Can Systems Engineering be taught at Undergraduate Level?

Sue Goodlass
BAE SYSTEMS,
Lancaster House,
Farnborough Aerospace Centre,
Farnborough,
Hants, GU14 6YU, UK
Tel: (+44) 7801 713050
Email: sue.goodlass@baesystems.com

Fourteenth Annual International Symposium of the
International Council On Systems Engineering (INCOSE)
21 June – 24 June 2004

Abstract. Everyone knows that Systems Engineering is complicated and difficult. It takes a long time to become sufficiently experienced to be a good practitioner and people need to make mistakes in order to learn from them. How successfully then, can such a difficult topic be taught at undergraduate level? In the early 1990's, BAE SYSTEMS engaged Loughborough University to develop and deliver an undergraduate systems engineering programme and has recruited engineers from it since the first cohort graduated in 1997. This paper describes how the programme was designed and developed and compares systems engineers graduating from this programme with other engineers in BAE SYSTEMS.

Introduction

In the late 1980's British Aerospace (BAe) realised that the future success of the company would require a change in the way it did its engineering. Traditionally, UK MOD's approach towards defence procurement had been the acquisition of separate sub-systems from individual suppliers (e.g. aircraft, weapons, communications). Integrating the individual components together was often an afterthought, with inevitable consequences of incompatible interfaces in equipments never originally designed to operate as an integrated system. The emergence and importance of Systems Engineering was slowly being recognised, and, together with a shortage of Mission and Flight System engineers on aircraft programmes, an important decision was taken – to create an undergraduate programme to provide graduates with the capabilities to address the shortfall.

BAe Military Aircraft Division approached a number of eminent educational establishments in the UK with a request to work with them to create a new undergraduate programme. The aim was to produce graduates who could act as the 'glue' in project teams – people who could understand the principles in several specialist engineering areas and have the capability to integrate them together. Another major

objective was involvement of the company to assure the industrial relevance and practicality of the course. Yet a third strategic objective considered the future of the business – the new graduates would facilitate a change in emphasis and approach for the organisation as a whole.

At the time, there was significant doubt about the viability of such a programme. The subject matter was immature and relatively unknown, raising the question of how to attract young people onto the course itself. The attitude of the academic world was generally immature in relation to partnerships with industry, with some considerable reluctance on the part of academia to acknowledge the fact that, at the time, academia was not producing what industry wanted.

The stakeholders and their requirements

The company. As mentioned above, the primary requirement from BAe was a need for Systems Engineering graduates who could perform an integrating role within the company. At a platform level, systems engineers provide the capability to integrate diverse engineering specialisms together in a successful project team. From this point of view, every team needs to have one or two systems engineers amongst the many specialists. With an eye to the future corporate strategy, it was recognised that increasing systems complexity coupled with continued long product lifecycles would require new ways of working, with a greater emphasis on a whole life view. The end of the cold war and subsequent emphasis on world wide collaborative ventures meant that teams would be drawn from several organisations, working together across international boundaries and time zones. BAE SYSTEMS itself is a world-wide organisation, operating at all levels of the ‘food chain’. This leads to the requirement for employees (i.e. graduating systems engineers) who take an holistic approach to design and develop systems and supporting systems that can provide continuity across the whole life of a product and the people involved.

The university. The university already had a strong Engineering tradition, with many specialist engineering courses including industrial placements. It also had a tradition of co-operation across departmental boundaries, with a number of departments providing teaching to students undertaking courses in other departments. The main requirement from the university perspective was to capitalise on this experience, maximise the use of existing teaching and minimise the creation of ‘new’ modules required specifically for the new programme. The new course needed to fit into the existing university administrative structure (which meant that a single department would take responsibility for managing recruitment, timetabling and course regulations) and minimise the risk that the students would not perform well. It had been observed that students taking joint honour programmes (i.e. studying subjects in more than one department) often performed less well than students undertaking single subjects – this was particularly noticeable in exam results when the joint honour students took the same specialist modules as the single honour students. The contributory factors were thought to be the high staff expectations (expecting the same background knowledge from both joint and single honours students) and the low student expectations (where joint honours students felt at a disadvantage compared to the single honours students). Since the new course was intended to cover a wide range of specialist disciplines, there was a

significant risk that the students would come out as ‘Jack of all trades, master of none’. It was important that the academic standards expected of the students were not compromised.

The students. From the students’ perspective, this would be a new course with no direct comparison with any other course in a UK academic institution. Scary! The planned spread of subjects (in sufficient depth to avoid the concerns raised above) and the 5 year duration was academically and practically even more scary! Thus the requirement from this viewpoint was reassurance of support from both the company and the university, together with a high level of confidence that the outcome would be a degree desirable to a number of companies to ensure their career prospects.

Development of a solution

The initial concept that was agreed was to use existing expertise in training specialist engineers (i.e. use existing modules on specialist degree courses) and to create a new inter-disciplinary thread to run through the course. The question to be answered was: how much of which specialist areas should be taught and how much ‘systems’. Since each part of the company and the university wanted the students to be taught as much as a specialist engineer in ‘their’ particular area, it quickly became apparent that the ‘required’ specialist teaching was far in excess of what could realistically be included in a course of four academic years. Whilst it was considered essential that the students did reach the same depth in some areas as those students studying in the same specialist areas, it was agreed that not all areas could be covered at this depth and the ‘systems’ aspect of the course should arm the students with the capability and the confidence to augment their knowledge in the future, should they need to. This approach prevents the ‘jack of all trades master of none’ label, and demonstrates to the students that they have the ability to understand specialist areas if and when they need to.

One area that could have been a concern was the lack of systems engineering, systems thinking or systems approach in the specialist modules – their focus was most likely to be in the relative specialist area with no consideration of any systems issues – after all, that was how they were designed. Hence, the ‘systems thread’ was the most important aspect of the new programme. It needed to integrate the specialist areas together as well as provide an accelerated learning environment in order to realise a number of key skills which are usually only gained by experience - encouraging the students to try out new things, providing praise when successful and support if not. Key areas identified were:-

- demonstrating to the students that they could do what was asked of them, i.e. give them confidence in their own abilities
- getting the students used to working together as part of a team, allocating and doing the work, anticipating the problems, managing the team, supporting other members of the team
- encouraging the students to practise the art of concise and effective written and verbal communication, identifying issues and describing them in different ways to meet the needs of the intended audience

- identifying strengths and weaknesses of people as well as technology, understanding the impact of human factors on the system
- analysis and synthesis – experience of deconstructing and reconstructing systems and arguments
- identifying and preparing for different possible outcomes of a course of action (or inaction)
- learning about the systems lifecycle and the tools to support it.

A very different method of teaching was required. Groups of students were to be put into challenging situations and asked to report back to the whole cohort, encouraging them all to reflect on what had actually happened and what could have been done differently. The students would be encouraged to try new ways of working and to find ways to get more output for a fixed amount of work (in essence, to realise that the sum of the parts exceeds the whole). A crucial factor would be how the students responded to these 'experiments' and were able to learn for themselves, rather than through a traditional 'chalk and talk' approach.

Course Structure and Content

The MEng in Systems Engineering at Loughborough is a five year undergraduate programme consisting of two "foundation" years (Parts A&B), an optional year in industry and then two "advanced" years (Parts C&D). Successful completion of the industrial year results in the award of a Diploma in Industrial Studies. A four year alternative is available for those students who elect not to complete the industrial year. Entry onto the course is based on a points system, where points are awarded for each A level (or equivalent) qualification. Generally students need to gain a minimum of 3 grade B passes (where A is highest, B second, etc.), two of which must be in scientific or numerate subjects (and if Mathematics is not one of them, then a further qualification in Maths is required).

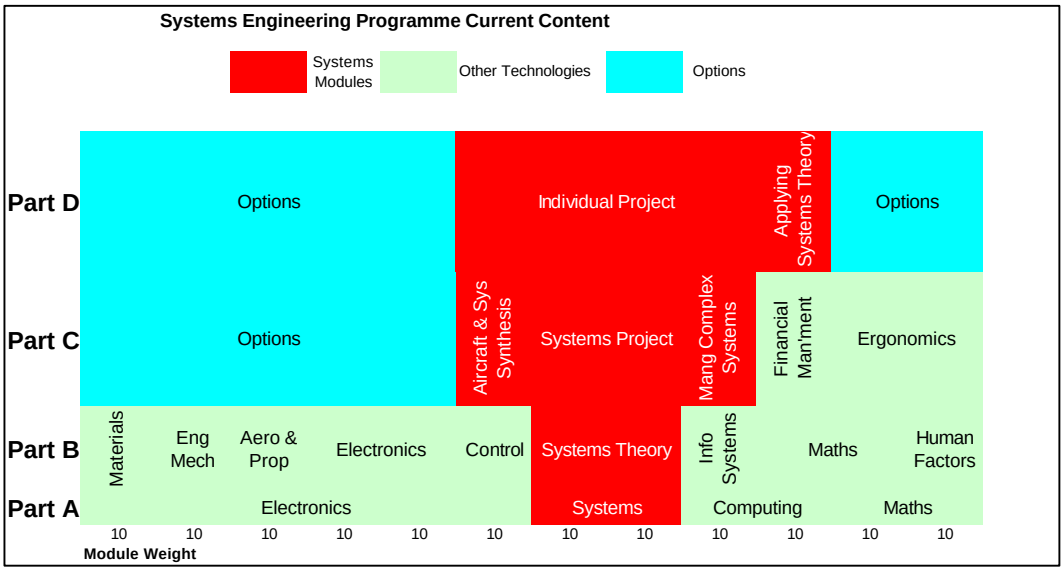

Figure 1 The overall structure of the course

Throughout the programme, Systems Projects are used to reinforce the learning:

- Part A includes a paper based project to develop an awareness of systems.
- Part B includes an introduction to processes; requirements analysis & development tools.
- Part C includes a Group Project involving the bidding process and building engineering solutions. Group size is generally 5 or 6 people.
- Part D includes an individual Project requiring systems engineering process to be demonstrated.

Both Parts A and C involve the students formally presenting the results of their project to representatives from the company and academia. In each case, this presentation is assessed in terms of their understanding and their ability to communicate the systems aspects of the work they have undertaken.
The systems element of the course contributes about one sixth of the overall course in the foundation years, and one third in the third academic year. Although the initial intention was for the company to provide problems for the projects, current practice is for the group project in the third year to tackle a problem proposed by an academic sponsor, usually from one of the specialist areas. Many of the projects roll over two or more years, allowing the students to experience two viewpoints – that of working on legacy projects and that of passing on their knowledge to future teams.
Although there is no formal systems teaching in the final year, the students are expected to apply their systems know-how in their individual project (which contributes a third of the final year) and to perform well in the 'specialist' areas (alongside subject specialists in their final year). They are also required to apply their knowledge as they mentor and guide other students who doing their third year project.

The Industrial Year

The Industrial Year provides an opportunity for the students to practice what they have learnt in a real work environment. The year usually consists of three placements (each of typically 20 weeks) in different projects and possibly in different parts of the business. This allows the students to experience different parts of BAE SYSTEMS in order to make a judgement of their preferred career route and gain experience in other areas that contribute to their professional development. A number of guidelines have been identified to define what makes a good placement:

- Real existing project work (i.e. not a made up task specially for the student)
- Has technical content where student can use engineering judgement or skill
- Task setting should be challenging but achievable
- Should allow a measure of responsibility (for self, for deliverable) commensurate with age/capability
- Contributing member of a team (i.e. develop interpersonal skills, management skills depending on age)
- Identified line manager (responsible for day to day technical activities)
- Identified personnel contact (for other issues)
- Mentor (to provide a systems engineering view)

- Plan should allow clear objectives to be set by week 3
- Deliverable or measurable output
- Tasks should be identifiable within the engineering process model (level 3) if possible but at least process area should be identifiable (requirements, analysis, design, integration & test, support, bid, specialist), together with specific tasks / skills/ tools (e.g. RTM, design spec, test box…)
- Identify how task contributes to the business
- Identify how task complements and builds on academic studies
- Identify any Engineering institutions requirements
- End of placement presentation (student) and reports (manager) – be honest

Part C: Managing Complex Systems Module

This module is designed to give students an understanding of established methods and techniques for developing large, complex systems and managing a project which employs many engineers to develop a product of this nature.

The objectives of this module were:

- To equip students with a conceptual 'tool-kit' for Systems Engineering and an awareness of the usefulness and limitations of such tools.
- To enable students to work as part of a large project team and understand how quality, development time and expenditure are controlled.
- To give students the ability to produce a detailed project management plan for a complex project.

The module consists of two parts: 'System Engineering Management' (where the topics covered include the Development Life Cycle, Requirements Capture & Analysis Methods, Performance Analysis and Prediction Methods, Fault Tolerance, Reliability and Safety Assessments, Integration & Test, Verification & Validation, Concurrent Engineering, System Certification and Release, Trials Management, Customer Acceptance and Demonstration, Quality Management, Configuration and Change Control, a template for a Systems Engineering Management Plan) and 'Project Management' (topics include Statement Of Work, Work Breakdown Structure, Organisational Breakdown Structure, Responsibility Assignment Matrices, Logical Network Analysis, Planning & Scheduling, Critical Path Analysis, Cost Estimates, Financial Management, Risk Management, Contract Management, Teamworking, Project Planning, Reviews (Process, Progress & Performance)). This module was delivered by a BAE SYSTEMS employee (yours truly) in order to bring additional industrial experience into the academic forum. Anecdotally, it has provided the students with a significant insight into how a large system developer like BAE SYSTEMS must operate in order to be successful.

Example Part C Group Projects

Students in groups of 5 or 6 undertake a project during their third academic year (Part C). These project can range from an entry to Robot Wars or Robofootball, to an examination of the effects of seatbelts on pregnant women. Some example projects are shown below.

Systems students working with an underwater exploration vehicle: the aim of the project is to enable the vehicle to operate autonomously, eliminating the need for the umbilical cable linking it to an operator at base. The technology being developed here is equally applicable to Unmanned Air Vehicles and the next generation of combat aircraft.

This project involved Systems Students developing a headset and supporting equipment that could be used by disabled people to control a PC by eye movement alone. This project drew on many fields of study, including computing, electronics and virtual reality. If developed further, this could be a useful technology for use in a future fighter aircraft cockpit, easing the pilots workload in a difficult and busy environment.

Delivery of a solution, a Systems Approach

It was quickly realised that the new programme itself, a multi-disciplinary course within a system of academic specialisms, provided many systems challenges. In addition to defining the content of the course and integrating the different modules together to obtain the required emergent properties (i.e. graduates with the requisite skills and knowledge), methods were needed to sell the new course to prospective students with no knowledge of the emerging discipline.

Sponsorship. The enhanced nature of the Systems Engineering MEng Programme inevitably makes it more costly to deliver, and such costs exceed the funding availability from University and HEFCE sources. From its inception, the company agreed that additional funding would be available each year to enhance the programme delivery and facilities. Such funding was focused in the following key areas:

- Increased staff time for the Part A, B and C Systems modules: Part A & B Systems modules demand approximately twice as many staff as conventionally taught modules. Multi-disciplinary 'master class' sessions are a feature of delivery. Part C Systems Project groups have the assistance of a Systems Support Team to help with the Project process.
- Exposure to specialists in areas such as Avionics, Aircraft Systems and Complex Systems. It is beneficial if these are practitioners, and are familiar with the latest techniques and technologies.

- Provision of dedicated Systems Engineering Laboratory, and subsequent development and updating of the facilities, including part funding of full time technician support.
- Equipment for Part C group systems projects and Part D individual systems projects
- Focused programme promotion above that of normal undergraduate programmes - found to be necessary since the majority of school leavers – even those choosing to study engineering – will not have heard of Systems Engineering. Experience over the past 10 years has demonstrated that the intake to the programme dropped considerably in those years without specific targeting & promotion.

From a student perspective, a certain number of sponsored or assisted places are available each year. For those students successfully gaining one of these places, the company provides an annual payment to supplement other sources of income, a guarantee of paid work experience in the summer vacations and during the industry year and, more than likely if they are successful, the offer of employment.
Sponsored students were originally selected by assessment centre during their final year at school and offered sponsorship conditional upon being offered and taking up a place on the course. Academic qualification to enter the assessment centre was set higher than the entry requirement for the course and candidates had to pass various numerical and verbal reasoning tests, and technical and personal interviews.

Measures and metrics

How do we measure the success of the programme?
The following table identifies the number of students graduating from the MEng since it started in 1992. It also shows the number of sponsored students recruited into BAE SYSTEMS and the number who entered employment elsewhere [based on Figures provided by Loughborough University]. In addition to students entering employment, each year there are some who decide to continue their education (in the UK or abroad) or decide to travel (on a gap year).

Cohort Start	Year of graduation	Number in cohort	Number sponsored	Number recruited	Other Employment
1992	1997	31	26	25	6
1993	1998	36	30	22	7
1994	1999	33	27	20	10
1995	2000	45	37	20	19
1996	2001	45	38	21	21
1997	2002	43	32	24	6
1998	2003	43	33	29	No data

Table 1 - Number of Students Graduating per year

Clearly in order to determine the value to BAE SYSTEMS of such a scheme, the key question is “does it work?”, i.e. Does the programme deliver graduates with the skills and capabilities originally envisaged? A rigorous analysis has not yet been undertaken against the original objectives but hearsay evidence is strong.

Academic Success

Academically, the first cohort of students who graduated in 1997 performed very well, with 8 first class honours degrees and 19 upper second class degrees being awarded in a group of 32. As a group, they outperformed the subject specialists taking the same final year modules in a number of departments and as individuals, achieved the top mark for their projects in three of the five co-operating departments (in competition with specialists in those departments).
This trend has been maintained with, on average, 20% of each cohort being awarded first class honours degrees and almost 60% being awarded upper second class degrees.

Figure 2 Happy Graduates (graduating in 2000)

Competition

Most BAE SYSTEMS businesses or Joint Ventures are keen to take as many of the MEng graduates as possible. External competition to recruit the graduates increased after the first couple of cohorts graduated and the output from the course became beter known in the wider market – their capability was certainly not limited to the Aerospace and Defence market. Evidence strongly suggests that the graduates are a sought after commodity, with about 20% finding employment in other high-tech companies, banks and consultancy firms such as Arthur Andersen, Accenture, Barclays, Schlumberger, Deloitte & Touche, Logica, Deutche Bank, PriceWaterhouseCoopers, Goldman Sachs, Ford, Sony, and many others. A higher proportion were recruited outside BAE SYSTEMS during the ‘dot com’ boom years, when it was difficult for BAE SYSTEMS to compete with the attractive salaries offered, although the investment made by BAE SYSTEMS in the sponsorship scheme (time, money and effort) has been effective in allowing many of the students to experience a real working environment to which they wish to return on graduation.

Performance

In one part of BAE SYSTEMS, a recent review of graduate progression noted that graduates from this programme tended to out-perform their peers in terms of career advancement (and salary).

From a technical viewpoint, the depth of their technical capabilities does not appear to be seriously impacted by the breadth of material covered in the programme, and they are generally considered to be comparable to their “single discipline” peers. They are not, however, well suited to traditional, single-disciplinary roles, and tend to be frustrated by these – both as placement students and as graduates. They do best in roles demanding a broader perspective and an ability to deal with complex, multidisciplinary issues – both in “pure” engineering and in associated fields such as project management, marketing and procurement.

Graduates Perspective

To investigate career progression, perceptions of the course and any issues or hurdles faced by the graduates from the programme, the graduates from the original cohort (1992 graduating in 1997) through to 1995 (graduating in 2000) were asked a series of questions. [Those graduates joining BAE SYSTEMS since 2001 have just finished or are still undertaking the Graduate Development Programme and hence were not included n this survey.]

These are some of the quotes from their responses:

> ‘degree certainly has helped through my systems thinking approach to issues … these abilities are vital in the project management environment’
> ‘the unique way of learning gave me the mindset to question and improve the way BAE SYSTEMS carries out systems engineering’
> ‘it did give me the broad grounding in multi disciplines which other graduate with whom I have worked appear to be lacking’
> ‘it was essential to gaining an American work visa’
> ‘it helped me gain Chartered status earlier than I might have gained it otherwise’

Areas in which the graduates are currently employed vary considerable and include Project Management, Systems Engineering, Software Development, Team Leaders or Managers, Flight Test, and Supplier Management. In some cases the degree course has provided sufficient technical depth in the graduates chosen area, in others, sufficient breadth to be able to work across a project, in others still, a way of thinking which has been beneficial.

None of the graduates felt hindered by their choice of degree – in a number of cases, the ‘systems thinking’ aspects or broad engineering base was felt to have been a benefit compared to their peers – although some felt it made little difference, other than in their managers’ higher expectations of them, based on previous experience of graduates from the course.

In summary, there is little difference in the diversity of the positions within the company which graduates from this programme have attained, compared to the general diversity of the general engineering population. What they have gained is breadth and depth, which may have given each individual a greater flexibility in his/her career path. It is acknowledged that graduates from this programme have an advantage compared to other graduates – they enter the company ‘up and running’, understand the business and have been exposed to a number of different project areas. This generally results in

accelerated pay awards and so these graduates are often thought to progress ‘faster’ than their peers.

Room for Improvement

Work is ongoing within BAE SYSTEMS to examine the current programme provision and identify areas for improvement, both within the taught programme and the infrastructure surrounding it. There is scope to create a Bachelor of Science (BSc) degree, which could be completed after three academic years, and there is scope to create different streams within the degree – where individual choice of options would be limited to a themed set, rather than completely open at present. The Systems Engineering Innovation Centre (described by Tony Jackson et al at INCOSE 2003) is taking an increasing interest in the graduates and their projects. Within Engineering Developing You (EDY), the BAE SYSTEMS career management framework for engineers (described by this author at INCOSE 2002), the benefit of systems engineering training has been recognised and a commitment made at the highest level to provide this at a basic level for all engineering graduates on the Graduate Development Programme.

Conclusion

The simple question that this paper aims to answer is ‘Can Systems Engineering be taught at Undergraduate level?’ Let’s examine the evidence:

1. The Loughborough University Systems Engineering MEng programme has attracted sufficient new students each year to remain viable in an increasingly competitive environment.
2. Graduates are increasingly sought after by various high-tech companies and consultancies.
3. The course is accredited by the Institute of Electrical Engineers, The Royal Aeronautical Society and the Institute of Measurement and Control
4. The graduates themselves appear to experience no disadvantage and in some cases experience positive advantages compared to their peers.
5. Perception of managers employing graduates from the course is mostly positive.
6. All graduates employed by BAE SYSTEMS requires specific skills training in the toolsets used within the business to achieve the required depth no matter what their single discipline. Graduates from this programe benefit from their broad base in multi-disciplines, their capability to communicate across many different disciplines and the the system thinking capabilty resulting from the programme.
7. Graduates from this programe appear better equipped to deal with complex interactions and dependencies between people, products and processes.

So the answer to the question is a resounding ‘Yes’.

Biography

Sue Goodlass (BSc) began her career in 1982 as a Systems Engineer in the Guided Weapons Division of Marconi Electronic Systems. Much of her early career was involved in research, design and development of guided weapons, later specialising in Risk Management on a Missile Seeker program.
In 1998, Sue became a Systems Engineering Tutor at the GEC Management College with responsibility for Marconi Electronic Systems students on the assisted MEng programme at Loughborough University. This led to her developing and delivering the 'Managing Complex Systems' module on the Systems Engineering MEng programme.
In 1999, Sue moved into the BAE SYSTEMS Virtual University, where she is now responsible for developing the EDY framework and associated training programmes.

Acknowledgements

Thanks to John Hooper, Programme Manager, Systems Engineering MEng course, Loughborough University, for providing much of the data relating to the graduates and their employment outside BAE SYSTEMS, and also the photographs. More information on the programme can be found on the website:
http://www.lboro.ac.uk/eng/systems/programmes-meng.html

FOOTNOTE: Updates since 2004

This paper was originally written in 2004 and delivered to the INCOSE International Symposium. Since then, a number of evolutionary changes have been made to structure and content of the MEng course itself, summarised in the diagram below.

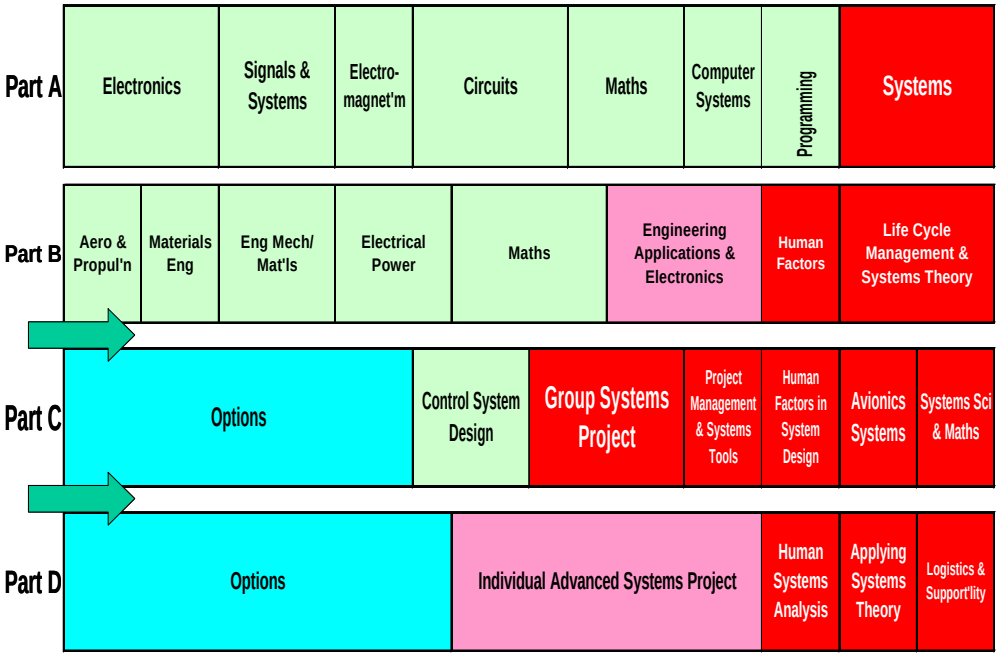

Figure 3: Evolution of MEng Modules.

In addition, we now have more data about the number of students graduating from the course

Cohort Start	Year of graduation	Number in cohort	Number sponsored	Number recruited	Other Employment
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1993	1998	36	30	22	7
1994	1999	33	27	20	10
1995	2000	45	37	20	19
1996	2001	45	38	21	21
1997	2002	43	32	24	6
1998	2003	43	33	29	No data
1999	2004	61	32	14	No data
2000	2005	41	27	14	No data

Table 2 - Number of Students Graduating per year (updated)