Engineering the links between design & technology, mathematics and science".**
This requires innovative curriculum development particularly as since the introduction of the National Curriculum these subjects have pursued their own teaching with little reference to each other. Systems engineering demands the use of knowledge, understanding and skill from a wide range of subjects and beginning with developing links between these three subjects is a good way to start. There is a feedback section to let the authors know about the projects you are using to build links

- **Third, there is "Systems Engineering Case Studies" to introduce pupils to the world of systems engineering and provide insight into the impact of systems thinking.**
There is a feedback section so that you can let the authors know how you are using the studies and how they might be improved.

BAE Systems Engineering and the authors hope that you and your pupils will enjoy using this resource pack. It is available as a single unit or single elements on the BAE Systems Engineering website at www.baesystems.com/education/systemsengineering.

For further information about how to use this pack you should refer to p32.

Systems Thinking Concepts

Introduction

Systems ideas as a tool for supporting pupils' thinking about a wide range of situations in Design and Technology (D&T) are now well established in the UK National Curriculum, in exam specifications and in school texts. In particular they have proved to be powerful in helping pupils from Key Stage 2 onwards design and make in the area of control and, in particular, electronics. This is because a systems based approach allows pupils to fully engage in design work in these areas by suppressing technical complexity while bringing to the surface those features of the design context that are within pupils' grasp.

Systems thinking is used in D&T in a variety of ways; to support high level approaches to complex situations when pupils are designing and making control systems, to help pupils analyse and describe the designs of others, for example in product analysis activities, and as a descriptive tool when pupils need to understand the operation of complex entities such as a manufacturing system or some element of an eco-system. It is noteworthy that systems thinking is also used in science education (especially the biological sciences), in ICT to support the teaching of programming and in the humanities as an explanatory tool when dealing with complex entities (for example trade relationships).

At the heart of systems thinking are system diagrams used to illustrate the key elements of a system and the relationships between these elements. The development of systems thinking started about a hundred years ago and in that time a wide range of diagrammatic tools has been developed to support thinking in a wide range of contexts from biology to control engineering to describing how businesses work. In secondary D&T education, just two types of system diagram are in common use: block diagrams derived from control theory and flow diagrams, often based on those used in software development. There is, however, evidence from examinations, books and observation of work in lessons that the understandings and uses of both kinds of system diagram are diverse and, often, confused both with each other and other types of system diagram. Pupils can be helped to achieve clarity about the uses of these two kinds of system diagram if they are encouraged to think about what the blocks and lines in the diagrams are supposed to represent.

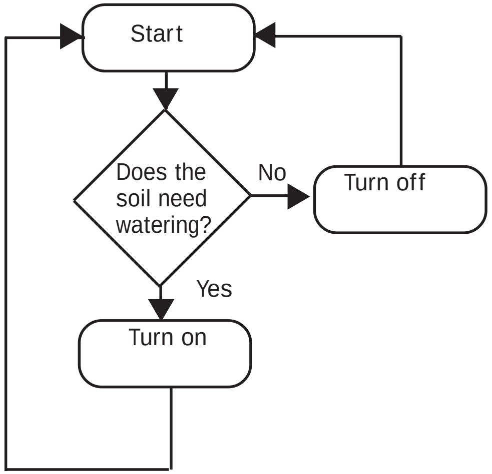

Figure 1 A flowchart for a simple plant watering system

Flowcharts

Flowcharts are generally used to define sequences of instructions; in D&T this is generally either in the context of computer control programming or to describe a pupil's (or an industrial) manufacturing sequence.

In a flowchart the various blocks represent actions or operations that are to be carried out with different block shapes representing different types of operation. For example diamond-shaped decision boxes are used where there is a choice about the sequence of actions. The arrowed lines simply show the sequence of execution of these operations.

So, flow charts are about events and the sequence in which events should be carried out. When using them the design question focuses on *"what does the control system*

BAE SYSTEMS

need to do next?".

Block Diagrams
The second type of diagram frequently met in D&T is often simply called a 'system diagram', despite the broad range of such diagrams that exist; for clarity these will be called 'block diagrams' here. These diagrams use arrowed lines to show signals that transfer information between blocks whose purpose is to operate in some way on these signals. These are commonly used to describe the functional operation (as op-posed to the physical construction) of a range of control systems including electronic and mechanical systems.

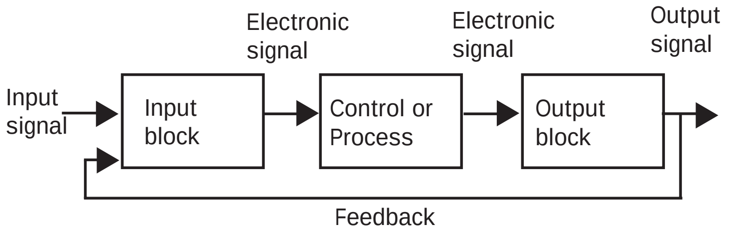

Figure 2 A block diagram

Signals
Each arrow in a block diagram represents a signal. Any physical variable (e.g. light, voltage, sound, force, height etc.) can be represented as a signal that will have a measurable value.

A control system will detect one or more signals at its input and produce one or more signals at its output. The block diagram shows the route of the signal(s) into, through and out of the system.

Signals are either analogue or digital:
An **analogue** signal can have any value (between upper and lower limits). For example the level of light, sound and temperature where you are now are all analogue signals; they are constantly varying.

A **digital** signal has fixed values. In most work that pupils do just two fixed values are allowed.

For example a doorbell switch may be either pressed or not pressed. The temperature is either less than 20°C or its 20°C or above.

Within digital electronic systems (including digital computers) all the signals are digital, the two possible values are labelled as high (or '1') and low (or '0'). Combinations of digital signals are used to provide codes that represent a wide range of things from approximations to an analogue value to an alphabet character or the colour of a dot on a computer monitor.

Functions
Each block in a block diagram represents a function that affects a signal, for example by:
- Changing the type of signal.
- Changing the signal's size.
- Combining signals.

The three blocks in the 'standard' diagram to the left represent the three *kinds* of block that exist.

An **input block** takes signals from the environment and turns this information into a useful form for the system; for example in an electronic system this will be an electronic signal.

An **output block** turns systems signals (e.g. an electronic signal) into a signal that is sent out into the environment, such as motion, sound or light.

A **process block** operates on signals within the system for example combining, timing counting etc.

The function of a block is always well defined, so that the operation of the control system is predictable.

Using block diagrams

As with all design tools, block diagrams get easier to use the more you practice with them. There are some practical issues to consider when incorporating their use into work with pupils:

- Block diagrams can be used to design and describe all types of control system; including computer, electrical, pneumatic, hydraulic and mechanical control.
- A block diagram should have both input and output signal arrows. These are often omitted in textbooks, which is a mistake that can only lead to confusion. A system with no input and output output arrows suggests a system with no information entering or leaving it; it is difficult to imagine a use for such a system.
- Power supplies and interfaces are not shown on block diagrams. These things may be necessary for the final operation of the system, but they don't operate on signals directly. A system diagram is a way of describing how a system should work – what it should do. It will not necessarily describe how the desired system should be implemented; a block diagram indicating a particular function could often be implemented in range of control technologies.
- For similar reasons drivers such as transistors and Darlington pairs (used to amplify the current to power hungry output devices) don't need to appear on a system diagram. From a signal point of view these components have no effect on the system, though they are clearly required to allow many output devices to work.
- You do not always have to have one each of the blocks shown in the 'standard' input-process-output diagram. In a complex system you will probably have multiple inputs and outputs as well as a series of processing steps. In a simple mechanical system there may be no sensible 'process' block at all. For an example look at the diagram for a bike brake system.

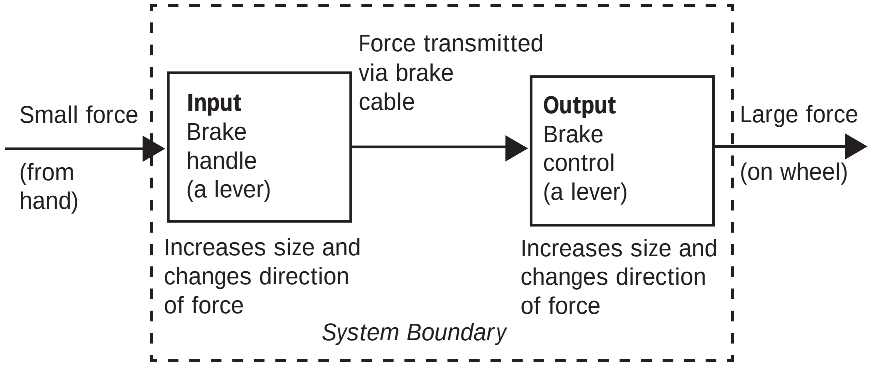

Figure 3 A block diagram of a bike braking system

A mistake in many school text books is to try to force every system into the 3 block model, ignoring the fact that these are generic block types.

BAE SYSTEMS

Boundaries
Drawing an imaginary boundary around your system will help you see what you need to include in the diagram.

For example, in the diagram for a bike brake system, the bike rider and the wheel have not been included as a part of the system (nor has the road surface or the presence of other traffic); the system boundary has been drawn to just describe the mechanical braking system.

In a different design situation you might want to either:

- Draw a tighter boundary. For example, to focus on just one part of the system such as the brake handle.
- Draw a looser boundary. For example, you might want to include the cyclist as a part of the total braking feedback system or you might want to consider the effect of the road on the wheel.

Designing with Block Diagrams
When designing with bock diagrams, the design question focuses on "what needs to happen to the signal next?".

Start by asking what signals the control system will need to detect and to produce. "What kinds of physical signal are going into the computer?"

Each input signal you wish to detect will need an input block in the system diagram and the associated input signal arrow. When designing an electronic system, each input block represents a single sensor that changes a physical signal from the environment into an electronic signal.
"What kinds of physical signal are going to be produced by the computer?"
Each output signal you wish to produce will need an output block in the system diagram and the associated output signal arrow. When designing an electronic system, each output block represents a device that changes an electronic signal produced by the system into a signal sent out into the environment.

Next, ask what the system needs to do to the input signal to achieve the desired output signal. This where the hard design thinking takes place. Often it is useful to start with a very broad description of the desired function of the system and then gradually break this down into subsystem elements.

Designing a bike alarm
For example, in designing a tamper alarm for a bicycle, you might quite quickly decide that you need to detect motion of some kind and that you want to produce a loud noise:

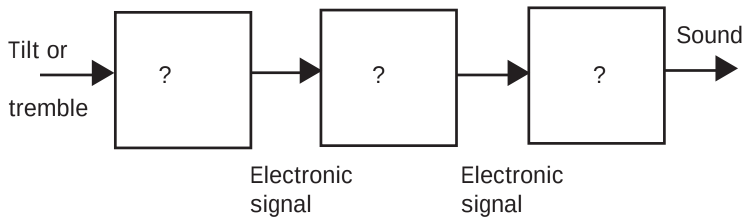

Figure 4 Designing a bike alarm; step 1

After some research into possible motion sensors and ways to produce a loud sound, you might settle on a tilt sensor and a siren:

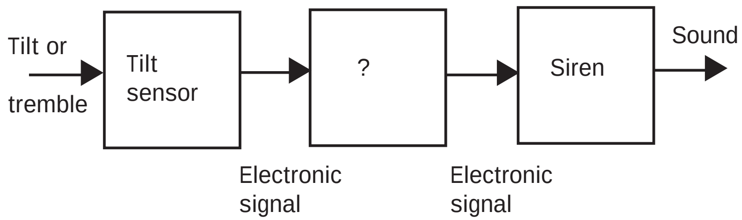

Figure 5 Designing a bike alarm; step 2

How to control the siren based on the signal from the tilt sensor is a critical system design question. The system could simply cause the siren to come on whenever the tilt switch is activated:

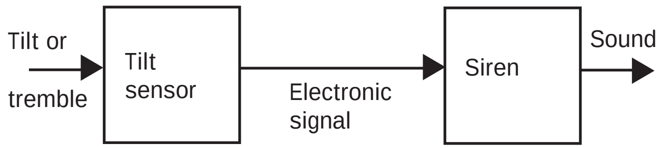

Figure 6 Designing a bike alarm; step 3

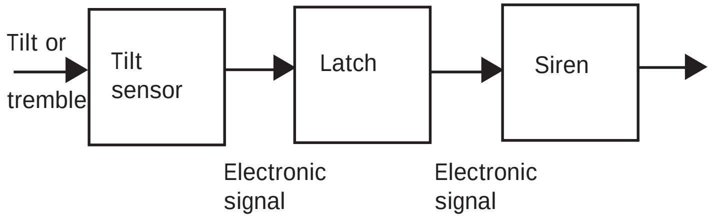

Figure 7 Designing a bike alarm; step 4

This is however not a very sophisticated system; a careful thief could take the bike without making much sound. The more sophisticated control options available are wide. The siren could stay on once the sensor is triggered, it could stay on for a fixed time, it could pulse on and off (either continuously or for a fixed time), and so on. See Figure 7 for a final block diagram, describing a system where the siren is latched (to stay on once the sensor is triggered).

Having defined the system operation the designer then needs to decide on an appropriate technology of realisation. This could be via hard wired electronics, a programmable system (for example a PIC) or, in some situations, other control technologies such as pneumatics or mechanisms.

Describing Control Systems

There are two broad types of control system:

- **Continuous** control systems,
- **Sequential** control systems.

Continuous Control

In many control systems, the input signal is being continuously monitored and the output

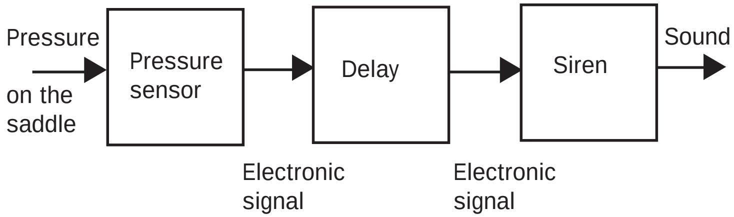

Figure 8 Another bike alarm

signal is being continuously controlled.

For example the bicycle alarm could have a pressure sensitive switch in the saddle; if someone sits on the saddle when the alarm is enabled a loud siren would be set off.

You might arrange things so that the siren continues for a while even if the thief got off the saddle again. A process block called a delay provides this function; when the electronic signal going into the delay goes high, the signal out of the delay goes high as well and remains high for a fixed time after the signal into the delay goes low.

A block diagram for such a system is shown above in Figure 8. The signals in this system are continuously active, even when it appears to be doing nothing:

- The amount of pressure has a continuous influence on the signal between the sensor and the delay.
- The electronic signal from the sensor has a continuous influence on the signal out of the delay.
- The electronic signal from the delay has a continuous influence on the level of sound made by the siren.

	Red	Amber	Green	Delay
Step 1		Off	Off	60 seconds
Step 2			Off	10 seconds
Step 3	Off	Off		60 seconds
Step 4	Off		Off	10 seconds
		Back to step 1		

Figure 9 State table

Systems like this are called continuous control systems and are easy to describe using block diagrams.

Sequential Control
Some systems don't work in the same way as the bike alarm. Instead of continuously monitoring what is happening and reacting, they simply carry out a fixed sequence of operations that are separated by fixed delays.

A very common example of this is a set of traffic lights. Once the lights are switched on, the sequence of lights simply repeats constantly. At each step in the sequence the pattern of lights changes, with a set delay between each step.

Systems like this are called sequential

control systems and are particularly easy to describe use flowcharts or state tables.

Many control systems actually have a mixture of sequential and continuous parts. For example a pedestrian crossing often uses a set of traffic lights that only stop the traffic when a pedestrian presses a 'Stop' button.

- The part of the control system that is monitoring the 'Stop' button is continuous.
- The part of the system that controls the fixed steps that occur when the traffic is stopped is sequential.

Feedback

Control systems often need to do more than simply sense their environment; they may also need information on the effect they are having.

For example you might design a system to water your plants automatically.

One way to do this would be to calculate the daily water requirement. You could then arrange for this amount of water to be pumped into the soil each day. However, this system might not be very effective; in very hot weather more water would be used and the plant could still dry out. Or you might swamp the plants in cold weather.

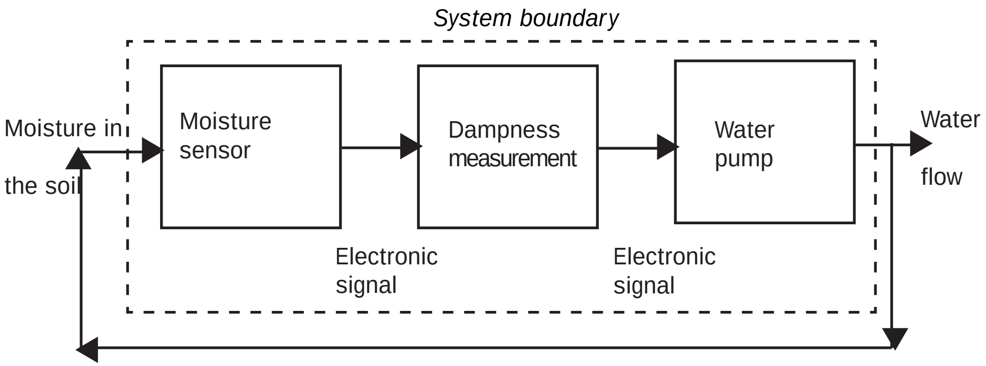

Figure 10: A plant watering system

It would be much better to actually sense how damp the soil is and only water it when dry. The system diagram for such a system is shown below. The thing to notice about this diagram is that the signal produced at the output of the control system is fed back to effect the signal at the input of the control system. This is called feedback.

The feedback signal is not an electronic signal in this example; it is the level of moisture in the soil. As water is pumped into the soil (the output of the system), the moisture level increases (the input to the system). However, when you are designing the system you don't need to concern yourself with this process or include the soil in the diagram because it is outside the system boundary.

Most control systems, apart from the simplest, make use of feedback and can monitor the effect they are having on the environment they control.

These notes, so far, have concentrated on the use of systems in the KS3 and KS4 national curriculum. Beyond secondary education the concept of what a system is broadens out considerably and there are lessons that D&T education can learn from this.

In its fullest sense, a system is an assembly

Systems Engineering

or collection of different elements that together produce results that the elements alone couldn't achieve. These elements can include people, hardware, software, facilities, policies, and documents.

Systems Engineering works at this broad systems level to not only create products but also the process for producing the product, as follows:

State the problem
Investigate alternatives
Model the system
Integrate
Launch the system
Assess performance
Re-evaluate

These functions can be summarized with the acronym SIMILAR. This Systems Engineering Process is shown below. It is important to note that the Systems Engineering Process is not sequential. The functions are performed in a parallel and iterative manner.

State the problem
The problem statement starts with a description of the top-level functions that the system must perform this will include mandatory requirements (that must be met) and preference requirements that may be traded-off to find the preferred alternatives. The problem statement will be in terms of what must be done, not how to do it.

Investigate Alternatives
Alternative designs are created and are evaluated based on performance, schedule, cost and risk. No design is likely to be best on all aspects and systems engineers use a range of analytic techniques to find the preferred alternatives. This analysis is repeated whenever more data is available. For example an initial analysis will be based on estimates by the design engineers. Following this models (both physical and electronic) and prototypes will be constructed and evaluated. Tests will also be run on the final system.

Model the system
Models are developed for most alternative designs. The model for the preferred alternative will be expanded and used to help manage the system throughout its entire life cycle. Many types of system models are used, such as physical analogues, analytic equations, state machines, block diagrams, functional flow diagrams, object-oriented models, computer simulations and mental models. As already noted, Systems Engineering is responsible for creating a product and also a process for producing it. So, models should be constructed for both the product and the process. Process models allow engineers to, for example, study scheduling changes and perform sensitivity analyses to show the effects of delaying or accelerating

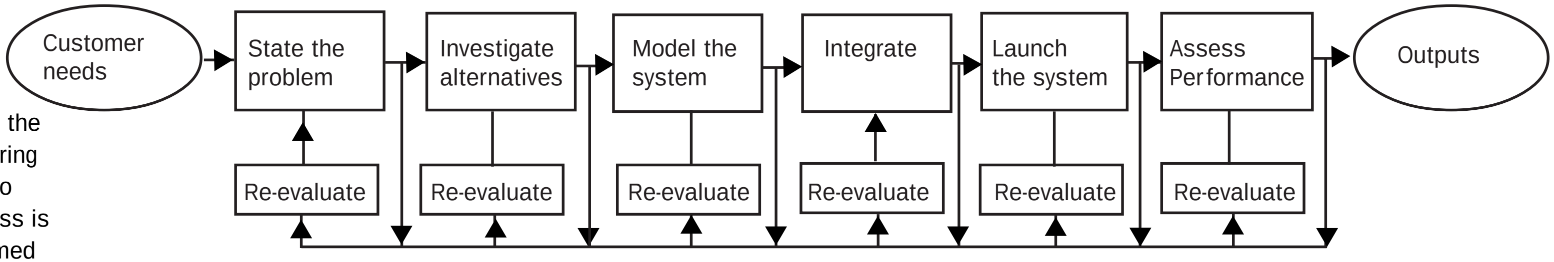

Figure 11 The SIMILAR process

certain subprojects. Running the process models reveals bottlenecks and fragmented activities reduces cost and exposes duplication of effort. Product models help explain the system. These models are also used in tradeoff studies and risk management.

As noted, the Systems Engineering Process is not sequential, it is parallel and iterative; as an example of this models must be created before alternatives can be investigated.

Integrate

Systems, businesses and people must be integrated so that they interact effectively with one another. The way that subsystems interact must be designed. For example subsystems are usually defined along natural boundaries but also defined to minimize the amount of information to be exchanged between them. Feedback loops around individual subsystems are easier to manage than feedback loops around interconnected subsystems. Processes of co-evolving systems also need to be integrated.

Launch the system

Launching the system means running the system and producing outputs. In a manufacturing environment this might mean buying commercial off the shelf hardware or software, or it might mean actually making things. Launching the system means allowing the system do what it was intended to do. This also includes the system engineering of deploying multi-site, multi-cultural systems.

This is the phase where the preferred alternative is designed in detail. The parts are built or bought and integrated and tested at various levels leading to the certified product. In designing and producing the product, due consideration is given to its interfaces with operators (humans, who will need to be trained) and other systems with which the product will interface. In some instances, this will cause interfaced systems to co-evolve. The process of designing and producing the system is iterative as new knowledge developed along the way can cause a re-consideration and modification of earlier steps.

The systems engineers' products include a requirements document including routes for verification and validation, a description of functions and objects, a test plan, a drawing of system boundaries, an interface control document, a listing of deliverables, models, a sensitivity analysis, a tradeoff study, a risk analysis, a life cycle analysis and a description of the physical architecture.

The requirements should be validated (are we building the right system?) and verified (are we building the system right?).

Assess performance

Technical performance measures are used to mitigate risk during design and manufacturing. Data (including customer satisfaction comments, productivity, number of problem reports, or whatever is critical) are used to help manage a company's processes. Measurement is the key. If you cannot measure it, you cannot control it. If you cannot control it, you cannot improve it. Important resources such as weight, volume, price, communications bandwidth and power consumption should be managed. Each subsystem is allocated a portion of the total budget and the project manger is allocated a reserve. These resource budgets are managed throughout the system life cycle.

Re-evaluate

Re-evaluate is arguably the most important of these functions. For a century, engineers have used feedback to help control systems and improve performance. It is one of the most fundamental engineering tools. Re-evaluation should be a continual process with many parallel loops. Re-evaluate means observing outputs and using this information to modify the system, the inputs, the product or the process. Figure 11 on page 13

BAE SYSTEMS

summarizes the Systems Engineering Process. This figure clearly shows the distributed nature of the Re-evaluate function in the feedback loops. However, all of these loops will not always be used. The particular loops that are used depend on the particular problem being solved.

Summary

Most systems engineers accept the following basic core concepts:

1. Understand as much of the problem as possible before you try to solve it

2. Translate the problem into measurable requirements.

3. Examine all feasible alternatives before selecting a solution.

4. Make sure you consider the total system life cycle. The birth to death concept extends to maintenance, replacement and decommission. If these are not considered in the other tasks, major life cycle costs can be ignored.

5. Make sure to test the total system before delivering it.

6. Document everything.

Using WJEC D&T GCSE in Systems and control for systems engineering

WJEC have agreed that they will be happy to accept collaborative projects based around the principles of Systems Engineering from pupils following their D&T: Systems and Control specification.

This means developing collaborative coursework projects based in D&T that also tap into expertise in the Maths and Science curricula.

Developing collaboration in Design & Technology

An essential requirement of developing a systems engineering approach to design & technology is that the designing and making assignments tackled are too demanding for a single student. Success necessitates collaboration. Patricia Murphy of the Open University has made extensive observations of collaborative problem solving in the design & technology classroom. Through her research she has identified a set of optimal preconditions for success. These provide schools with a powerful framework with which to develop and evaluate systems engineering based work:

Teachers need to be committed to support learning through collaboration and should understand collaboration as a learning mechanism.

The task context should set the conditions for joint decision making during design and construction. Critical elements are:

- An explicit negotiated purpose to the task, linked to individual learning and a genuine need or function to the world;
- Student autonomy and participation in decision making during design and problem solving
- A shareable task. There should be opportunities for making thinking processes explicit and developing shared meaning through verbal and physical interactions.
- School and classroom organisation that supports small groups (including enough time to do so, consistency between classrooms in fostering collaborations, and reinforcement of the value of collaboration through evidence of teacher collaboration).

A range of pedagogic strategies should be used to support collaboration including:

- Knowing how to select appropriate tasks, i.e. tasks whose demands are within individuals capabilities but which challenge them to develop and refine solutions of increasing sophistication;
- Knowing how to scaffold students' problem solving through offering both ideas and tools to make students' thinking explicit to themselves and others;
- Having the means to recognise and make explicit alternative perceptions of salience and valuing these through discussion and reflection between peers and between peers and teachers;
- Monitoring individual understandings as solutions evolve over time and helping students to reflect on their thinking and the sources of changes in it;
- Addressing dissonance within groups to the benefit of all individuals and as part of this recognising when collaboration is no longer constructive etc., modelling ways to resolve negotiations;
- Monitoring individual engagement with group activity in terms of both establishing and enhancing shared reference points;

- Maintaining students' focus on productive problem-solving paths;

- Encouraging discussion of decisions. This should include both students and teachers justifying their suggestions for action. It is important that the students retain ownership of the decision making process. To achieve this it might be necessary for the teacher to allow students to follow a decision path with which the teacher disagrees. In such cases the teacher should present her reasons for disagreement but allow the students responsibility and autonomy.

- Developing an ethos where learning from feedback is a continuing process throughout the stages of activity rather than seeing activity as enactment of a closed solution. A consequence of this is that products may not be achieved or what constitutes a product may need re-conceptualising. The emphasis should be on the learning achieved, not the product outcome.

Students need:

- a shared frame of reference regarding the task, its purpose and the expected outcome (or the opportunity to negotiate these once individual perceptions are developed to some extent; these must then be common or negotiable and the goals of individuals' separate tasks need to overlap) personal authenticity and investment in outcome (authenticity is individually constructed and enables student engagement and participation in the activity);

- appropriate social skills and cognitive strategies to support collaboration (especially willingness to communicate and co-operate in the activity and to engage in shared decision making; encouraging and valuing partners' contributions negotiating about alternatives, critical evaluation).

In her work Patricia makes the important distinction between learning to collaborate and collaborating to learn. Where teachers lack an understanding of collaboration as a learning mechanism they will be unable to support pupils working in this way. Central to this understanding is realising that pupils need some social skills and cognitive strategies for collaboration.

It is important that the teacher models the sort of behaviour required from students. Listening carefully to students and commenting constructively on what they have said pays big dividends. It encourages the students to listen to each other and take into account what has been said in planning next steps. If the teacher does not do this it is unlikely that the students will develop the social skills and cognitive strategies for collaborative learning and powerful opportunities for learning will be lost.

Through her work Patricia has observed and described the work of teachers who did understand the nature of collaboration for learning and had a pedagogic style that supported this. As a result the students not only enjoyed the opportunity to work together but also understood the cognitive benefits that accrued from it.

This identification of the factors important in enabling collaboration to take place in the design & technology classroom first appeared in the *International Journal of Design & Technology Education Journal* (Volume 11, No. 3, 2001). In particular Patricia noted that it was the teacher's views of the learner that were crucial in enabling the teacher to appreciate potential for collaborative learning. Teachers who view learners as passive in the learning process, simply as receivers of information 'delivered' by the teacher, are unlikely to see the benefits of collaborative learning or of adopting a pedagogy that will support it.

The challenge for schools wishing to adopt a Systems Engineering approach is to use the work of Patricia Murphy and her colleagues to ensure the student is viewed as an active participant in the learning process and that the conditions for fruitful collaboration are met in their classrooms. A major part of this challenge will be developing course work tasks that meet the criteria of the Examining Body and have contexts the set the conditions for joint decision making during design and construction.

Groupwork guidelines
Suitable criteria for establishing a group based designing and making assignment might include:

- the designing and making task is too demanding for a single individual; Provide clear guidance on matching the number of students in a group to the demand of the project.
- pupils sign up to group work course work and its implications at the beginning of major coursework;
- each student has to produce their own 'evidence portfolio' in which it is clear what is their own work, the work of others and the group's work;
- each candidate has to contribute significantly to both the designing and the making of the final product(s);

The group is responsible for monitoring its own group performance using given criteria and individuals should comment on this in the portfolio.

The teacher should also monitor group performance using the same given criteria and comment on this; grades are awarded on quality of designing and making.

The best collaborations tend to have the following structure:

- an initial, ill-defined stage, where the students debate ideas and approaches as a whole team.

Followed by,

- a gradual transition to a clearer plan and some subdivision of responsibilities, but still a lot of general discussions. Often at this stage students will do some of the sub-tasks in pairs,
- in the later stages of the project, more of each student's time would involve working on their own sub-tasks, but there would still be regular reporting back to the entire team and discussion, and also some work would still be in pairs e.g. one student doing work and a second student checking it.

Suitable tasks include any multi-part communication system (candidates can work individually on the parts, still having to take into account such things as agreed signalling protocols, agreed product form and style etc.).

In fact any decent scale electronics project should be suitable for collaborative work. The main criterion is that the work needs to be able to be split up. Electronics based specifications are so good for group work because systems can be split into sub-systems, subroutines etc.

A possible problem area is manufacturing, because only one person can work on a PCB, or product moulding etc. at a time (but subsystems could in some cases, legitimately from a product design perspective, be manufactured on separate PCBs with an agreed protocol for connecting the PCBs).

An audit approach to establishing links between design & technology, maths and science

Developing cross curricula links between design & technology and other subjects is not an easy task but the following four step approach provides a straightforward way of beginning the task. To begin with the teachers of design & technology must ensure that the curriculum they teach is robust.

A robust curriculum will have designing at its core and involve pupils in making design decisions for themselves. Teachers will orchestrate the number and complexity of the design decisions that their pupils have to make in carrying out a design and make activity in order to ensure that the assignment is appropriately challenging without being daunting and requires pupils to use particular parts of the design & technology programme of study.

Step 1 Auditing a single designing and making assignment

An important first step in developing a designing and making assignment is to audit the range of design decisions that are likely to be made by pupils tackling the assignment.

This audit can be carried out using five key areas of design decision: conceptual (overall purpose of the design, the sort of product that it will be), technical (how the design will work), aesthetic (what the design will look like), constructional (how the design will be put together) and marketing (who the design is for, where it will be used, how it will be sold). This can be represented visually with each feature at a corner of pentagon and each area of design decision connected to each other area.

This inter-connectedness is an important feature of design decisions. A change of decision within one area will affect some if not all of design decisions that are made within the others.

For example if the way a design is to work is changed this will almost certainly affect what the design looks like and how it is constructed. It may also have far reaching effects in changing some of the purposes that the design can meet and who might be able to use it.

Step 2 Auditing a sequence of designing and making assignments

For step 2 this audit is carried out across all the designing and making assignments tackled by pupils across a key stage. This gives an overview of the designing that is taking place and if and area of design decision is missing, under-represented or over-represented the nature of the assignment can be adjusted accordingly.

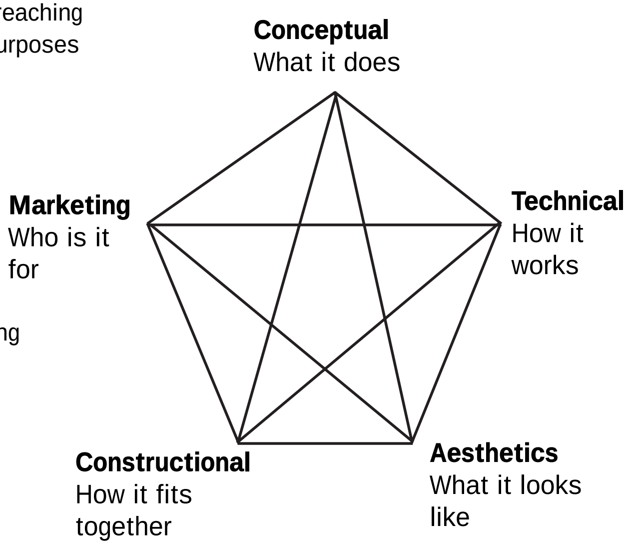

Figure 12 A representation of design decisions in a designing and making assignment

Step 3 Identifying design decisions that could use maths and science

Step 3 involves looking at each area of design decision made in a designing and making assignment and asking two simple questions. What mathematics can pupils use to inform and improve these design decisions? What science can pupils use to inform and improve these design decision?

In many cases the use of maths or science will not be particularly useful in which case there is no cross curricula link. However in a few cases the use of maths or science will considerably enhance the quality of design decisions made. It is here that efforts should be made to establish the links.

Step 4 Important conversations

Step 4 involves talking to colleagues in maths and science departments about the results of your audit. Almost certainly they will be looking for ways to make their subjects useful through 'real world' application and the links you have discovered will provide them with opportunities to do this.

Of course there is still the tricky business of organising the lessons in the different subjects so that these potential links can be made effective but the four-step approach has identified areas of cross curricula work where this is likely to pay considerable dividends to the benefit of all the subjects involved.

Creating a systems engineering designing and making assignment

The links with maths and science that you identify through the audit approach will enable you to develop a culture in your classroom where your pupils expect to use maths and science to enhance their design & technology.

This is an important first step on the path to systems engineering as part of design & technology.

It is likely that most if not all the design & make assignments in your curriculum will involve pupils working as individuals rather than as members of a team. This is in part caused by the necessity to assess pupils on an individual basis. However it is only when a design & make assignment is too complex for an individual pupil that it will require a systems engineering approach for successful completion. A suitably complex designing and making assignment will require pupils to design and make individual items that depend on their interaction with one another for good performance.

You can use the following three-phase approach to plan for a systems engineering designing and making assignment.

Phase 1 Achieving commitment
Identify an ambitious design and make assignment that you think pupils might find attractive. Here are some possibilities.

KS3 – the scary story— designing a puppet performance
KS3 – the haunted house – designing a ghost train ride
KS4 – the white-knuckle ride – designing a theme park
KS4 – the smart room – designing an interactive environment
KS4 – the safe house – designing an intruder proof house

Use the attractiveness of this idea:

- To get the commitment of senior management,
- To get commitment from three teachers – one maths, one science, one design & technology,
- To get the release of large blocks of time where team teaching can take place.

Phase 2 Use the audit approach
Ensure the idea is related to the scheme of work or specification and is large enough in scope to require pupils to collaborate. Audit from a design & technology perspective to ensure there is a range of demanding design decisions to be made.

Consider improvements that would involve explicit use of maths and science. Develop part constructed starting elements so that the task isn't overwhelming.

Phase 3 Detail the teaching
Identify small task activity in single subject lessons (maths, science and design & technology) to provide knowledge, skill and understanding that is likely to be useful in tackling the designing and making assignment.

Make the best use of subject expertise by thinking through the design decision path that the groups of pupils might take and how you can support them by enabling the following:

- Use of systems thinking,
- Use of design & technology subject knowledge,
- Use of maths subject knowledge,
- Use of science subject knowledge.

Organise the availability of members of the teaching team so that they can provide appropriate support for identified critical moments in the designing and making

BAE SYSTEMS

assignment. It is likely that the design & technology teacher will need to be present throughout the entire designing and making process.

The maths and science teachers will need to be present when design decisions relevant to their specialisms are being made. They are not critical during the making process. They will be extremely useful during modification and evaluation sessions.

Engineering the links between design & technology, maths and science KS3 feedback

Name of School

Question	**Response**
Did you use the audit approach to identifying design decisions in a **single** designing & making assignment at KS3?	
What did it reveal?	
What changes, if any, did you make as a result?	
Did you use the audit approach to identifying design decisions in a **sequence of** designing & making assignments at KS3?	
What did it reveal?	
What changes, if any, did you make as a result?	
Did you identify any links with maths and science in the design decisions made in any of the designing and making assignments at KS3? If so what were these links?	
What changes did you make as a result?	

Please look at the next page

Question	Response
Please provide details of any designing and making assignments taught in your school that make good use of links with maths and science at KS3.	

Please send this completed form to Richard Hamer.

As an attachment to richard.hamer@baesystems.com

As a fax to 01252 383 237

Thank you for completing the feedback.

Engineering the links between design & technology, maths and science KS4 feedback

Name of School   Focus Area

Question	Response
Did you use the audit approach to identifying design decisions in a **single** designing & making assignment at KS4?	
What did it reveal?	
What changes, if any, did you make as a result?	
Did you use the audit approach to identifying design decisions in a **sequence of** designing & making assignments at KS4?	
What did it reveal?	
What changes, if any, did you make as a result?	
Did you identify any links with maths and science in the design decisions made in any of the designing and making assignments at KS4? If so what were these links?	
What changes did you make as a result?	

Please look at the next page

Question	Response
Please provide details of any designing and making assignments taught in your school that make good use of links with maths and science at KS4.	

Please send this completed form to Richard Hamer.

As an attachment to richard.hamer@baesystems.com

As a fax to 01252 383 237

Thank you for completing the feedback.

Systems engineering designing and making assignment feedback for KS3

Name of School Focus Area

Question	Response
Did you create a systems engineering designing and making assignment? If yes, please comment on how useful you found the following.	
The Phase 1 approach to achieving commitment	
The Phase 2 approach to using the audit approach	
The Phase 3 approach to planning the teaching	

Please look at the next page

Question	Response
Please provide details of any systems engineering designing and making assignments taught in your school at KS3.	

Please send this completed form to Richard Hamer.

As an attachment to richard.hamer@baesystems.com

As a fax to 01252 383 237

Thank you for completing the feedback.

Systems engineering designing and making assignment feedback for KS4

Name of School **Focus Area**

Question	**Response**
Did you create a systems engineering designing and making assignment? If yes, please comment on how useful you found the following.	
The Phase 1 approach to achieving commitment	
The Phase 2 approach to using the audit approach	
The Phase 3 approach to planning the teaching	

Please look at the next page

Question	Response
Please provide details of any systems engineering designing and making assignments taught in your school at KS4.	

Please send this completed form to Richard Hamer.

As an attachment to richard.hamer@baesystems.com

As a fax to 01252 383 237

Thank you for completing the feedback.

Introduction to the case studies

Case studies are a useful and effective way of bringing the world outside school into the classroom. In this section you will find guidance on using the studies, 5 studies, and a feedback sheet to allow you to let the authors know how you are using the studies and how they might be improved.

The first case study, ***Calculated fitness***, is a short study that shows how equipment in a modern gymnasium uses simple mathematics to provide performance information to those using the equipment.

The second case study, ***To the power of two***, describes the HybriDrive system developed by BAE Systems engineers to help decrease pollution caused by buses.

The third case study is in two parts. Part 1, ***A balanced approach to transport***, describes the thinking behind the development of the Segway, a self balancing, electrically powered personal transporter. Part 2, ***Designing magic***, describes in more detail how the Segway was developed and how it works.

The fourth case study, ***It's all in the software***, describes how advances in the technology of display systems have led to changes in the way aircraft are controlled.

The final case study, ***Losing power*****,** describes what goes wrong when systems engineering fails, in this case the power supply disruption that took place in northern USA and Canada in the summer of 2003.

Please use the feedback sheet to provide the authors with information on how you used the case studies, their effectiveness and how they might be improved.

BAE SYSTEMS

Using the Systems Engineering Case Studies

As the basis for a whole class teacher led discussion
Some of the information in the case studies may be quite new to you and, as such, they provide useful inset in terms of subject knowledge. You can use the information and images in the case studies as the basis for a lesson in which you tell the story 'from the front', without giving the students the printed material. You can produce a series of overhead projector transparencies or PowerPoint slides from the printed materials and use these to construct a question/answer based lesson that moves your class through the exposition.

This has the advantage of providing a completely customised approach although it might be difficult to keep the concentration of a wide range of ability through out the lesson with this approach. It also has the disadvantage that it requires a lot of preparation time.

As individual reflective reading and small group discussion
You may wish to give each pupil a copy of a case study. If so it is important to explain the structure of the case studies to your pupils. Tell them that the studies are in two parts.

The first is about a product that was designed using systems engineering. It will describe some or all of the following:

- What it does
- How it works
- What it is for
- Who will use it
- How it is used
- How it is sold or marketed

By reading part 1 of the study they will gain insight and understanding of what is achieved by systems engineering.

The second part is about how the product was designed and produced. It will describe some or all of the following:

- Which engineers and designers were involved
- Which engineering knowledge and skills were required
- How these were used to develop the systems
- How the project was managed
    - *Inception*
    - *Development*
    - *Manufacture*
    - *Installation*
    - *Training and support*
    - *Eventual disposal*

By reading part 2 pupils will learn what it means to do systems engineering and be able to apply these principles to their own project work.

Explain that there are several devices in the studies to help make them reading them active so that they are easier to learn from. These are:

- *Discussion points*
  Questions for the reader to discuss with other pupils
- *Research*
  Opportunities to find out more outside school time
- *Activities*
  Specific questions requiring written answers
- *Links*
  Websites with more relevant information

Explain that using a Systems Case Study is not like doing a worksheet. It treats them much more like 'grown ups' reading an article in a magazine or a professional journal, expecting them to read carefully and use the questions and research sections to develop

BAE SYSTEMS

their understanding. Tell them that it is quite alright to underline new words they don't understand yet or draw circles around text they find difficult. The aim of reading the study is to increase their understanding and if they understood it all to begin with then reading the study wouldn't be achieving that. You might find it useful to make an overhead transparency or PowerPoint slide of parts of the study and project it with annotations.

Using several case studies simultaneously with a class

This is a more complex way of using the printed materials and should only be used once students have become familiar with and successful at using the case studies.

- Organise the students into groups - five groups of four for example.
- Give each group a different case study.
- Ask each group to read the study and prepare a short oral report on, for example, the way the product was manufactured. Give the groups a time limit for this task, 15 minutes maximum.
- Each group then reports back to the whole class (2 minutes maximum for each feedback) and you note key points on the board.
- You then use a whole class question - answer session based on the key points to develop the class's understanding of manufacturing and the principles of manufacturing that can be applied to the production any product. You can use this approach to develop understanding about a range of issues concerned with systems engineering.

Writing your own case studies

Once you and your pupils are familiar with the case study approach to exploring systems engineering you may find that they are able to research and write their own case studies. There are several approaches to this task.

You, the teacher, carry out most if not all of the research and provide your pupils with an information pack from which each pupil develops their own case study. An alternative to this is for the pupils to use the information pack in groups and work collaboratively to develop the case study.

You, the teacher, require the pupils to carry out the research so that they develop their own information pack from which they write the case study. There are several variations on this. Each pupil carries out their own research and writes their own case study. The pupils work in groups to carry out the research and use the information to write individual case studies. The pupils work in groups to carry out the research and write the case studies as a group activity. You can make the task demand extra communication skills by requiring pupils to prepare information packs that are then used by other pupils to prepare case studies.

If you are fortunate enough to have a BAE Systems engineer visit your school you can arrange for him or her to be interviewed by pupils as a source of information for case study writing and also as a judge of case studies that have been produced

The format of the case studies can vary. They can take the form of written illustrated pieces as in this BAE Systems Engineering pack. Or they can take the form of live presentation to the rest of the class. These can be simple oral presentations supported by flip charts or overhead projection transparencies or full blown PowerPoint presentations.

BAE SYSTEMS